Quantifying impacts of bioenergy

Model advancements to analyse indirect land use change mitigation and socio-economic impacts

Marnix Brinkman

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mitigation and socio-economic impacts

Kwantificeren van de effecten van bio-energie

Modelontwikkelingen voor de analyse van sociaaleconomische
effecten en de mitigatie van indirecte landgebruiksverandering

(met een samenvatting in het Nederlands)

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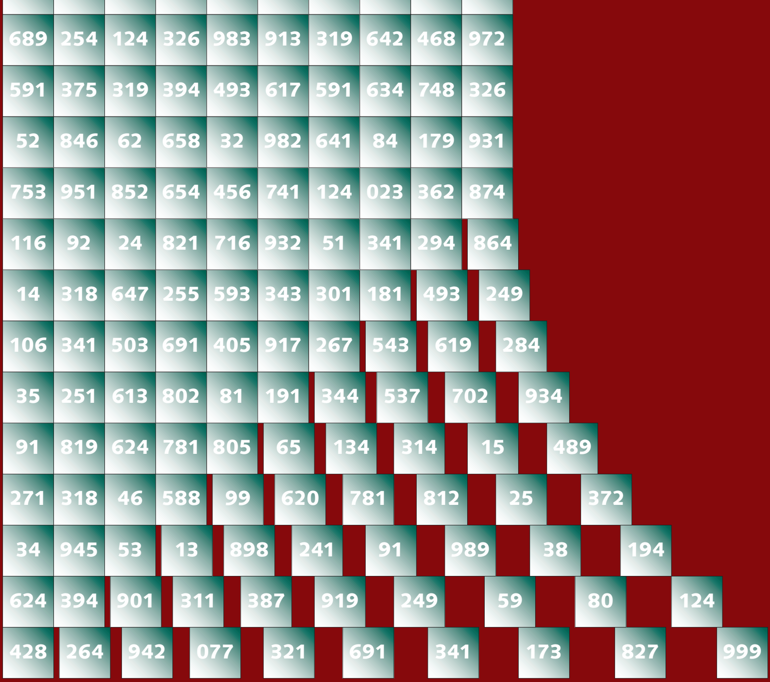
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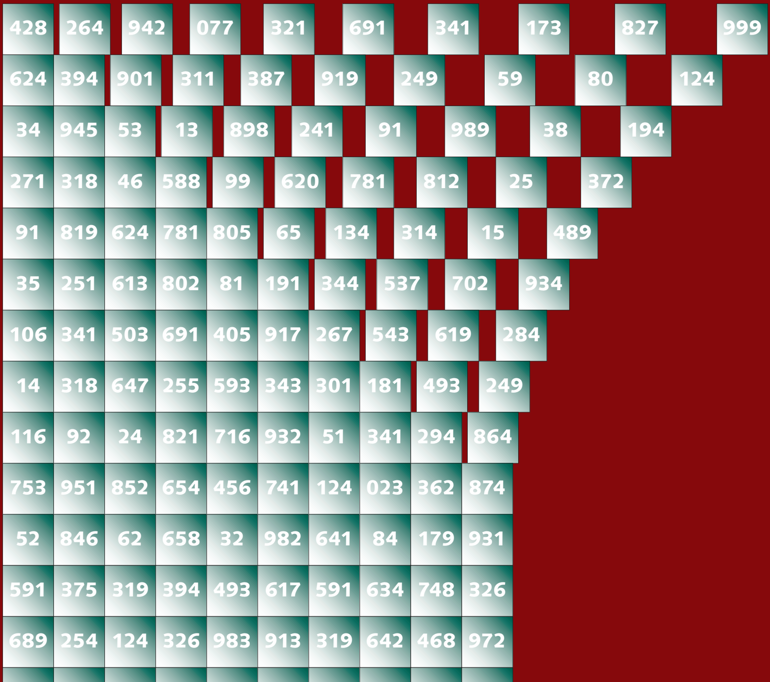
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1 Introduction

1.1 The need for sustainable bioenergy

Energy is used for the provision of most needs of everyday life: from heating and food preparation to transport and manufacturing, society requires energy [1,2]. Although the availability of energy enables societal development and growth, the present, fossil fuel-based energy mix [3], is also connected to many of the world's most pressing environmental and social issues [4,5].

Since the rise of fossil fuel use from the mid-18th century onwards, the concentration of CO_2 and other greenhouse gasses (GHG) in the atmosphere has increased steeply [4]. Although a significant share of the emissions result from agriculture and land use change, fossil fuel (coal, oil and natural gas) use is responsible for two thirds of the annual global anthropogenic GHG emissions [6–8]. The consequence of this rising concentration of GHG is a change in the Earth's climates [4]. Effects such as increased temperature, more extreme weather events and changing hydrological cycles can cause reduced agricultural yields, decreased water availability and direct health effects. This, in turn, negatively affects livelihoods and human security through for example, reducing economic growth, exacerbating poverty, harming food security and triggering migration [9–14]. For all these effects, the most vulnerable people, who are least equipped for adaptation, will most likely bear the heaviest burden [9,15].

In addition to the effects from climate change, the production of fossil fuels in itself has also substantially negative impacts on the environment and human well-being. Resource extraction is associated with large scale pollution and in some cases destruction of entire landscapes [16]. In addition, it is considered as one of the most dangerous sectors in terms of occupational health risks [17,18]. Also, emissions of sulphur, particulate matter and other substances from burning fossil fuels have major public health impacts [18,19]. Furthermore, fossil fuel resources are concentrated in a limited number of countries with large reserves [20], making other countries dependent on their supply, with strong geopolitical consequences. Although these fossil fuels represent a high economic value, exploiting these do not always lead to prosperous societies. Instead, fossil fuel reserves are even referred to as a resource curse [21,22]: where natural resources are a cause of slow and inequitable growth [23,24]. In addition, resource exploitation is also connected to large scale human rights abuse [25,26] or even civil wars [27].

At the present time, not all people have access to modern energy. Despite strong development and economic growth in poor countries, today one in eight people in the world do not have access to modern energy sources [28]. In Sub-Saharan Africa this is even three in five [28]. Furthermore, around half of the world's population still relies on traditional bioenergy for cooking and heating [3,29]. This lack of access to modern energy access has negative consequences for human and economic development [1,29]. In response to this situation, the United Nations Sustainable Development Goals include the explicit goal to provide affordable and clean energy for all [30], with a specific target to increase the use of renewable energy sources.

Currently, bioenergy, including traditional usage, is the most employed renewable alternative to fossil fuels [3]. The term bioenergy is used to describe liquid, gaseous or solid fuel produced from organic matter, excluding fossilised material [31,32]. Because plants sequester the CO_2 during their lifetime, the net GHG balance of bioenergy can be favourable compared to fossil fuels [33]. In 2015 bioenergy covered nearly 60 EJ, or about 10% of the world's total primary energy supply [34]. In some countries, it already plays an important role in replacing fossil fuels in the transport sector [35]. The most prominent example of this is Brazil, where 22% of the transport fuel is produced from biomass, mainly ethanol from sugarcane [35,36]. But also the world's largest energy consumers, China, US and the European Union, use bioenergy in the transport sector to reduce the use of fossil fuels and stimulate renewable energy sources [37–39], although it is limited to 2-5%[35].

Further expansion of bioenergy can be expected: without new climate policies, the International Energy Agency (IEA) projects a 15% increase in global bioenergy use until 2025 (including traditional use) [34]. With climate policies, this is likely to increase significantly. Studies projecting future energy demand and supply under strict climate policies, show a much stronger increase of bioenergy use in the energy mix [34,40]. For example, IEA projects an increase in the total primary energy supply from 9 to 16% in 2040 [34]. Also, nearly half of the countries that submitted a Intended Nationally Determined contribution in preparation for the 2015 climate summit in Paris included bioenergy as a mitigation measure [41].

Beside the potential environmental advantage over fossil fuels, bioenergy is also promoted because it can have positive socio-economic effects [42–44]. Countries that introduce a bioenergy mandate expect it to bring benefits such as economic growth, job creation and reduced dependence on the import of fossil fuels [45,46]. Especially for the development of rural areas, bioenergy is expected to provide a significant boost [47].

Despite the various positive potential impacts of bioenergy, past studies have shown sustainability impacts of bioenergy not to be unequivocally positive. For example, forests have been cleared to be replaced by plantations for biomass feedstock production [48,49]; there have been reports of land-grabbing and conflicts on land tenure [50,51]; negative impacts on biodiversity have been recorded [52]; and there are claims of rising food prices as a result of increased bioenergy use [53] which endangered food security [54,55]. Furthermore, the GHG emission reduction benefits are sometimes contested, despite the carbon uptake of the feedstock during its growth. Agricultural production and conversion of feedstock to secondary energy carriers require energy and result in GHG emissions, reducing the net GHG benefit of bioenergy as replacement of fossil fuels [56,57]. In addition, when bioenergy triggers conversion of high carbon stock lands to accommodate feedstock production, the GHG emission benefits can be annulled and bioenergy can even cause higher emissions than fossil fuels [58,59]. As a result of bioenergy's potential to contribute positively and negatively to the sustainability of the energy supply, the sustainability of bioenergy has received a lot of public and academic attention. The increase in academic attention in the last years is for example illustrated by the large growth in scientific publications in this field (see Figure 1.1).

The mix of potential positive and negative environmental and socio-economic impacts that is found underlines the importance of studying the sustainability of bioenergy. When bioenergy is used as a means to promote a more sustainable energy supply, it should not create new sustainability problems: a situation where bioenergy is implemented, but would cause additional GHG emissions or lead to other negative impacts is undesirable [60,61].

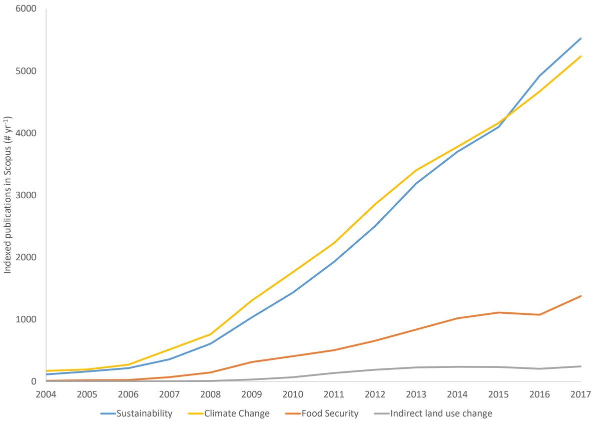


Figure 1.1 Annual number of new publications on sustainability impacts of bioenergy added to academic search engine Scopus. The lines display four sustainability themes that are often linked to bioenergy and represent the number of publications found in combination with "bioenergy" or "biofuel".

1.2 Measuring impacts

The sustainability impacts of bioenergy are diverse and the magnitude and direction of impacts can vary based on diverse aspects such as the local conditions, feedstock choice, technology used and management applied [62,63]. This complicates general claims on the sustainability of bioenergy [47,62]. The variation in the direction of potential sustainability impacts, and the factors that influence the outcomes are illustrated in Table 1.1, adapted from the Global Bioenergy Partnership (GBEP, [32]) and Creutzig *et al.* [64].

Table 1.1 Potential positive (+) and negative (-) impacts of bioenergy on the three sustainability themes. For the impacts marked (+/-) the direction of the effect is dependent on the implementation and local situation. Adapted from GBEP [32] and Creutzig et al. [64].

Impact	+/-	Scale
Environmental		
Lifecycle GHG emissions can be reduced from replacing fossil fuels, improved soil carbon on degraded lands or smart modernisation and intensification	+	Local to global
Land use change and intensification (e.g. fertiliser use) can lead to increased GHG emissions	-	Local to global
Can displace activities and other land uses, leading to land use change	-	Local to global
Effects on soil quality can be positive when plantations are on degraded land	+/-	Local
Biofuel plantation can promote deforestation or forest degradation, under weak or no regulation	-	Local to global
Emissions of non-GHG air pollutants, including air toxics / reduction in lead and other additives to fossil fuels	+	Local to global
Large-scale bioenergy crops can have negative effects on biodiversity, soil quality and biodiversity.	-	Local to global
Biological diversity in the landscape can be stimulated when on degraded lands	+	Local to global
Social		
Can improve or decrease land tenure rights and lead to conflicts	+/-	Local
Competition with food security, including availability (reduced local production), usage (diversion of food to fuel production) and stability. Wastes, residues and by-products are an exception	-	Local to global
Investment in agricultural sector, integrated production and improved management can improve local productivity and stimulate food security	+	Local
Change in income, economic activity and income diversification	+	local
Job creation from increased labour demand or reduction through new technology	+/-	Local to national
Gender equality (e.g. change in time spent by women collecting biomass)	+	Local to national
Bioenergy used to expand access to modern energy services		
Change in mortality and burden of disease attributable to indoor smoke from efficient biomass techniques	+	Local to national
Incidence of occupational injury, illness and fatalities can increase from harsh conditions, but reduce with mechanisation	+/-	Local to regional
Impacts on labour rights among the value chain	+/-	Local to national
May lead to concentration of wealth or poverty if sustainability criteria and strong governance is not in place	-	Local to regional

Economic		
Gross value added and economic growth	+	Local to national
Can contribute to changes in feedstock prices	+/-	Local to global
Change in consumption of fossil fuels and traditional use of biomass; increased diversity in the energy mix	+	Local to national
Can contribute to energy independence, especially at the local level / reduce dependency on fossil fuels	+	Local to national
Training and re-qualification of the workforce	+	Local
Increased investment in infrastructure and logistics, but access can be reduced to few social groups	+/-	Local
Technology development or technology transfer	+	Local to global
Potentially profitable investment, but uncertainty on mid and long term	+/-	Local to regional

The assessment of the sustainability impacts of bioenergy is preferably quantitative [44,65,66]. This is because quantitative measurements help to present the environmental and socio-economic effects in a transparent and objective manner, providing insight into the trade-offs between the positive and negative impacts. This insight could contribute to informed decision-making regarding bioenergy projects [67–69]. In order to enable decision making regarding bioenergy, a sustainability assessment should preferably be done before a decision is made and implemented. Decision makers can use the ex-ante knowledge of the sustainability impacts of bioenergy in the decision-making process to weigh the positive and negative impacts and potentially steer on continuation, crop selection, location, size, or other attributes of the bioenergy implementation.

However, the potential to ex-ante quantify the impacts of bioenergy depends on the availability of methods. For environmental impacts, methods such as life cycle assessment [70] and carbon footprinting [71] are well developed and standardised. There are even specifically regulated calculation methods and tools available to quantify the GHG emissions of bioenergy (e.g. [56]). However, there is still no consensus on all aspects of the GHG emission calculations [64,72]. For the social and economic impacts, the availability of suitable models is much lower and methods to determine these impacts have to be further defined [67,73–76]. Compared to the environmental impacts, knowledge on ex-ante quantification methods for the socio-economic impacts lags behind [77].

1.3 Indirect effects

When assessing the socio-economic or environmental impacts of bioenergy, it is important to consider that bioenergy can also have indirect effects [78]. As the production of bioenergy takes place in a complex and dynamic system with multiple interlinkages between e.g. energy, land use, and agriculture, bioenergy also affects many aspects indirectly. Indirect effects occur through competition, displacement, or second order supply relationships. The direction of these indirect effects does not necessarily align with the direct effects, increasing the importance to include these in sustainability assessments, especially as the indirect effects of bioenergy can play a large role in the total impacts of bioenergy (e.g. [79]).

A key example of the indirect effects of bioenergy is indirect land use change (ILUC). Land use change is one of the main determinants of the GHG emissions of bioenergy [62]. LUC can be direct, where land is converted from one land use to agricultural land for the production of bioenergy feedstock, e.g. when forest is cleared to make land available for a bioenergy plantation. However, if the feedstock production displaces other agricultural production and demand does not decrease proportionally, additional land use change and associated emissions may occur elsewhere to continue to meet the agricultural demand. Thus the expansion of bioenergy feedstock production leads to displacement of other agricultural production to other regions [58,80–83]. This process is called indirect land use change. When ILUC occurs at the expense of forest or other high carbon stock lands, this can be a source of large GHG emissions. When including ILUC emissions in the GHG balance of bioenergy, it can even lead to emissions above those of a fossil fuel reference [58].

There are also indirect socio-economic effects of bioenergy. Extra demand for bioenergy leads not only to additional production in the bioenergy production chain, but also companies supplying to the bioenergy sector see increased demand and employment [84]. In contrast, for fossil fuels companies and their suppliers are likely to see decreased demand and employment from additional bioenergy. These indirect effects can be substantial [43], but are not always included in analyses, thereby potentially overlooking positive and negative sustainability effects of bioenergy.

Because measuring of indirect sustainability impacts is difficult, including these in sustainability criteria is equally difficult. Because the global dynamic system in which bioenergy operates makes it problematic to link a specific bioenergy impact to specific bioenergy production, the impacts fall outside a bioenergy producer's control [78]. However, in order to improve the sustainability of bioenergy, negative indirect impacts have to be avoided. Therefore, new ways have to be explored in order to account for the indirect (but still causal relation) between bioenergy and impacts (see also section 1.5).

1.4 Distribution of effects

The distribution of the impacts of bioenergy is geographically and socially unequal, and resilience of different groups [85] and ecosystems [86,87] to negative impacts varies. Therefore, it is important to assess who wins and who loses from the implementation of bioenergy [88,89]. The distribution of the sustainability effects of bioenergy needs to be determined to avoid placing a burden on the most vulnerable.

Geographically, sustainability impacts of bioenergy are not evenly spread across the world, a country or even a sub-national region [90,91]. Instead, the direction and magnitude of impacts depend on the context and dynamics that vary between locations (e.g. biophysical, stimulation of technology etc.) and are therefore unequally distributed [62]. For example, the presence of feedstock processing industry can lead to a concentration of employment and economic activity in an area. In contrast, areas that lack suitable land for bioenergy production are likely to still be affected indirectly from production elsewhere. This means that the geographical distribution of the effects also needs to be included in the sustainability assessment. Especially since the location and context also define the relative importance of the various impacts [76,92]. For example, the positive effect of job creation is much larger in regions with high unemployment than in regions where unemployment is low [44]. Similarly, occurrence of child labour can be an important aspect to consider in some high-risk areas, but irrelevant elsewhere [93].

The spatial level of analysis plays a role for providing insight into the distribution of the impacts. Using assessments at a global level effects are averaged over the whole world, providing little information where the impacts actually occur. Global level analysis disregards the variation in the impacts between countries and regions, making it impossible to draw conclusions on who wins or loses from bioenergy implementation. On the other hand, analyses zooming in on only those areas with bioenergy, miss the effects that occur outside those regions or the cumulative effects from multiple bioenergy, projects in a country [90]. Previous studies mostly focused on a single spatial level, without considering the differences in impacts at the various spatial aggregation levels. In addition, for some impacts, such as food security, impacts have not yet been ex-ante quantified on local scale, despite the evidence that there are measurable effects on sub-national level [33].

The distribution of socio-economic effects over different groups in society is also not equal. There are clear differences in impacts within a country between rural and urban populations [94,95] and between different income groups [96,97]. For example, rural households are in general more tied to agriculture than urban households, this means changes in the agricultural sector affect rural and urban households differently [94,95]. People's income also affects their resilience to negative impacts, with lower incomes being less resilient [9,98]. The unequal distribution of the impacts of bioenergy should not be neglected in sustainability assessment [99,100]. Whereas previous studies showed differentiated effects between different countries or regions (e.g. [101,102]), the social distribution is only included to a limited extent in bioenergy studies (e.g. [96,97]). Quantitative ex-ante assessment of socio-economic impacts is not well-developed in this area and needs more methodological development (see also section 1.2).

1.5 Improvement strategies

An ex-ante sustainability assessment of bioenergy implementation is likely to show a mix of positive and negative impacts. To promote the overall sustainability of bioenergy, there are a number of options to limit the negative impacts and promote the positive impacts.

Multiple certification schemes and codes of good practice have been introduced to mitigate the negative effects and stimulate sustainable bioenergy [75,103,104]. These certification schemes include sustainability criteria with which bioenergy production needs to comply. Certification schemes include effects that can be controlled directly by the operator, such as direct land use change, working conditions and water quality. Certification should confirm that the operators comply with the given sustainability standards [105]. However, the effectiveness of certification to ensure a sustainable outcome is sometimes questioned as the scope of the certification schemes, the adoption and the verification are insufficient in some cases [106,107]. There are examples where, as a result of high competitiveness between the certification schemes, the standards and verification became less strict [106,107]. In addition, the indirect effects of bioenergy, such as ILUC, are much harder to include in a certification scheme, as it is impossible to link the effects directly to a single bioenergy producer (see section 1.3) [75,78].

For indirect land use change effects, policy options have been proposed to avoid its GHG emissions [108,109]. One policy measure that has been explored is to introduce an ILUC factor in the obligatory bioenergy GHG emission calculations, to account for the indirectly caused GHG emissions. As bioenergy policies often prescribe minimum GHG emission savings (e.g. 60% in the EU [37]), some production chains would become less attractive, as it would be difficult or even impossible to meet these reduction targets when including the ILUC factor [110,111]. A disadvantage of this approach is that it applies a uniform factor to all bioenergy supply chains of the same crop type, irrespective of the location and measures to improve the standard performance. This means operators would have little incentive to reduce the ILUC they may cause as it would not reduce their ILUC factor.

Another option to mitigate negative indirect effects of bioenergy is to consider the agricultural sector as a whole when improving the sustainability of bioenergy [112]. Improving the whole agricultural sector in a region can provide additional land for bioenergy crops, without a risk of displacing other agricultural production and thus mitigating the risk of indirect land use change. This option of ILUC-risk mitigation is being explored by the EU [113]. However, this strategy leans heavily on options for agricultural intensification [114,115], and can thereby cause other unintended sustainability effects. The intensification could for example lead to additional GHG emissions in agriculture or have negative effects on employment as a result of increased mechanisation. This means these impacts need to be considered before implementation of ILUC-risk mitigation measures, to avoid shifting the burden elsewhere.

However, knowledge on the measures to improve the agricultural sector and their potential to reduce the risk of ILUC is limited. Therefore, the options need to be tested in different settings to account for the differences between various regions in terms of agricultural development and potential to implement these measures. In addition, the GHG emissions and socio-economic effects of these measures have only been studied to a very limited extent and need to be further explored to improve the sustainability of bioenergy.

1.6 Problem definition and aim

The previous sections identified a number of knowledge gaps regarding the quantification of sustainability impacts of bioenergy. These knowledge gaps are summarised below and lead to the aim and research questions of this thesis.

An increased role for bioenergy in future energy supply will have socio-economic effects. Neither the expansion of bioenergy nor the related impacts will be evenly spread over the world, a country or region. Rather, the direction, size and relative importance of impacts in each area depend on specific dynamics and characteristics of that area. Furthermore, the effects will also not be evenly distributed across different groups in society as, for example, rural households are in general poorer, less energy secure and more tied to agriculture than urban households in the same country. This means effects of changes in the agricultural sector affect rural and urban households differently, potentially creating winners and losers from the development of bioenergy. Hence, it is important to understand not only the global net socio-economic impacts of expanding biofuel production, but also the distribution of these impacts. This information can help to identify socio-economic opportunities and threats of biofuel expansion for different regions and different groups in society. Assessing this distribution is complicated by the fact that some effects fall outside the direct bioenergy supply chain and are only indirectly caused by bioenergy. The distribution of the sustainability impacts is only included to a limited extent by previous studies, especially the distribution of the indirect effects is lacking. In addition, knowledge on the ability and suitability of ex-ante quantification methods for socio-economic impacts of bioenergy is lacking. Knowledge of the availability and suitability of the methods for ex-ante quantification of socio-economic impacts of bioenergy can help to improve the sustainability assessments of bioenergy and can point towards priorities for method development in the future.

Despite the interest in the concept of low-ILUC-risk biofuels, strategies to reduce the pressure on agricultural land and methods to quantify its potential are still under development. Gerssen-Gondelach *et al*. [116] and van der Laan *et al*. [117] applied a method developed by Brinkman *et al*. [115] to quantify the potential of various measures to reduce the pressure on agricultural land and make land available for low-ILUC-risk biofuels. This quantification method needs to be tested for various settings to account for the differences between various regions in terms of agricultural development and potential to implement these measures. Although these measures aim to prevent GHG emissions from ILUC, implementing the measures can also lead to additional GHG emissions, e.g. when increased yields are obtained via increased fertiliser application. To avoid a situation in which the GHG emissions of the ILUC mitigation measures are higher than those of ILUC itself, it is necessary to better understand the emissions of ILUC mitigation. Gerssen-Gondelach *et al*. [118] found that application of the ILUC mitigation measures can reduce the GHG emissions in a region, under strict sustainability criteria. An important reason for this finding is the use of the perennial crop miscanthus to produce bioethanol, which is generally associated with low GHG emissions. Knowledge on the GHG emission performance of the ILUC mitigation measures applied for first generation biofuels is lacking. In addition, the measures to reduce the demand for agricultural land also have socio-economic effects. For or example, increased mechanisation in the agricultural sector can result in negative employment effects. Also positive effects can occur, when extra productivity in the agricultural sector leads to higher economic activity in the rest of the economy. Currently, there is little knowledge on the socio-economic impacts of these measures.

Although it is important to ensure bioenergy production leads to positive sustainability impacts and avoids negative impacts, there are still gaps in knowledge how to quantify the impacts of bioenergy. Therefore, the aim of this thesis is twofold. The first aim is to quantify impacts of bioenergy in different settings and on different spatial scales, and identify and develop methods for quantifying these impacts. The second aim is to determine the impacts of strategies to improve the sustainability performance of bioenergy. In order to meet these aims, the following three research questions will be answered in this thesis:

1. What are available and suitable methods to ex-ante quantify socio-economic impacts of bioenergy and how can different methods for various spatial scales complement each other?
2. What is the geographic and social distribution of bioenergy impacts, and what explains the variations?
3. What strategies are available for reducing competition for land and what are their socio-economic and GHG emission impacts?

1.7 Outline

The following five chapters address the three research questions. Table 1.2 gives an overview of the research questions that are addressed in each chapter and the spatial level and geographical scope of each chapter. The final chapter then summarises the findings of these studies, answers the research questions and presents the conclusions of this thesis.

Table 1.2 Overview of the research questions, spatial scale and geographical focus of each chapter of this thesis.

Chapter	Research questions addressed			Geographical scope	Spatial level
	1	2	3		
2			•	Hungary	National
3			•	Eastern Romania	Regional
4	•	•	•	Brazil	Micro regional to national
5	•	•	•	Ghana	Household and national
6	•			-	Project to global

Chapter 2 presents a method to assess the potential to mitigate ILUC risk and to produce low-ILUC-risk biofuel in a region, and applies this method to Hungary. Starting from top-down macroeconomic projections on agricultural production in 2020, the projected future land use in Hungary is assessed. Additional bioenergy production

above this baseline would potentially lead to ILUC. Through the application of four measures that reduce the demand for agricultural land or expand land availability, this risk can be mitigated and surplus land can become available. Using this surplus land to produce maize for ethanol would result in the production of low-ILUC-risk biofuel. This chapter addresses research question 3.

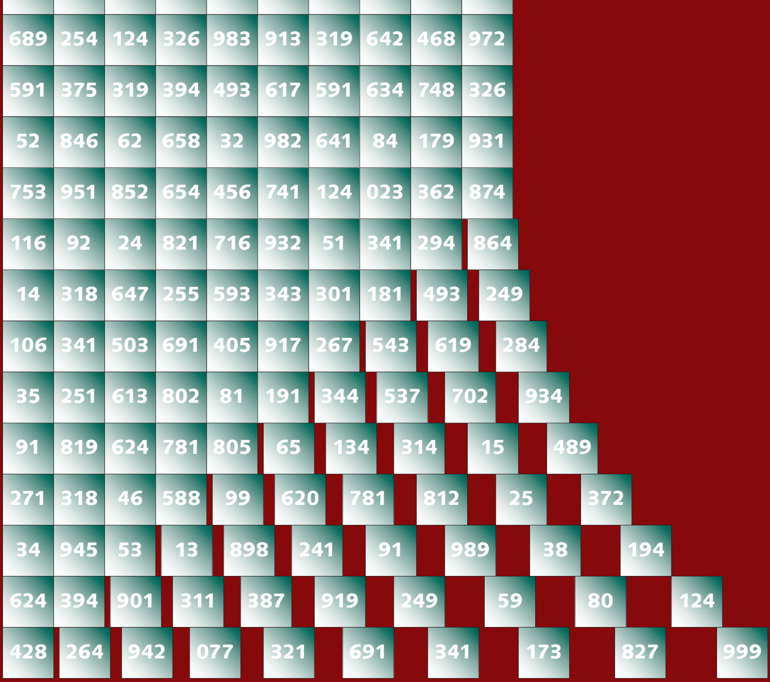
Chapter 3 builds on the previous chapter to answer research question 3. In this chapter, the ILUC mitigation measures that were identified in chapter 2 are applied to Eastern Romania in order to quantify the low-ILUC-risk rapeseed biodiesel potential in the region. Furthermore, in this chapter the GHG emissions from the application of the ILUC mitigation measures are quantified. Because the measures to reduce the ILUC risk partly depend on agricultural intensification, ILUC mitigation could potentially lead to additional GHG emissions. As the EU Renewable Energy Directive (RED) mandates a reduction in total GHG emissions compared to fossil fuels, the viability of the ILUC mitigation measures within this limit is verified.

In **Chapter 4**, all three research questions are addressed. In this chapter, a combination of a computable general equilibrium model, a land use change model and a multi-region input-output model is used to assess the effects of an expansion in sugarcane ethanol in Brazil in 2030 on employment, gross domestic product and trade. These socio-economic impacts are quantified at the level of the microregion, state, macroregion and the country and are differentiated between twelve income classes. This combination of models for socio-economic impact assessment at various spatial levels is a novel method for the ex-ante quantification of socio-economic impacts. The use of the input-output model makes it possible to compare the socio-economic effects between three microregions in the sugarcane producing area of the country and to assess the spill-over effects to other regions. In addition, the chapter includes the quantification of the socio-economic impacts of two measures that reduce the demand for land for biofuel and other agricultural production: second generation bioenergy and agricultural intensification.

In **Chapter 5** again all research questions are addressed. In this chapter a computable general equilibrium model is used to assess the food security effects of a 10% biodiesel and 15% ethanol mandate in Ghana in 2030. The impacts are determined for the four pillars of food security: availability, access, utilisation and stability in the other three. The impacts are determined for rural and urban households. This demonstrates how the distribution of food security effects of bioenergy implementation can be determined for different societal groups in a country.

Chapter 6 addresses research question 1 by reviewing recent literature on socio-economic impacts of bioenergy. The chapter provides an overview of the most relevant indicators of socio-economic impacts of bioenergy and the ability and suitability of methods to ex-ante quantify these impacts. The overview also distinguishes the spatial levels on which the methods can be applied and the indicators can be quantified. Thereby, the chapter gives a comprehensive picture on the availability of methods for socio-economic assessment of bioenergy and their current blind spots.

This thesis ends with an overview of the main findings of chapters 2 to 6, answers to the research questions and overall conclusion in **Chapter 7**.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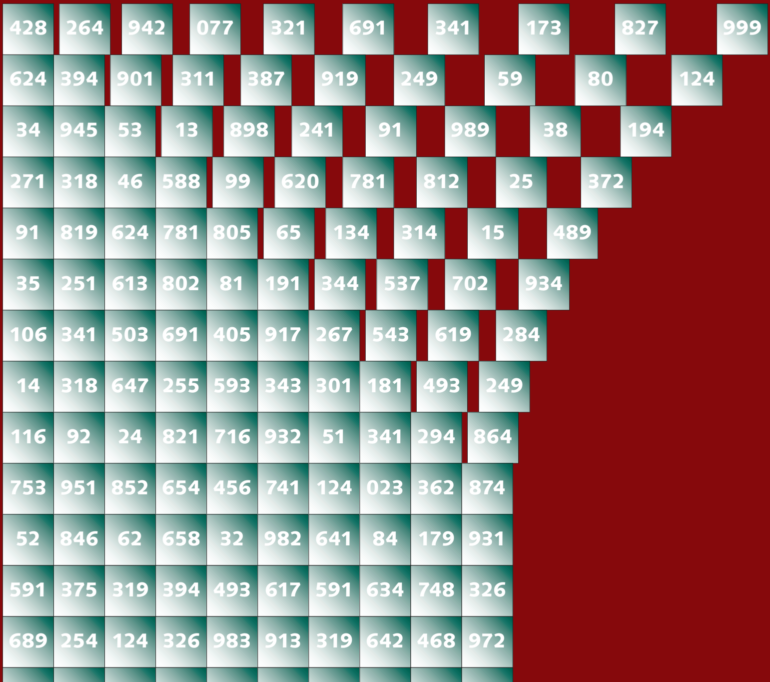
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2 Low-ILUC-risk ethanol from Hungarian maize

Abstract

Indirect land use change (ILUC) is a serious threat to the sustainability of bioenergy because of the extra GHG emissions (and other environmental impacts) it causes when feedstock production diverts other agricultural production and causes expansion onto high carbon stock lands. However, multiple measures exist to reduce the risk of ILUC. But these measures and their potential to mitigate ILUC are not yet well understood. Therefore, we assessed the ILUC-mitigation potential under three scenarios for possible developments in agricultural production and supply chains for a case study on maize production in Hungary for ethanol. Our results show that ILUC-risk mitigation is possible in all three scenarios: agricultural land demand is reduced by 3500-16,000 km^2 in 2020 compared to the current situation (6-29% of the agricultural area). This surplus land, is not needed anymore for food and feed production and can be used for biomass production for energy at a low risk of causing ILUC. For example, when maize is cultivated and converted to ethanol, this surplus land can provide 22-138PJ of ethanol. This is equivalent to 10-60% of the projected 2020 transport energy use in Hungary. Yield improvements of maize, other crops and livestock contributed most (55-90%) to this low-ILUC-risk potential. To sustainably increase productivity and efficiency in the entire agricultural sector, an integrated approach to food and fuel (as well as other non-food) production is needed. Thereby, ILUC risk can be mitigated and is not an irreversible fact as often presented in previous studies.

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2.1 Introduction

Indirect land use change (ILUC) induced by increased biofuel production is a widely discussed topic in academia and the policy arena. ILUC occurs when a growth in biofuel feedstock production in a region leads to displacement of agricultural production to other regions [58,80–82]. This displacement can trigger deforestation or other large carbon stock changes, which reduce or even cancel out the beneficial greenhouse gas (GHG) emission effects of biofuels [58].

Due to the indirect nature of the effect, it is not possible to classify specific land use change as an indirect effect of biofuel expansion. Rather, all land use changes will have a complex mix of multiple drivers that steer them. Therefore, models are used to project direct and indirect land use changes (LUC) induced by additional biofuel demand and the resulting emissions [119]. Most studies about ILUC use global macroeconomic models to assess the effects of an increase in biofuel production on the economy, which is then translated into a land-use change effect by comparing a business-as-usual scenario without extra biofuel use, to a scenario with additional biofuel use [58,120–124].

The results of these studies show largely different impacts of ILUC, but the projected CO_2 emissions from LUC are always above zero [109,112]. Despite the uncertainties about the precise impact, this indicates that the risk of ILUC needs to be tackled. A policy measure that is often proposed to limit the extent of ILUC emissions is an ILUC emission penalty, which has to be added to the GHG balance of the biofuel product [125]. Since biofuels have to meet criteria for GHG emission savings compared to reference fossil fuels (e.g. -35% now; -50% from 2016 onwards in the EU Renewable Energy Directive [37]), this policy would make it more difficult for biofuels, and in some supply chains impossible, to achieve these savings.

While such a LUC penalty is already implemented in California [122], the EU chose not to do so now in the 'ILUC directive' of 2015 after intensive negotiations between members states, commission and parliament [113]. The criticism on the use of an ILUC penalty is threefold. Firstly, the proposed penalties are based on the outcome of macroeconomic models, which are associated with large uncertainties [109,126–128]. This results in a penalty that does not reflect the actual impact of the biofuel, but rather a value choice. This problem is enhanced by the fact that some of the models are not open to public scrutiny. Secondly, it imposes a uniform penalty on each feedstock, irrespective of where and how it was produced. It thereby disregards that some regions or companies try to mitigate the ILUC risk e.g. by using otherwise under-utilised land or increasing yields. Thirdly, the ILUC penalty approach also disregards the fact that all ILUC caused by biofuels is also the direct land use change of other production. This means the problem is larger than just biofuels and requires a holistic approach to the agricultural sector as a whole.

Given these shortcomings of the ILUC penalty approach and limited attention for alternative approaches so far [112,129,130] as well as the decision of the EU's ILUC directive to focus on ILUC mitigation [113], this study aims to assess and quantify the extent to the risk of indirect land use change can be mitigated. We explore the potential for low-ILUC-risk biofuels by assessing four ILUC mitigation measures for a case study on maize for ethanol in Hungary. Hungary is chosen as a case study because it is an important agricultural country, with a large production of maize. Moreover, it is a country in Central and Eastern Europe (CEE), where large future biomass supplies are projected [131–134]. Part of the potential in Hungary originates from the start of the 1990s, because after the end of the communist era the demand from Russia for meat and thereby also for intermediate products collapsed. This resulted in lower land demand and lower productivity and thus a larger yield gap [135,136].

2.2 Methods and materials

2.2.1 General approach

The approach applied here was developed by Brinkman *et al*. [115], and was applied by Gerssen-Gondelach *et al*. [116] and Van der Laan *et al*. [117]. It aims to analyse and quantify ILUC mitigation measures. We assess how much additional biofuel feedstock can be produced on surplus land (the biofuels from these surplus lands are hereafter also called the low-ILUC-risk potential) as a result of these measures. Surplus land is i) land that is included in current agricultural land use, but that is not required anymore for food, feed or fibre production in 2020 as a result of the application of the ILUC mitigation measures, or ii) land that is currently not in use, but has low carbon stocks. The approach to calculate the amount of surplus land is based on a combination of a top-down and a bottom-up assessment, and it distinguishes three main steps that are summarised in Figure 2.1 and described below.

The total land use change that is caused by biofuel expansion (direct and indirect) can be measured by calculating the difference between the land use for food, feed, fibre and current amount of biofuels in a baseline (or business-as-usual scenario) and a biomass target scenario that includes additional demand for biofuels. The additional biofuel production that is projected (step 1) can lead to a expansion of agricultural land elsewhere (section 2.2). Then we assess the potential of four different measures (section 2.3) to make more land available for biofuel feedstock (step 2), without the need for diversion of production to other regions. We do this for three different scenarios (see section 2.3.1). The comparison (step 3) between the top-down demand and bottom-up supply shows to what extent we can mitigate LUC with the four measures.

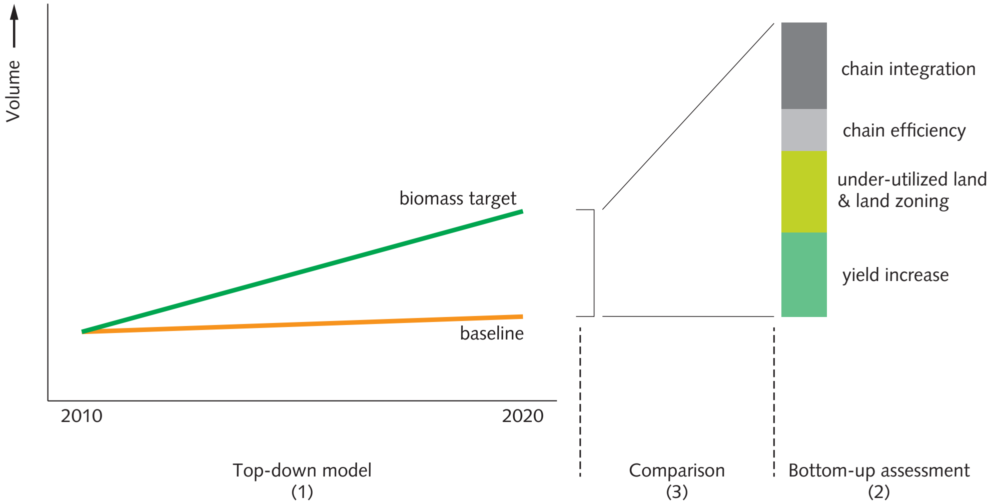

Figure 2.1 Three steps to analyse the potential low-ILUC-risk biofuel potential of a region (from Brinkman et al. [115]).

2.2.2 Step 1: Agricultural production in 2020 prescribed by top-down model

In the first step, we used the outcomes of the MIRAGE economic model to establish top-down a crop-specific biomass production baseline (without additional biofuels) for 2020 [123]. MIRAGE (Modelling International Relationships in Applied General Equilibrium) is a computable general equilibrium model from the International Food Policy Research Institute (IFPRI). The version used here is MIRAGE-Biof which was used for 2011 study for the DG Trade of the European Commission and was the basis for the ILUC penalties proposed by the EC [123]. Based on changes in demand for agricultural products resulting from development in macroeconomic conditions (e.g. economic and population growth, trade policies), the model projects the production quantities in 2020. We applied the results specific to the “status quo” trade policy projection of the MIRAGE model.

The MIRAGE crop production data for the EU27 were disaggregated to Hungary by taking the current share of Hungary in the EU-wide production of each crop [137]. For this, we used the ten most important crops (by land use) in Hungary today, of which six matched the crop categories of the MIRAGE model. The crops that were not included as a separate category in the MIRAGE model were included under other crops, and the disaggregation within that category was again based on the current share of the production of that crop within that category. For the production data, we used a five year average (2008-2012) to account for the yearly variations in production caused by weather. The crop production volumes were converted to the land use for the production, using the MIRAGE-projected yield of each crop. For the current yield, data from FAOSTAT [137] and the Hungarian Central Statistics Office [138] were used. As the MIRAGE model aggregated the EU27 countries into one region, with one yield for each crop, there is no distinction in the yield development between the countries. In order to avoid complicated disaggregation methods, we assumed for the yield in 2020 the growth percentage in Hungary will be the same as projected for the whole EU27. These crop productions and yield projections are presented in Table 2.1 alongside the other land uses in Hungary in 2010, based on FAOSTAT data [137].

Table 2.1 Overview of production, yields and land use in Hungary for the crops used in this study. Current production and yield data were taken from FAOSTAT, future production is disaggregated from MIRAGE EU27 data [123]. This production is for food, feed fibres and current amount of fuels. Forest area and meadows and pastures are taken from FAOSTAT [137].

Crop	Production 2010 (kt)	Production 2020 (kt)	Yield 2010 (t ha^{-1})	Yield 2020 (t ha^{-1})	Area 2010 (km^2)	Area 2020 (km^2)
Maize	7229	8190	6.2	6.3	11,700	13,000
Wheat	4328	4979	4.1	4.1	10,700	12,100
Sunflower seed	1277	1573	2.3	2.6	5600	6000
Barley	1092	694	3.7	3.8	2900	1820
Sugar beet	751	805	55	59	140	140
Potato	559	356	25	26	220	140
Rapeseed	541	736	2.3	2.5	2300	2900
Oats	136	87	2.5	2.6	540	340
Rye	83	53	2.2	2.3	380	230
Soybean	79	103	2.2	2.3	360	440
Total					34,900 [a]	37,100
Meadows and pastures					8730	
Forest					20,400	

[a] the area of other crops combined is 4 400 km^2

2.2.3 Step 2: Bottom-up assessment of the measures

In the second step, a bottom-up approach was used to assess the biomass production potential from key ILUC mitigation measures (Section 2.3.2-2.3.5). A baseline and three scenarios -*low*, *medium* and *high* progress- are applied in order to indicate the variability and uncertainty in the developments in the agricultural sector (Section 2.3.1).

2.2.3.1 Scenarios

Three scenarios are applied to illustrate different routes along which implementation of the ILUC mitigation measures may take place and to reflect the varying extent to which ILUC mitigation measures may be implemented and the speed of progress in the Hungarian agricultural sector. In addition, the use of scenarios helps to identify the ranges for the low-ILUC-risk potential. In order to contrast and compare the effect of these scenarios, also a baseline scenario was needed. Below we shortly describe the general blueprint in which the scenarios fit; Table 2.2 gives an exact overview of the assumptions per measure of the three scenarios and the baseline Table 2.3 and [139] give a more elaborate overview of the precise numbers for each scenario.

The baseline scenario was based on the reference assumptions of the MIRAGE model (see also section 2.2), which was also used in the past to assess the extent of ILUC and its associated GHG emissions [123]. The reference scenario included changes in demand for food, feed and fibre, but not for biofuels. Also the trade policy was assumed not to change. As current agricultural policies in Hungary are not focussed on increasing the efficient use of agricultural land, only little progress is assumed in the *low* scenario. In view of the current political situation, the stance to favour smallholders over productivity gains was not expected to change in the coming years. The assumption behind the *medium* scenario is that there is a potential within the country to learn from other regions in the country or from the past, if better results were achieved then. It is likely that previous performances can be matched in the present, or that some regions can achieve the current best as Hungary is a relatively small and agriculturally homogenous country, with few regional differences. The *high* scenario is the upper bound of the development and assumes fast progress. We assumed for the *high* scenario that the country can reach the level of the rest of the EU, as it has joined the EU and the Common Agricultural Policy in 2004.

2.2.3.2 Above baseline yield increase

The first measure is above baseline yield improvement. The baseline projections for the yield growth are presented in Table 2.1. Maize and wheat yield growth are 2.6% and 2.1% respectively, over the entire 2008-2020 period [123]. This is a low increase, and current yield in other European countries and past experience show a higher yield increase could be feasible, even over multiple years. A historical comparison of yield developments of key crops and livestock products produced in Western and Central and Eastern Europe (CEE) by De Wit et al. [132] showed that between 1961 and 2007 the annual yield growth rates averaged over ten year periods ranged between -1% and 6%, with the largest yield increases in CEE. The feasibility is further illustrated by the fact that between 1967 and 1981 yearly maize yield growth in Hungary did not fall below 3.1% [137]. Furthermore, the yield gap in those days was significantly smaller than today. Analyses by Gerssen-Gondelach et al. [140] showed yields grow faster in areas with a higher yield gap. Maize yields in Hungary were almost 70% of the highest maize yields in the world in the 1970s; now it is only 23% of the current best [137]. An additional reason to assume higher yield increases are achievable is that the main cause of the low yield is not biophysical, but related to management. Implementing better management practices can lead to a rapid increase in crop yield. Currently, agricultural management practices in Hungary lag behind those in Western Europe, with low mechanisation, fertiliser and pesticide use [135,137,141]. Optimising fertiliser use can improve production and thereby decrease GHG emissions per unit of crop. However, at the moment farmers often lack capital, knowledge and incentives to invest in agricultural productivity. Therefore, policies to improve the yield need to stimulate and provide incentives these investments in order to improve mechanisation and proper use of fertilisers and pesticides. Thereby, performance of the agricultural sector as a whole can be increased and GHG emission savings from biofuels raised. For maize this is illustrated in Figure 2.2. Because higher yielding crops require less land for the same production, land demand decreases and the surplus area increases. Equation 1 calculates for each crop the amount of land that is required to produce the desired crop production volume in 2020 with the baseline yield development and a yield defined in the scenarios:

Eq 1: $$SA_{\mathrm{ABY,crops}} = A_{\mathrm{baseline}} - A_{\mathrm{ABY}} = \sum_{i=1}^{n} \frac{P_{\mathrm{i}}}{Y_{\mathrm{baseline,i}}} - \sum_{i=1}^{n} \frac{P_{\mathrm{i}}}{Y_{\mathrm{ABY,i}}}$$

Where $SA_{\mathrm{ABY,crop}}$ – surplus area (ha) that becomes available from above-baseline yield increases (ABY) for crops;
A_{baseline} – area (ha) needed for projected target crop production, applying the MIRAGE yield growth rate;
A_{ABY} – area (ha) needed for projected crop production, applying an improved yield growth rate;
$Y_{\mathrm{baseline,i}}$ – projected baseline yield for crop i (t ha^{-1} y^{-1});
$Y_{\mathrm{ABY,i}}$ – projected above-baseline yield for crop i (t ha^{-1} y^{-1});
P – projected baseline production (tonne) for crop i, as derived from the MIRAGE model.

For the surplus land as a result of intensification in the livestock sector only grazing cows and sheep are considered. Other studies (e.g. [132,140]) only considered cattle because it has the largest land-use impact. The land intensity of pigs and poultry are much lower, as these are mostly held inside [140]. Because of a large sheep flock of 1.2 million units in Hungary, compared to 0.7 million units of cattle [138], sheep were also considered here. As we focus on the reduction of land use change, we only consider grazing cattle and sheep. There was 8730 km^2 of meadows and pastures (see Table 2.1) available for the livestock. Two types of yield improvement were taken into consideration: i) productivity per animal, which reduces the number that has to be held, and ii) the heads per hectare. For cattle, we considered both meat and milk production and for sheep only wool production as the sheep milk and meat production is very low compared to that of cattle. In contrast to our projections of crop production, for livestock, we did not use results from the MIRAGE model. The MIRAGE model does not present livestock production in terms of physical units, instead, the value added of the cattle sector is presented. This is project by the MIRAGE model to grow by 4% (2008-2020), with a very slight change in prices (-0.2%). Based on these available data we were unable to discern the price effects from the volume effects [123]. An alternative approach for projecting changes in future production volumes in the livestock sector is to extrapolate FAOSTAT data of meat and milk production. While these data show some changes in Hungary over time, no definitive upward or downward trend could be discerned [137]. Therefore, we choose not to include a growth in production of meat, milk and wool in Hungary in the coming years.

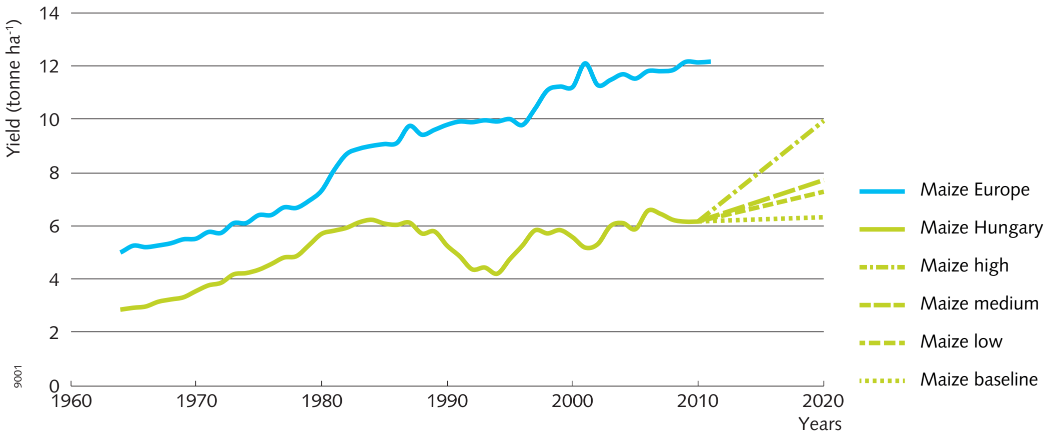

Figure 2.2 Maize yield development in Hungary and Europe in the period 1964-2020. Data for the period up to 2010 are a five year moving average, from FAOSTAT data [137]. The yield growth in the period 2010-2020 is based on the low, medium, and high scenarios (section 2.2.3.1).

For beef and milk productivity per cow, we used production data from FAOSTAT as these are data that can be compared to other countries and over time [137]. We considered the milk production per cow and the carcass weight per cow. It was assumed in all scenarios that a rise in productivity per animal would be matched by an equal reduction in the number of animals in such a way the total production of milk and beef would not change. The productivity increases per scenario are defined in Table 2.2 and 2.3.

For the increase in the heads per hectare a metric for the density was needed for the calculations. Therefore, we multiplied the amount of grazing cows and sheep by their respective National Livestock Unit equivalents [141]. The amounts of grazing cattle (27%) and sheep (67%) were calculated using the data from the Hungarian agricultural census of 2013 [141], the amount of animals was taken from FAOSTAT in order to make comparisons possible. These calculations implicitly assumed the grazing pattern would not change, however data collection is insufficient to assess this. The difference between the land use before the yield improvements and after the yield improvements is defined as the surplus land.

2.2.3.3 Improved chain integration

The second measure is improved chain integration. Co-products from feedstock cultivation and biofuel production can be used to replace other products, which decreases the demand for these. Co-products that are included in this analysis are distiller grains and solubles (DGS) that can be used as animal feed, and maize stover that can either be used for animal feed or second generation ethanol production. Because the MIRAGE model includes the use of DDGS as animal feed in its calculations an equal amount of agricultural production was added to the projected production in 2020 to avoid double counting (this is the only diversion from the baseline scenario as described in section 2.3.1). Although the MIRAGE model includes this effect already, we calculated it separately in order to be able to quantify the effect and assess how the key variables influence this. The additional DDGS production from MIRAGE was calculated using the co-production factor and the replacement rate of the co-products as defined in the study by Laborde [123], which in the case of maize DDGS are very high. The amount of maize allocated to ethanol production was based on the European average (2.2%) in the 2020 reference case of Laborde [123].

To calculate the land use savings, the principles of consequential LCA [142–148] were applied in order to see the effects of DGS use on the total land use. Here we considered the consequences of increasing the amount of DDGS in the feed production and the reduced demand for crops as a result. The co-production factor, or DDGS yield, is 0.32 t DDGS for each tonne maize [149]. The rate of replacement of regular production by DDGS was varied among the three scenarios (see Table 2.2). The replaced production was then converted to a land use reduction, using the projected yield (see section 2.2.3.2). For the reduction of imported soy we used the Comtrade [150] database to establish the source of the agricultural production (average 2008-2012) and FAOSTAT for the local yields. The same method as described in section 2.2.3.2 was used to calculate the projected yield growth abroad. Despite the Netherlands and Slovenia being the main suppliers of soy to Hungary, we used the weighted average of their main suppliers: Argentina and Brazil as no noteworthy quantities of soy are grown in the Netherlands and Slovenia. While we focus on land use in Hungary, we also show possible benefits outside the region, by presenting the land use savings abroad.

2.2.3.4 Reducing losses in the supply chain

Food losses and food waste are often thought to be around half of the food production [151–153]. Food losses is the term used to indicate the pre-consumer losses, whereas food waste is used for losses from the consumers [154–157]. Although the gains of limiting food waste could be very large, it would involve behavioural changes by consumers. This falls outside the scope of this study, which instead focusses on the losses in agriculture and the rest of the supply chain. Reducing the losses in the chain between production and consumption of both food and fuel will help to fulfil food demand on less land. In the calculations, the difference between the baseline losses (current loss, FAOSTAT data) and the potential lower losses in the three scenarios led to a reduced demand for agricultural products; the difference is the surplus land.

The current losses are based on FAOSTAT data [137] because this is the only known source with crop and country specific data [158]. The FAO used a combination of local experts and generic loss percentages to estimate the losses during storage, distribution and processing per crop in each country, and explicitly excluding the losses in agriculture and households. The crop-specific food losses were used to calculate the share of each crop lost expressed as a percentage of the total supply. The total supply of a crop was the sum of the production, imports and stock withdrawals. This, rather than only production, was used because the losses can occur in all stages of the supply chain. The data from FAOSTAT (average 2007-2011, because more recent data were not consistently available for all crops) were used to calculate the share of crops lost in Hungary, this varies between 0.3% for rapeseed and 2.7% for potato (see Table 2.8 in the Supplementary Information). Where estimates for Hungary were not available for a crop, the average for the other CEE EU countries has been taken as a proxy, because these are more representative than the whole EU. The crop specific reduction is defined in each scenario.

2.2.3.5 Using under-utilised lands

The fourth measure is land zoning and use of under-utilised land including set-aside land, abandoned land, degraded land, marginal lands and other land that does not currently provide services [114,159]. This land can supplement the surplus land from the three other measures and be used to cultivate extra biomass for bioenergy. After the collapse of agricultural demand by the Soviet Union post-1990, the agricultural land use in Hungary has seen a decline by 11,000 km^2 (18%) [137]. As no statistics on the amount of under-utilised land exist for Hungary, this was used as a proxy. However, to avoid the use of high carbon stock lands or causing other undesired land use changes in Hungary, not all this land can be used. Part of it will have converted to forest or other land uses. The forest area in Hungary has grown by 2500 km^2 since 1990 (14%) [137]. In order to exclude these areas from the calculated potentials, we followed the observation of Schierhorn *et al.* [160] that carbon stocks start to increase rapidly ten years after abandonment. Therefore, this study excludes areas abandoned longer than ten years ago from the estimates of the available lands. The maximum available abandoned land is the decrease in agricultural area in the period 2003-2012, limited by the expansion of forest in that period in Hungary. This means a maximum of 4 000 km^2. Availability of this area is defined per scenario in Table 2.2. Fallow land (2 400 km^2 in 2010, [137]) is not included in this estimate because the amount of fallow land is expected to decrease rapidly as a result of the 2014-2020 reform of the European Common Agricultural Policy (CAP) [159]. The reform will see an end to payments to farmers for leaving their land fallow and thus it may not be available for bioenergy production in 2020 without risk of displacing other production.

Multiple studies [161,162] found abandoned lands to be spread evenly over the different agricultural suitability classes from IIASA. This would suggest these lands can provide an average productivity when used for maize production. However, to account for potentially lower productivity a suitability between 0.5 and 1 is included in the calculations that indicate the share of the average productivity that can be achieved.

2.2.3.6 Overview

Table 2.2 presents the assumptions at the basis of each of the scenarios. Table 2.3 gives the input values for each measure for each scenario and how these were derived.

Table 2.2 Overview of the scenarios for the various measures. Table 2.3 shows the corresponding data for the calculations.

	Above baseline yield increase (crops)	Above baseline yield increase (livestock)	Increased chain integration	Increased chain efficiencies	Land zoning and biofuel feedstock production on underutilised lands
Baseline *Reference scenario from MIRAGE [123] with growing food, feed and fibre demand, but no additional biofuels compared to 2008.*	Crop specific projections from MIRAGE for the EU27 disaggregated to Hungary based on the current yield in Hungary as a share of the current EU27 average.	No change in the productivity per cow or hectare [a].	None	Current losses, estimated using FAOSTAT crop-specific data. No change in the losses	Underutilised lands will remain non-productive.
Low *Progress is low and will not rise above the current rate or the absolute minimum.*	Yields keep increasing at the average linear rate of the period 1961-2012.	Yields keep increasing at the average linear rate of the period 1961-2012.	Replacement of marginal protein source of animal feed on basis of protein content of DDGS (i.e soy imported from Argentina and Brazil is replaced). No use of stover other than current practice.	Meet the EU target of 50% food loss reduction throughout the whole chain.	Half of the abandoned land will be taken into production at 50% of the average productivity.
Medium *Knowledge in Hungary will spread, and agriculture will improve to the current or past best level in the country or CEE.*	The average yield in Hungary reaches the yield level in the current (2008-2012) best county.	The best historical productivity in Hungary.	Replacement based on feed tests in Hungary and division data to the livestock sectors from the US.	Gain the same level of chain losses (per crop) as the current best CEE country	75% of the land will be used, at 75% of the average yield.
High *Large progress in the agricultural sector. The country will catch-up with Western Europe.*	The ratio between the maximum attainable yield and currently achieved yield in Austria is applied to the maximum attainable yield in Hungary.	The highest productivity in the EU27.	Replacement on energy basis (i.e. domestic barley, maize and wheat).	Gain the same level of chain losses (per crop) as the current best EU country.	Almost all lands in the estimate can be taken into production at a productivity of 99% of the future average yield.

a The pasture land expansion elasticity is close to zero for the EU27 in the MIRAGE model, denoting low tendency to change.

Table 2.3 Assumptions for the calculations in each of the scenarios.

			Baseline	Low	Medium	High
Above baseline yield increase	Yields 2020 (t ha^{-1})	Maize	6.3 [a]	7.1 [b]	7.7 [c]	9.8 [d]
		Wheat	4.1	5.0	5.0	4.6
	Grazing NLU (ha^{-1})		0.24 [e]	0.24 [f]	0.44 [g]	0.45 [h]
	Cow milk productivity (m^3 y^{-1})		5.5 [e]	7.2 [f]	4.3 [g]	7.1 [h]
	Cow beef productivity (kg y^{-1})		75 [e]	105 [f]	100 [g]	138 [h]
Chain integration	Product replaced by one tonne of DDGS (t)		0 [i] 0.61 [j]	soy: 0.31; 0.27 [k]	maize: 0.38; soy: rapeseed:	barley: 1.04; wheat: 0.96 or maize: 0.92 [l]
Chain efficiency	Losses 2020 as mass fraction (%)	Maize	2.1 [m]	1.1 [n]	1.2 [o]	0.1 [p]
		Wheat	1.8	0.9	0.6	0.3
Abandoned lands	Assumed area available (%)		0	50 [q]	75	99
	Assumed productivity as share of average yield (%)		0	50	75	99

[a] The baseline yield development comes from the results of the MIRAGE model [123]. The model projects a maize yield in the EU27 in 2020 of 8.1 t ha^{-1} and a wheat yield of 8.0 t ha^{-1}. As Hungary has a lower than average productivity, the baseline yield for Hungary assumes a constant ratio between the Hungarian yield and the EU27 yield between 2010 and 2020, based on the yields (2008-2012) FAOSTAT [137].

[b] The linear yield trend in Hungary of the period 1961-2012 is extended until 2020 to calculate the yield growth until 2020. The historical yield data come from FAOSTAT [137].

[c] The *medium* yield projection assumes for each crop the current yield of the best county in Hungary can be extrapolated to the whole country (average 2008-2012). Yield data on county level are from the Hungarian Statistics Office [138].

[d] The high yield projection considers the suitability and is calculated following the methodology of Smeets et al. [163]. Here the average maximum attainable yield for Hungary was calculated based on the IIASA Global Agro-ecological Zone (GAEZ) database [164]. In the IIASA GAEZ database, Hungary is divided into 1606 grid cells. For each crop the crop suitability is determined for rain-fed high-input agriculture in the 2020s. The suitability falls in either one of nine categories: Very high (suitability larger than 85); High (>70); Good (>55); Medium (>40); Moderate (>25); Marginal (>10); Very Marginal (>0); Not suitable (0) and water. For each grid-cell also a crop-specific agro-climatic maximum attainable yield is available. Here grid cells with a higher than average quantity of forest (22%), with more than 15% build-up area or less than 50% cultivated area are excluded in order to avoid an over-estimation of the available lands. Smeets et al. (2004) assume for each crop that production will take place on the most suitable land [163]. In 30 iterative steps, all the future production is allocated to the best available land. After allocating the baseline production to the land the average maximum attainable yield is calculated by dividing the production by the required land. Using the same methodology, the ratio between the maximum attainable yield and current yield (average FAOSTAT 2008-2012 [137]) in Austria has been assessed. This ratio is applied to the maximum attainable yield in Hungary to calculate the maximum yield for each crop. The maximum attainable yields are presented by IIASA in dry weight, whereas the FAOSTAT data (that we use for the other calculations), include the water content of the crops. The water content of the crops presented in the GAEZ methodology document is used for the conversion [165].

[e] The amount of national livestock units (NLU) in Hungary is for cattle 0.8 and 0.0714 for sheep. In 2013 27% of cattle grazed and 67% of sheep [141]. The amount of sheep (1,190,400), cattle (969,400) and meadows and pastures (8600 km^2) were taken from FAOSTAT [137] (average 2008-2012).

[f] low yield growth is determined by the linear yield increase in the period 1961-2012. For milk productivity this is 88 l y^{-1}, for meat 0.2 kg y^{1}. For the density the NLU decreases by 0.02 ha^{-1} y^{-1}.

[g] The best productivity that has been registered in the past in Hungary, this was in 1983 [137]. This was the year with the most optimal combination of productivity per animal and animal density.

[h] The highest productivity in the EU is in Germany [137]. This is the country with the most optimal combination of productivity per animal and animal density.

[i] current productivity in the Hungarian livestock sector is taken from the FAOSTAT data for the milk yield per cow

(average 2008-2012) [137]. Beef productivity is determined by dividing total meat production [137] by the amount of beef cows (difference between the total amount of cows and the milk cows). For the baseline no productivity growth was assumed.

[j] The marginal source of protein (soy meal and soy oil cake) was replaced by the DDGS. DDGS contains 27% protein [166], soymeal 44% [166]. A tonne for tonne replacement of the soy production yielded 0.61 tonne soy products replaced by a tonne of DDGS. Soymeal in Hungary was imported (average 2008-2012) from The Netherlands (56%) and Slovenia (27%) that both imported from Brazil (NL: 55%; SLO: 92%) and Argentina (NL: 41%; SLO: 4%). The weighted mix was 70% from Brazil and 30% from Argentina [150]. Projected land use was 3.5 t ha^{-1} in 2020 in Brazil and 3.2 t ha^{-1} in Argentina [123]. It was assumed for each tonne of soy meal 1.29 t of soy beans was required, based on the data from Laborde [123] where 0.777 t meal is produced for each tonne of soy.

[k] American practice showed 87% of DDGS is used for cattle, 7% for pigs and 5% for poultry [167]. A feedtest by the University of Pannonia [168] showed a replacement per tonne of DDGS for cattle: 0.38t maize, 0.31t soy, 0.27t rapeseed. For pigs: 0.59t maize and 0.43t soy. For poultry 0.60t maize and 0.39t soy. In addition some minerals were replaced as well, but these have little land-use impacts.

[l] Barley (12%), wheat (21%) and maize (53%) were important feed crops for energy in Hungary (average 2007-2011) [137]. These were replaced on energy content by the use of DDGS. The energy content are 14.85 MJ kg^{-1}, 16.15MJ kg^{-1} and 16.74MJ kg^{-1} respectively for the crops and 13.47 for the DDGS [169] -for the crops this includes a correction for the water content [165]. To calculate the *high* scenario replacement, first the lowest yielding crop (i.e. barley) is replaced by the DDGS, to the current level of use for feed in Hungary (597 kt, [137]) followed by the wheat (1.1 Mt) and maize (2.8 Mt). This gave a replacement of 1.04 t barley for each tonne of DDGS. The replacement by a tonne of DDGS for wheat was 0.95t and 0.92t for maize.

[m] Current losses as reported by FAOSTAT [137]. The losses (average 2007-2011, as more recent data were not available) were divided by the total crop availability (sum of production, stock withdrawals and import). This was calculated separately for each crop.

[n] The EU has a target to cut losses in half by 2020 [170].

[o] Per crop the lowest loss that is found in a Central or Eastern European EU member (Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia, Slovenia) [137].

[p] Per crop the lowest loss that is found in the EU27 [137].

[q] In the uncertainty analysis of Laborde [123], the bandwidth over which the suitability of new lands is between 0.5 and 0.99, with an average value of 0.75. We use the same values here for the availability and suitability.

2.2.4 Step 3: Integrated analysis

In the third step, we compare the current land use with the land use for all agricultural production after application of the ILUC mitigation measures. When, after the implementation of the ILUC mitigation measures, the future land demand decreases compared to the baseline scenario, the measures help to reduce ILUC. If the land demand can be reduced even further, surplus land becomes available, that can be used for low-ILUC-risk biofuel production that does not lead to displacement. On the other hand, if the land use after the application of the measures exceeds the baseline land use, realising the biofuel target cannot be achieved without displacement of production. This would mean ILUC cannot be entirely mitigated by the measures included in this study alone, and additional actions need to be taken in order to prevent ILUC.

For the third step the measures were integrated -opposed to simply added up, because there can be synergies or trade-offs between measures. An example of this is an increased production of DDGS that has a smaller land-use impact when yields are higher.

In this study the integration applied the following order:

i. The basis was the current land use for the production of the ten crops and the grassland for livestock (section 2.2.2).
ii. To this, the additional area for the expanded production in 2020 was added, using the projected yields (section 2.2.2).
iii. Then the yield was replaced by the above baseline yield, this reduced the land demand (section 2.2.3.2).
iv. Then the demand was further reduced by the implementation of chain integration and chain efficiency (section 2.2.3.3 and 2.2.3.4).
v. The resulting land demand from iv was compared to the baseline from i. in order to calculate the surplus land.
vi. The available abandoned lands that are calculated (Section 2.3.5).
vii. Then the potential ethanol production on all surplus area (v and vi) was calculated, taking into account the lower yields on abandoned land (section 2.3.5), assuming all lands are used for maize production.
viii. Step iv, vi and vii were repeated to account for the extra DDGS resulting from additional ethanol production.

This resulted in a total surplus area and the potential low-ILUC-risk ethanol production. For this, an ethanol yield of 0.32 tonne ethanol for each tonne maize was applied [149]. Following Annex III of the RED [37], an energy density of 27 MJ kg^{-1} (or 21 MJ l^{-1}) was assumed.

2.3 Results

Table 2.4 presents the surplus land as a result of applying the ILUC measures. The above baseline yield development is the major source of surplus land. In all scenarios maize and wheat are more important than all the other crops combined. This can be explained by the share of these two crops in the total agricultural land use; as production increases the impact of a small yield increase is much larger. The negative amount of surplus lands for the other crops in the *low* scenario indicates that the projected yield growth in the baseline is larger than the yield growth in that scenario, and more land would be required to accommodate these crops. This is caused by a high baseline growth of rapeseed, sunflower seed and sugarbeet yields projected by MIRAGE. The additional land use for other crops is compensated by the yield growth in maize and wheat production, that are much larger. For sunflower seed, all three scenarios are below the baseline yield growth: but in the *medium* and *high* scenario the six other crops in the category other show a sufficient yield increase to compensate for this.

The results for the chain integration in Table 2.4 are presented separately for Hungary and abroad because the land-use savings abroad cannot be used for low-ILUC-risk maize production in Hungary. The domestic savings in the *low* scenario are zero, because the marginal source of protein in the feed is imported soy. This means there are no domestic crops replaced and surplus land in Hungary will be zero. In the *high* scenario the savings are all domestic because the marginal source of energy in the feed is domestic barley. The *low* scenario reduces the potential effect of ILUC, by reducing the pressure on the land in Argentina and Brazil, but it does not reduce the risk of displacement within Hungary.

The reduction in maize losses contributes most to the available surplus land from increased chain efficiency in the *low* and *high* scenarios. The combination of high production and relatively large baseline losses leads to a high potential to reduce the losses. A third important aspect is the crop yield. A reduction in food losses for a low-yielding crop (e.g. rapeseed or sunflower) leads to a higher amount of surplus lands than a high yielding crop (e.g. sugarbeet or potato) as more land was needed to produce the food lost from a low yielding crop. This is an important reason for the large land use impacts of the reduction of sunflower seed losses despite its low initial losses.

The under-utilised lands here are those lands that have been previously used for agriculture and have been abandoned less than ten years ago. This combines both the use of under-utilised lands and land-zoning of potentially high carbon stock areas. In contrast to the other measures, the maize grown on these surplus lands may have a lower yield, which is why the uncertainty range applied in Laborde [123] (0.5-0.99) is applied.

Table 2.4 Surplus land (km^2) as a result of the four measures in the low, medium and high scenario.

		Low	Medium	High
Above baseline yield increases (km^2)	Maize	1750	1520	4670
	Wheat	2060	2330	1180
	Other crops	-90	1070	450
	Livestock	1630	3870	5170
	Subtotal	5340	8790	11,480
Chain integration (km^2)	Domestic	0	90	170
	(Abroad) [a]	130	50	0
Chain efficiency (km^2)	Maize	140	120	260
	Wheat	110	140	190
	Other crops	60	50	90
	Subtotal	300	320	540
Under-utilised land (km^2)		2010	3010	3970
Total (km^2)		7650	12,210	16,160

[a] not included in the totals

2.3.1 Integration

In Figure 2.3 an overview is given of the land use consequences according to the disaggregation of results from MIRAGE and surplus land after implementation and integration of the four measures. As a result of overlap between some of the measures and synergies between others, the surplus lands presented in the figure differ slightly from the total in Table 2.4 It shows the measures generate a large amount of surplus land that can be used for energy crop production, even in the *low* scenario.

Table 2.5 presents the amount of low-ILUC-risk ethanol that can be produced from the surplus land in Hungary. The land use to accommodate the ten most important crops in Hungary can decrease compared to the baseline and even compared to the present. This leaves room for additional production of low-ILUC-risk maize for ethanol, ranging from 42 to 187 PJ of maize ethanol.

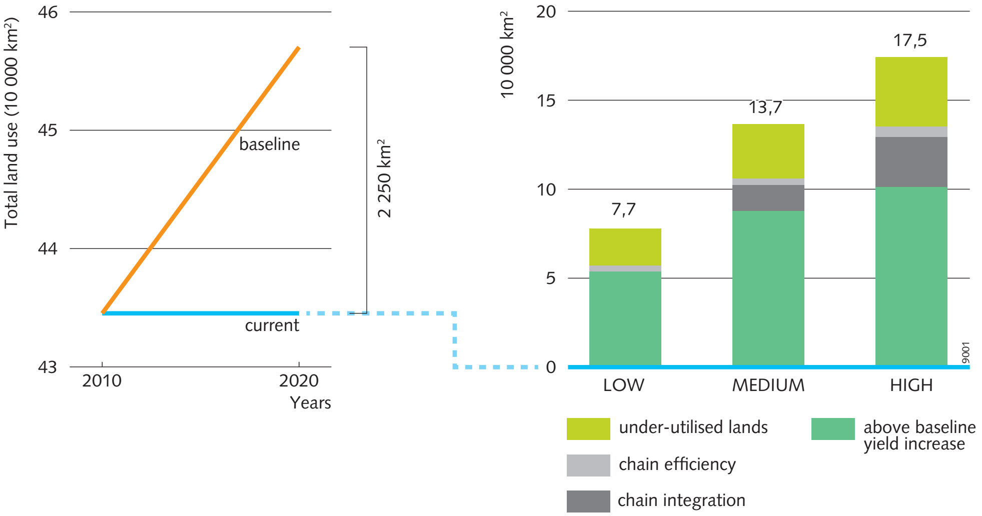

Figure 2.3 Comparison of land use change projected in MIRAGE (left) with land generated from ILUC mitigation measures (right). The left side of the figure shows the current and projected (baseline and biofuels target) land use in Hungary for the cultivation of crops according to a disaggregation of results from MIRAGE. Panel B shows the potential of each measure to overcome the gap between the target and current land use.

Table 2.5 Low-ILUC-risk maize production in Hungary on the surplus lands and the potential bioethanol production in 2020 at a yield of 0.32 tonne ethanol for each tonne of maize.

	Low-ILUC-risk maize production (Mt y^{-1})	Bioethanol production (PJ y^{-1})	Share Hungarian road transport energy 2020 (%)
Low	4.8	42	19%
Medium	9.5	82	37%
High	22	187	83%

2.4 Monitoring ILUC and ILUC mitigation measures

Monitoring the effectiveness of the measures is required to ensure the risk of ILUC is indeed minimised. Table 2.6 and 2.7 present the parameters that are ideally monitored in order to assess the effectiveness of general land use (change) and specific ILUC mitigation policies, respectively. The indicators in Table 2.6 are related to agricultural production and land use and can help to determine whether the policy measures are effective to limit unwanted land use change. The parameters presented in Table 2.7 can help to assess the specific ILUC mitigation measures. The desired frequency and spatial scale are suggested for each parameter, as well as the current availability and quality of the data. The parameters listed in the tables are explained in more detail below.

Table 2.6 Main parameters to be monitored in Hungary to ascertain no unwanted land use change takes place.

Parameter	Purpose of monitoring	Desired frequency	Desired spatial scale	Available data	
				Source	Quality
Land use	Is any land use expansion taking place? Are under-utilised lands taken into production? How much under-utilised land is still available? Are forests, biodiverse grasslands or other important ecosystem service areas converted to crop production? Where are the important carbon stocks?	Yearly	Spatially explicit	[137,138,171]	+/-
Production volume	Production developing as projected?	Yearly (at a five year average)	Country level	[137,138,171]	++
Trade balance	No major increase in imports of agricultural products or processed goods? Or decrease in exports? Decrease in soy and other feed imports?	Yearly (at a five year average)	Country level	[137,150,172,173]	++
Agricultural prices	Absolute price stability? Relative price stability?	Seasonal	Country level	[137,171,174], Nasdaq, euronext	++

Table 2.7 Parameters to assess the effectiveness of the ILUC mitigation measures.

Parameter	Purpose of monitoring	Desired frequency	Desired spatial scale	Available data	
				Source	Quality
Yields	Is the yield increase in the different crops as high as desired?	Yearly (at a five year average)	Country level (incl. ranges)	[137,138,171]	+ Yields are reported, but no spatial explicit data on farm level are available
Investments	Are investments in machinery increasing?	Yearly	Country level	[135,137]	- outdated and no specification what type of investments
Fertiliser use	Is fertiliser use increasing? Is it at the level of the rest of Europe? Is it used in bulk or in precision farming?	Yearly	Country level (incl. ranges), crop-specific	[135,137,174]	+/- Outdated and only country averages
Pesticide use	Is pesticide use increasing? Is it at the level of other European countries?	Yearly	Country level	[137]	+/- Outdated and only country averages
Chain losses	How high are the losses? Are they reducing as much as expected in the scenarios?	Continuously	Crop specific at country level	[137]	- Very uncertain for current losses and not up to date.
Development of under-utilised lands	How much abandoned land exists and where? What quantity is being taken into production and for what? Where is reforestation taking place and what are the carbon stocks? Where are abandoned areas used extensively and for what purpose?	Yearly	Spatially explicit	[137,138]	-- Current under-utilised lands not monitored. No information on location and quality
Quality of degraded lands	Is crop production possible on these lands? What yields can be achieved on the degraded lands?	Yearly	Spatially explicit	[164]	- Only the average quality of the lands, not specific forany of the forms of under-utilised land.
Quantity of degraded lands	How much degraded land is available and where? How much is taken into production?	Yearly	Spatially explicit		-- No information available
Feed use	How much DDGS is included in the feed? What and how much does it replace?	Yearly	Feed specific country level		- No macro data available

More accurate measurements of the land use can help to keep track of land expansion within the region in order to prevent large-scale expansion on high carbon stock lands (or other environmentally sensitive areas). The land use and land use change can be monitored with a combination of field measurements and usage of satellite and other remote sensing data. In addition, land that is abandoned or set-aside according to the statistics can be used in practice for extensive uses such as livestock herding. A yearly update of the data ensures these are up-to-date and helps to better track land use expansion.

The production volume of the major crops needs to be monitored in order to establish whether the projections from the model are accurate. Too low production can simply be a consequence of decreasing worldwide demand; or it can be a precursor of increased imports or reduced exports and thereby increased risk of undesired land use change as the extra production needs to take place outside Hungary. Too high production could indicate increasing demand, not accounted for in the model. This risks unwanted land expansion on e.g. high carbon stock lands in Hungary. Agricultural production is already well monitored and analysis by Kim and Dale shows FAOSTAT and national statistics differ less than one percent in most cases [158].

Large price increases in Hungary can indicate too low production to cover demand, and thus precede land-use expansion in order to meet demand. World market prices are very well reported and even daily fluctuations can be observed.

Data on many of the parameters are already reported by FAOSTAT [137], EUROSTAT [171] or the Hungarian Central Statistics Office [138]. To monitor the average yield developments in Hungary, this is sufficient. But more data on the variation in yields (e.g. yield ranges on national, provincial and county level and yields for different producers such as large vs. smallholder farms) can identify areas that need additional attention for increasing yields. The baseline yield increase can be set as a threshold value; when the actual yield is below this value, it denotes no low-ILUC-risk biomass production can be achieved from this measure.

Measures to increase the yields include increased mechanisation, modernising farm equipment and improved fertiliser use. FAOSTAT [137] and the World Bank [135] already keep records of investments, mechanisation and fertiliser use in agriculture. These data are often not up-to-date and only available for selected countries. However, if collected yearly, they could be a proxy for the yield improvements. Monitoring agrochemicals use and supplication for different crops will help to identify areas of improvements. Government support for agriculture can be derived from the OECD [174].

The first step for monitoring crop losses in Hungary would be to establish the current losses, as no accurate crop-specific data are available at the moment. FAOSTAT [137] has some data on losses, but not thoroughly. With continuous monitoring of the losses in the supply chain, it is possible to assess if the reduction matches the target.

The development of abandoned lands needs to be monitored to see how much land is available and to see if it is taken into production. Spatially explicit data would ideally be used for this. Current statistics are not sufficient as these do not include previous land-use or when conversion took place. Furthermore, comparison of satellite data with official data in Eastern Europe -especially on sub-national level- showed a difference between the two [175]. Using spatially explicit data can also be combined with the land suitability (e.g. IIASA data [164]) to monitor the potential yield on these lands.

Ethanol production from Hungarian-grown maize can take place in many countries. For DDGS a similar situation occurs, the DDGS can be used in Hungary and replace Hungarian agricultural production, but this is not certain. For monitoring we suggest to record the share of each feed crop in the Hungarian feed mix, this makes it possible to establish how much feed is replaced by the use of DDGS and where this feed originated. As the animal feed mix is continuously changing, a yearly overview of feed use is needed.

2.5 Discussion and conclusions

A key measure to minimise the risk of ILUC is to increase agricultural yields. By investing in productivity improvements and closing the yield gap, land can be released from food and feed production and then be used to produce low-ILUC-risk biofuel. But also other measures exist that reduce the pressure on agricultural land and thereby minimise the risk of additional production leading to displacement. Examples are efficiency gains in the supply chain in the form of reducing losses in production, transportation and processing; efficient use of co-products from biofuels; and bringing currently under-utilised lands, which do not conflict with nature conservation efforts and other essential uses or functions, into production. Using a case study of maize for ethanol production in Hungary, we demonstrate that these four measures can minimise the risk of ILUC. Because the combination of the four measures creates a large surplus area in addition to covering the slightly increased future food production, there is room for expansion of biofuel feedstock production in Hungary. As this biofuel feedstock can be produced on surplus agricultural area, the additional production has a low-risk of displacing other crops to high carbon stock lands in Hungary or abroad. Using this surplus land to grow maize for ethanol could provide 1 - 6.6 10^6 m^3 ethanol and replace the equivalent of 22 to 138 PJ gasoline per year. This equals 10% to 60% of the projected energy use of the Hungarian road transport sector in 2020 [176].

The relatively large impact of increasing yields on the total low-ILUC-risk potential (55% - 90%) suggests that other regions with a high yield gap may also be able to provide significant amounts of low-ILUC-risk biofuels. However, this also requires a low projected food demand increase (as Hungary has). Other regions in Central and Eastern Europe such as Poland, Romania and Ukraine share these characteristics [123,177]. For example, for Lublin province in Poland, it was already shown that abandoned lands and yield increases can account for three quarters of the surplus land to produce all projected second generation ethanol for Poland [116]. Large yield gaps are also found in Asia and Africa, but food production increases are likely to reduce the low-ILUC-risk potential there [123,177].

Developing the low-ILUC-risk potential requires a large effort in modernising and sustainably intensifying the entire agricultural sector. Although the yield gap in Hungary is large (4.2 t ha^{-1} for maize), the projected baseline yield increases until 2020 are low (0.1 t ha^{-1} for maize). Therefore a significant increase to the yields (up to 3.6 t ha^{-1} for maize) is considered feasible (for a more detailed discussion on this, see the Supplementary Information). However, monitoring the developments in the Hungarian agricultural sector is necessary in order to ascertain that the incentives to stimulate these efforts have sufficient effect on increasing productivity and preventing unwanted land use change. Slower progress than expected reduces the low-ILUC-risk biofuel potential and can be a warning signal for curbing any further expansion of biofuel feedstock production. This makes the biofuel production dependent on progress in agricultural productivity, which can help prevent biofuel production to grow above the low-ILUC-risk potentials.

An important limitation to this study is that it did not include the GHG emission effects associated with the implementation of the ILUC mitigation measures. Increasing yields through more mechanisation and fertiliser use may increase the overall GHG emissions of crop production. This can limit the GHG emission gains from preventing ILUC. However, the combined effect of higher productivity and decreased inputs per unit of agricultural production may result in lower GHG emissions per unit biomass. Although we did not assess this for our study, the analysis from Gerssen-Gondelach *et al.* [118] showed sustainable intensification for ILUC mitigation can lower the GHG emission footprint of the entire agricultural sector in Lublin. However, the emission balance largely depends on how intensification is implemented and what crop is grown for biofuels. Key determining factors include fertiliser management, application of tillage and the level of soil organic carbon (SOC). Given Gerssen-Gondelach *et al*. [118] assessed miscanthus, which can support SOC sequestration and therefore has low or negative emissions overall. It is unclear how this translates to the GHG emission balance of ethanol from maize. Therefore, more research is needed to better understand the effect of intensification in other settings, such as this case study.

The findings of this study emphasise that developing the biofuel potential of Hungary in a sustainable manner needs a focus on the agricultural sector as a whole, not only on the production of the biofuel feedstock. This is because such a holistic approach to the land use for food, feed, fibre and fuel production addresses the interlinkages between the biofuel and agricultural sectors that actually can cause ILUC. Thereby, the ILUC-risk is mitigated at the root cause of the problem. This is an improvement over the much-discussed ILUC penalty approach, which falls short in terms of applying uniform penalties independent of how and where the feedstock is produced and has many uncertainties in the quantification of the actual factors.

Acknowledgements

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Appendix

Additional discussion points

To realise the low-ILUC-risk potentials, yields have to increase rapidly. The maize yield is to rise at an annual growth rate of 1.6% - 4.9% in our scenarios. While this is a strong growth, we showed in the description of the choices for these scenarios (see Section 2.2.3.2) that this is considered feasible for Hungary. However, it is important to mention here that increasing yields can also have negative effects from a sustainability point of view. For example, a too narrow focus on the two crops that contribute most to the potential, in this case maize and wheat, can lead to monocultures and loss of biodiversity, but this is outside the scope of this study. In addition, not including other crops in the efforts to improve the yields, may cause them to require more area than projected and jeopardise the low-ILUC-risk potential. Intensification of the livestock sector can also draw criticism, if it does not happen with an eye for animal welfare. However, the increases in all three scenarios in the heads per hectare are rather modest, so a large impact on animal welfare is not expected. Since the yield increases are based on current situations in other countries, this means that it is already standard practice elsewhere.

In this study we assessed the replacement of feed production from DDGS for the chain integration. In the *low* and *high* scenario, we used two extremes of potential replacement options to illustrate the bandwidth for this measure. In the *low* scenario, no replacement is assumed to occur in Hungary, while in the *high* scenario it is assumed that all replacement occurs in Hungary. The calculations in the *medium* scenario mainly use data from the United States. It is debatable to what extent the US situation can be applied to Hungary; the market situation and thereby the cost structure of feed use are different, which influences the use of feed. Nevertheless, US data are the only available aggregated data for division of the DDGS to different sectors. No similar data is available for Hungary and the rest of Europe; there are only results of small-scale tests. Furthermore, the market in Europe is less mature, which makes it harder to draw conclusions on the division of DDGS to the various livestock sectors.

The most important factor determining the potential of chain efficiency is the extent of the current losses. The estimates based on the data from the FAO [137] are conservative and may well be an underestimation of the actual losses. Comparing the losses to other estimates, such as those by Rutten [178] and Parfitt [151], shows the FAO estimates are lower, but the advantage is that these are crop-specific, contrary to the other studies. An important extra source of reducing food losses is not included in this study: food waste at household level falls outside the scope. However, since food waste is very high, the potential to alleviate the pressure on the agricultural sector is enormous and a topic for further research.

Due to a lack of data only a share of the under-utilised lands has been included in this analysis. Excluding the land that has seen afforestation in the last ten years is a simple way to account for the high carbon stocks in revegetated agricultural land. Future research should focus on gaining more insight into the exact location of the abandoned lands in order to estimate the carbon stocks and the amount of abandoned land. Alcantara et al. [162] used satellite data to calculate the abandoned lands in Central and Eastern Europe and found for Hungary only 6% of the agricultural land being abandoned since the start of the 1990s, in contrast to the 14% reported by the FAO [137].

The yield of all the surplus lands is assumed to be equal to the average maize yield in each scenario, only for the abandoned lands the yields were lower. In reality there will be a variation in the yield according to the suitability of the land and production methods. Furthermore, an expansion in agricultural production will also lead to lower average yields as lower quality land has to be taken into production. In the *high* scenario this leads to a small decrease of 3% in the average maize yields (-4.5% in the low-ILUC-risk potential), following the method of Smeets *et al*. [163] which was described in footnote d in Table 2.3.

The ILUC mitigation measures that are presented here have to be implemented in order to reap their benefits. However, some measures are closer to realisation than others. DDGS is already used as animal feed and requires less stimulation. The reduction of losses in the chain are also already part of the policy initiatives in the EU, although these tend to focus on food waste in households, which are outside the scope of this research. As these are already partially implemented careful consideration is needed to avoid double counting of the benefits.

The chances of diverting production to other regions of course also depends on the size of the assumed production and the yields in 2020. As the MIRAGE model does not give country specific production data, we disaggregated the data to Hungary. The large impact of the above baseline yields on the final results shows this is a very important assumption. The contribution of the above baseline yield development in all three scenarios also illustrates that the baseline is very low and can be easily met and exceeded in Hungary. The importance of the baseline development on the low-ILUC potential is illustrated in the sensitivity analyses. The final result is very sensitive to changes in both the baseline yield and production (see Figure 2.4 and 2.5). The sensitivity to changes in the current yield and production is much smaller.

Uncertainty

Figure 2.4 shows the sensitivity of the low-ILUC-risk maize production on surplus lands in Hungary to changes in four parameters. Despite that the changes in current yield and production also effect the baseline yield and production, the results are more sensitive to the latter. Especially small reductions in the baseline yield and production lead to a large increase in the low-ILUC-risk potential. Changes in the input values of the current yields lead to smaller changes to the low-ILUC-risk potential.

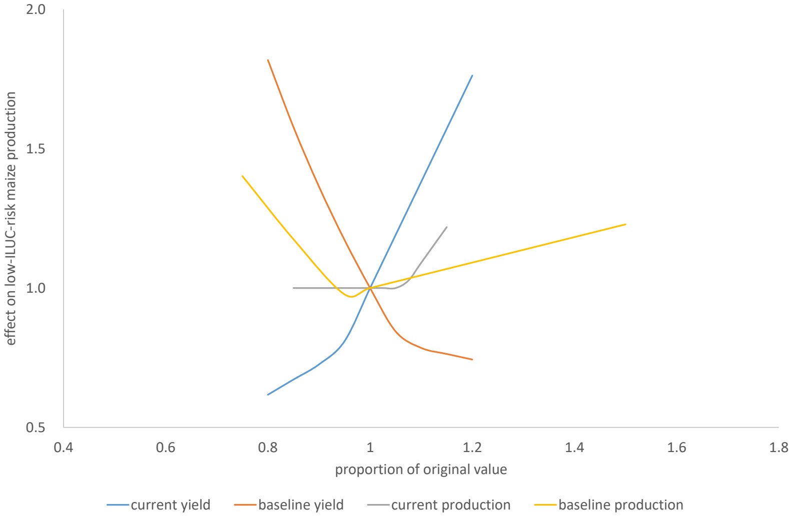


Figure 2.4 Spider diagram of the sensitivity of the low-ILUC-risk maize production on surplus lands in Hungary to changes in the current and baseline yield and production in the medium scenario.

The spider diagram of the sensitivity reflects the feedbacks in the integration step. For the current yield and production, the sensitivity is small and linear. A somewhat lower baseline yield gives a much higher low-ILUC-risk maize production as the gap between the baseline yield and the potential yield will increase sharply: a 20% reduction in the baseline yield will widen the gap between the baseline and the potential maize yield by an additional 50%. A small increase in the baseline yield will have the same effect, towards closing the gap, but at a certain crop-dependent increase this gap is closed and low-ILUC-risk potential is lowered. At a certain level the higher baseline yield will mean a lower demand for land and thus already reduce the land demand in comparison to the current situation.

Because the baseline yield and production are a given from an economic model it hard to verify this in reality. In this research a higher or lower baseline mean the scenarios lose their adequacy and should be changed to reflect this.

Figure 2.5 reflects the same effects as described above, but on the availability of surplus lands. In contrast to the previous figure, the effect of the yield improvement to calculate the low-ILUC-risk maize production in Hungary.

All calculations of the bioenergy potential are illustrated by the production of maize ethanol. In reality not all production on these lands will be maize, but a mix of multiple crops. The total production will therefore depend on the suitability of all the surplus land for multiple crops. Van Dam et al. (2007) already concluded in a study on CEE [179] that for a combination of high production, low costs and environmental benefits perennial crops such as willow and miscanthus, are to be preferred.

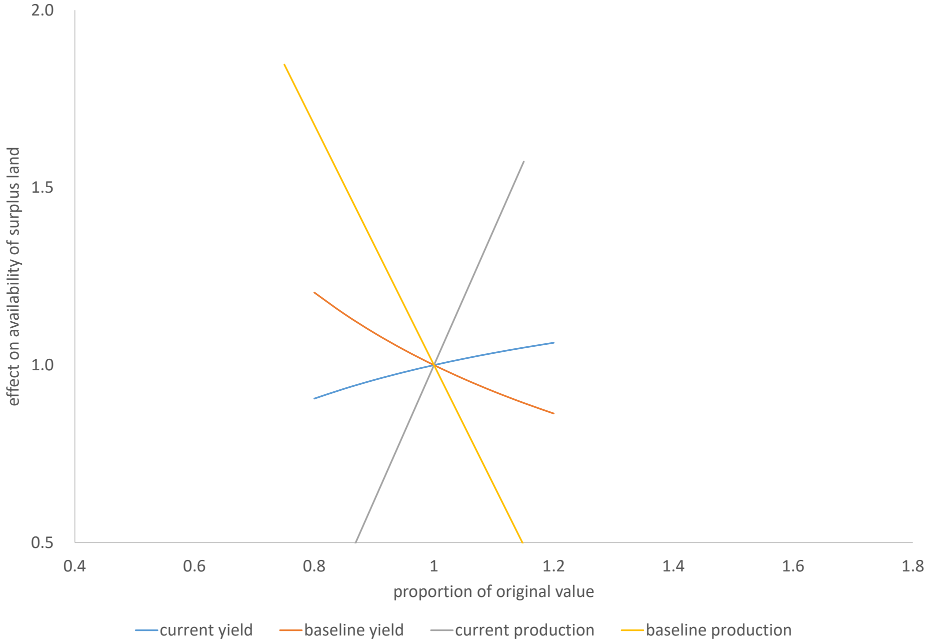
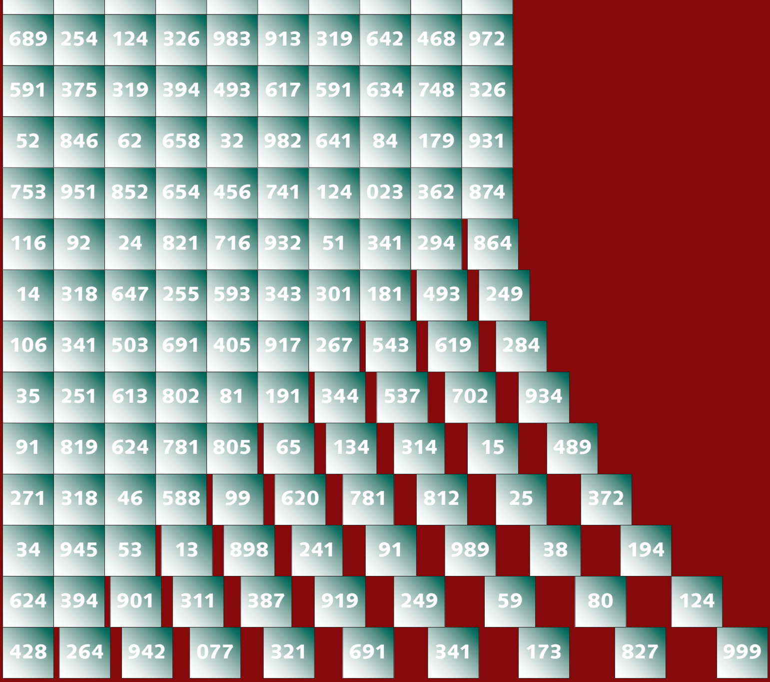


Figure 2.5 Spider diagram of the sensitivity of the surplus lands in Hungary to changes in the current and baseline yield and production in the medium scenario.

Crop losses in the agricultural chain

Table 2.8 Current and projected losses in the supply chain in Hungary, based on [137].

Crop	Current loss (%)	Current loss (kt)	Projected loss in 2020 (kt)
Maize	2.1	152	170
Wheat	1.8	80	91
Sunflower seed	0.9	11	14
Barley	2.1	23	15
Sugar beet	1.6	12	15
Potatoes	2.7	15	9
Rapeseed	0.3	2	2
Oats	0.8	1	1
Rye	1.4	1	1


689 254 124 326 983 913 319 642 468 972
591 375 319 394 493 617 591 634 748 326
52 846 62 658 32 982 641 84 179 931
753 951 852 654 456 741 124 023 362 874
116 92 24 821 716 932 51 341 294 864
14 318 647 255 593 343 301 181 493 249
106 341 503 691 405 917 267 543 619 284
35 251 613 802 81 191 344 537 702 934
91 819 624 781 805 65 134 314 15 489
271 318 46 588 99 620 781 812 25 372
34 945 53 13 898 241 91 989 38 194
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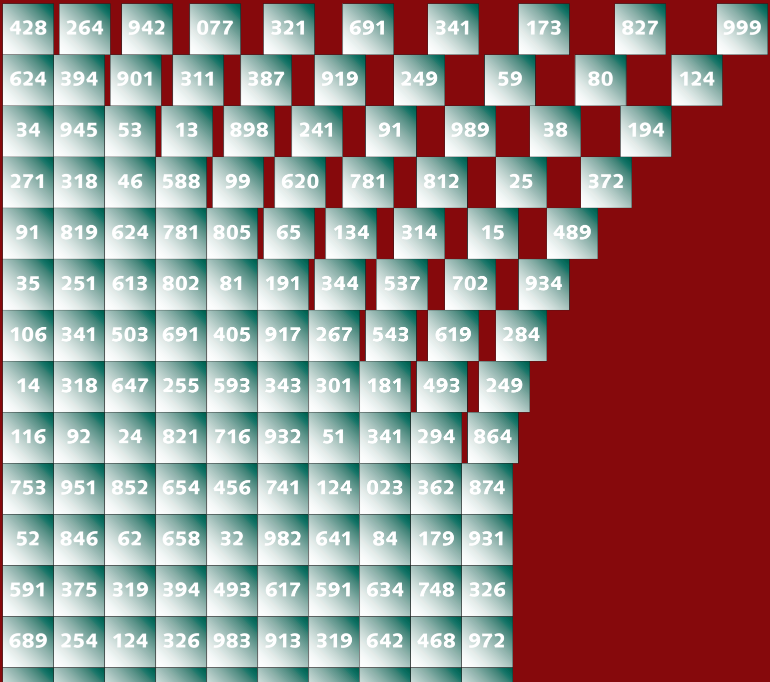
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3 Low-ILUC-risk rapeseed biodiesel: potential and indirect GHG emission effects in Eastern Romania

Abstract

Indirect land use change (ILUC) can have a severe impact on the greenhouse gas (GHG) balance of biofuels. Mitigating ILUC risk is important to avoid additional GHG emissions compared to fossil fuels. This is possible by making surplus land available through land demand reduction and using this for low-ILUC-risk biodiesel production. For a case study in Eastern Romania, we calculated the rapeseed biodiesel potential and the GHG emissions of four measures to make surplus land available in 2020. Four scenarios varying in assumptions on productivity and sustainability in the agricultural sector show the variation in the potential of these measures. We find that using surplus land to produce low-ILUC-risk rapeseed biodiesel has a potential of 3-64 PJ, 1-28% of the projected Romanian transport diesel consumption. The main contribution to this potential comes from yield improvements in crop and livestock production. Average GHG emissions of the ILUC mitigation measures are -11 to 22g CO_2-eq MJ^{-1} (maximum total lifecycle emissions are 34g CO_2-eq MJ^{-1}; 60% reduction from fossil fuel reference). This means ILUC mitigation is possible without necessarily missing the GHG emission reduction target, provided that the entire agricultural sector is sustainably intensified, going beyond a focus on biofuel production alone.

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3.1 Introduction

Bioenergy use is expanding to meet future worldwide energy demand and to reduce greenhouse gas (GHG) emissions [62,180]. However, additional production of biomass for bioenergy in one location could lead to additional agricultural land use elsewhere - through displacement or other market-mediated effects - a process commonly described with the term *indirect land use change* (ILUC) [58,181]. If this effect leads to conversion of high carbon stock lands, such as forests or peatlands, it could offset the GHG emission savings from bioenergy [58,123]. As climate change mitigation is one of the most important drivers of bioenergy demand [182], ILUC and its GHG emissions need to be minimised.

Policymakers have explored several options to prevent ILUC [108,111]. One option is to include an ILUC factor in the biofuels policy that prescribes the GHG emission savings that need to be achieved by the use of biofuel [122,183]. Under such a policy, an additional emission factor would be included in the obligatory GHG emission calculations of a biofuel, in order to account for the ILUC-caused emissions. This factor would reduce the attractiveness of biofuel with a high ILUC impact and several supply chains would likely not meet the desired reduction target, compared to fossil fuels, e.g. 60% in the EU [37,110,111].

As ILUC is an indirect effect, causal relations cannot be established directly and the effects of a counterfactual of no-biomass development cannot be measured. Therefore models are employed to estimate the size of the ILUC effect and the applicable ILUC factor [109,184,185]. Studies to calculate the magnitude of the ILUC factor use a partial equilibrium (PE) or computable general equilibrium (CGE) macroeconomic model to compare the global land use in a certain future reference year in a situation with and without additional biofuel production. The differences in additional land use and associated carbon emissions between the two scenarios are then attributed to the production of biofuels as the ILUC factor, thereby combining direct and indirect land use change [120,186]. These macroeconomic models often distinguish between bioethanol and biodiesel production. The resulting ILUC factors reflect the varying production methods and related carbon emissions for different feedstock crops. However, there are also some important drawbacks. For example, these models are very coarse and cannot link the production in a specific location to its impacts [112,126,184,187,188]. Furthermore, they generally do not account for possibilities to mitigate the risk of diverting agricultural production [189].

A second option to limit GHG emissions from ILUC is to reduce the risk of displacement due to bioenergy production expansion. The 2015 ILUC Directive from the European Union [113] opened a policy door to low-ILUC-risk biofuels and tasked the European Commission to set criteria for the identification and certification of biofuels with a low risk of ILUC [113]. Low-ILUC-risk biofuels are biofuels for which it can be demonstrated that the feedstocks have a low chance of displacing other agricultural production [190–193]. Four key measures to reduce the pressure on available agricultural land have been proposed in the literature: (1) above-baseline yield improvement in the entire agricultural sector; (2) chain integration through the use of biofuel co-products to replace other crop production; (3) crop loss reduction; and (4) biofuel feedstock production on under-utilised land [115]. These measures were assessed for their technical biofuel production potential in three previous case studies, considering bioenergy expansion in (1) Hungary [194], (2) a province in Poland [116] and (3) two provinces in Indonesia [117]. The studies in the European setting show it is possible to produce biofuels without expanding agricultural production on high carbon stock areas or displacing production to other areas, while still meeting the demand for food, feed, fibre and the current amount of biofuel feedstock [116,194]. In Indonesia this is only the case under certain stringent conditions of low agricultural expansion, enforced land zoning, strong yield growth and improved chain efficiencies [117].

Although these measures aim to prevent GHG emissions from ILUC, implementing the measures can also be a source of GHG emissions, e.g. when increased yields are obtained via increased fertiliser application. To avoid a situation where ILUC mitigation is a larger source of GHG emissions than ILUC itself, it is necessary to better understand the emissions of ILUC mitigation. Therefore, Gerssen-Gondelach et al. [118] calculated the GHG emission balances of the agricultural sector of Lublin province in Poland when producing ethanol from miscanthus with the application of the ILUC mitigation measures. The GHG emissions of the measures were calculated for three intensification pathways that varied in how intensification is implemented. The study showed a significant reduction in overall agricultural GHG emissions in the region is possible only if intensification is done sustainably (i.e. without increased inputs, but based on better practices [118]). An important reason for this finding is the use of the perennial crop miscanthus to produce bioethanol. Miscanthus cultivation leads to lower CH_4 and N_2O emissions than cultivation of other crops. Moreover, if miscanthus is produced on surplus agricultural land, above- and belowground carbon stocks are generally increased, which leads to a positive GHG emission effect of bioethanol.

However, biodiesel from first generation vegetable oils from Europe (e.g. rapeseed, sunflower) has higher GHG emissions [57] and higher projected ILUC GHG emissions than ethanol [195], while it is also produced from annual crops that do not sequester carbon in the soil, as for example miscanthus does. Furthermore, the mentioned studies in Europe [116,118,194] focussed on bioethanol crops, whereas in Europe, the production and use of biodiesel is higher than that of bioethanol [196]. Reducing the risk of additional GHG emissions related to ILUC in biodiesel production in the EU is therefore critical.

The objective of this study is therefore to calculate the low-ILUC-risk biodiesel production potential and the associated GHG emissions of the ILUC mitigation measures, differentiating among four intensification pathways. By analysing both the potential and the emissions of low-ILUC-risk measures, we can show the trade-off between reducing the ILUC risk and associated GHG emissions as these are often ignored [197].

In this study we zoom in on rapeseed for biodiesel production in Eastern Romania (see Figure 3.1) in 2020, the year of the first (10%) target for renewable energy in transport in the EU [37]. Romania plans to produce 20 PJ of biofuels per year in 2020 according to its National Renewable Energy Action Plan (NREAP) [198] of which 15 PJ will be biodiesel. Although 2020 is not far away, the timeframe 2010-2020 was selected as 2020 is the first milestone of the European Union Renewable Energy Directive (EU RED) [37] and the subsequent ILUC calculations of Laborde are also based on this period [123]. Furthermore, this is a theoretical assessment of the low-ILUC-risk potential, this is impacted less by the timeframe of the calculations.

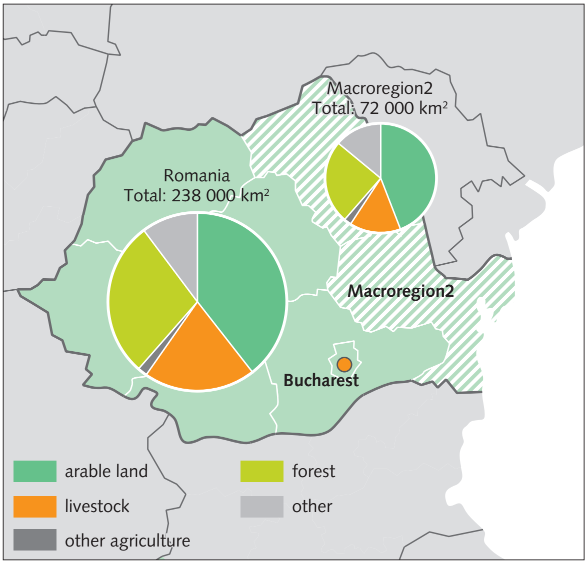

Figure 3.1 Location of Macroregion 2 in Romania, and key land use statistics in the country and region [40].

Romania has received increasing attention from businesses, farmers and governments due to the potential for growth in its agricultural sector [199,200]. Particularly Eastern Romania is currently relatively underdeveloped, with large yield gaps; this means intensification may provide large gains in terms of additional production and resource efficiency [201,202]. The size of Eastern Romania (Macroregiunea doi, in English Macroregion 2) is 72,000 km^2, of which 44,000 km^2 is classified as agricultural area. This is about 30% of the total agricultural area of Romania. The amount of arable land is 32,000 km^2, 34% of the Romanian total. In the period 2008-2012, Macroregion 2 produced 45% of the 615,000 tonne of Romanian rapeseed [201]. Rapeseed has been selected as it is already an important source of domestically produced biodiesel in the EU and based on the current production a crop suitable for the region.

3.2 Methods and materials

Expansion of biofuel production in Eastern Romania could lead to (high) land use change GHG emissions if it causes agricultural land expansion through displacement or other market-mediated effects. In this study, we calculated the potential rapeseed biodiesel (PJ yr^{-1}) that Eastern Romania could produce in 2020 with a low risk of ILUC and the associated GHG emissions (g CO_2-eq MJ^{-1} biofuel, hereafter just g CO_2-eq MJ^{-1}). The area available for low-ILUC-risk biofuel production, here called surplus land, comes from agricultural land that has recently been abandoned, or land that currently has an agricultural use, but will not be required anymore in 2020 for the production of food, feed or fibres as a result of intensification and increased resource efficiency. The steps to calculate this area and the resulting potential for low-ILUC-risk biofuels, are based on Brinkman *et al*. [115] and described below. A more detailed description of the specific application of the method for this case study can be found in [203].

The first step was to establish the baseline crop production in Eastern Romania in 2020 (see next section). This baseline is the biomass production in 2020 for food, feed, fibre for the growing population and gross domestic product (GDP), and the current amount of biofuel. Any additional demand for biomass for biofuel in the region above this baseline can be a cause of ILUC when it leads to expansion of agricultural land. This means, that the baseline production and production of any additional biofuel feedstock needs to take place within the current land use in order to avoid ILUC. In the second step, we calculated the potential effects of four measures to reduce land demand and thereby make land available for biofuel feedstock production. The four measures that were included are (1) above-baseline yield improvement in crop and livestock production; (2) use of rapeseed meal to replace feed crops; (3) decreased losses in crop production; and (4) biofuel feedstock production on abandoned land.

The application of these four measures can help to reduce the demand for agricultural land whilst still producing sufficient biomass to meet baseline demand. We did this for four scenarios that varied in their assumptions regarding potential developments in the agricultural sector, in terms of both productivity and sustainability. In the third step, we integrated the results and calculated the total surplus land (km^2) and potential biodiesel production (PJ) on that land. For this, the agricultural land available after covering the baseline biomass production was considered surplus land and available for the production of low-ILUC-risk rapeseed for biodiesel.

For each of the four measures, the resulting GHG emissions were calculated and we used these results to establish the GHG emissions of ILUC mitigation per unit of low-ILUC-risk biofuel (CO_2-eq MJ^{-1}). These indirect emissions need to be at least below 55 g CO_2-eq MJ^{-1} in order to constitute a saving compared to the European rapeseed biodiesel ILUC factor [123]. The complete life cycle emissions of biofuel production need to be below 34 g CO_2-eq MJ^{-1} in order to adhere to the 60% GHG emission savings compared to the fossil reference (83.8 g CO_2-eq MJ^{-1}) mandated in the EU RED for new biodiesel installations [37]. The life cycle emissions of rapeseed biodiesel in Romania are on average 20 g CO_2-eq MJ^{-1} for cultivation [204], and in the most optimistic situation 10 g CO_2-eq MJ^{-1} for transport and processing [57]; this leaves little room to allocate emissions resulting from ILUC mitigation. An overview of how the measures and the GHG emissions relate to each other is presented in Figure 3.2.

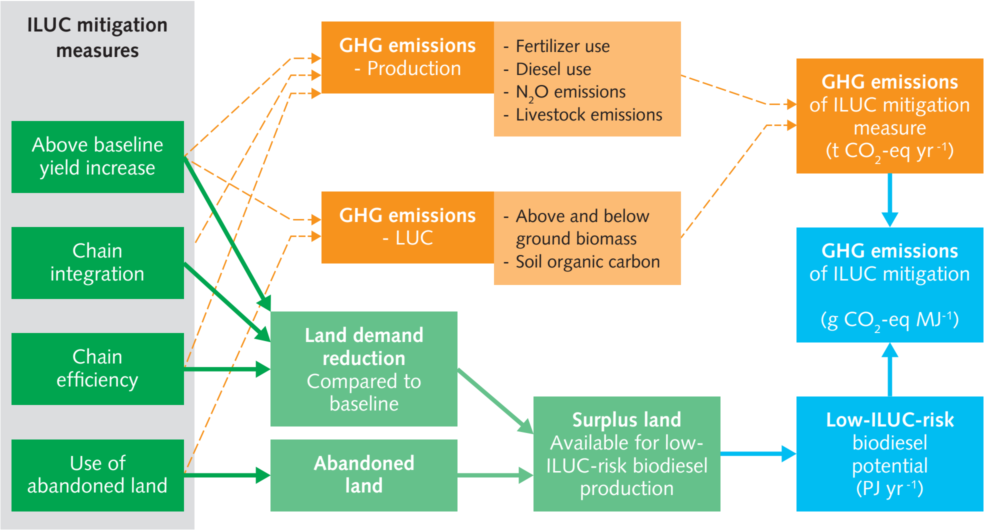

Figure 3.2 Overview of the surplus land and GHG emissions as a result of the implementation of the ILUC mitigation measures.

3.2.1 Step 1: Baseline agricultural production in 2020

The projections for the baseline crop production in Eastern Romania in 2020 are taken from the results of the MIRAGE (Modelling International Relationships in Applied General Equilibrium) [123]. This is a computable general equilibrium model developed by the International Food Policy Research Institute (IFPRI). The model projects the effects on supply and demand in all sectors of the global economy in response to an exogenous change (e.g. increased biofuel production) and includes developments such as population growth. Here we used the results from the Biof version of MIRAGE, which was also used for the report of the land use change consequences of European biofuel policies by Laborde [123]. This report was used by EU policymakers when considering establishing quantitative ILUC factors. For the baseline production, we used the reference situation in which no growth of biofuel production took place compared to the baseline. The results of the MIRAGE model are on the EU27 level. Therefore, the crop production volumes were disaggregated to Eastern Romania based on the share of the production of each crop (average 2008-2012) in Macroregion 2 within the EU27. For the disaggregation, the crop production data from FAOSTAT [202] and the Romanian national statistics office [201] were used. The total production, yield and area are presented in Table 3.1. Because of the large uncertainty stemming from the disaggregation, we varied this parameter in the sensitivity analysis that is presented in the results section. We included the eight most important crops in terms of production and area in the region in our analysis. These crops cover nearly 80% of the arable land in Macroregion 2.

In the baseline, demand for cattle increases by 15% until 2020, and the demand for other animal products decreases by 3% [123]. In the same period, the productivity of the cattle sector increases by 10%, and by 6% for other livestock production [123].

Table 3.1 Current (average 2008-2012) and future (2020) crop production, yield and area of eight selected crops in Eastern Romania. Production is for food, feed, fibres and the current amount of biofuels. Current production data and other land use data from INSSE [201]; 2020 production and yields disaggregated from MIRAGE based on the share of production in the EU27 from FAOSTAT [202]. Current cattle milk and beef production from [201]; projections based on Laborde [123].

Crop	Production (kt)	Production 2020 (kt)	Yield 2010 (t ha^{-1})	Yield 2020 (t ha^{-1})	Area 2010 (km^2)	Area 2020 (km^2)
Maize	2,923	3,283	3.3	3.4	9,000	9,770
Wheat	1,839	2,106	2.9	3.0	6,410	7,140
Sunflower	576	755	1.4	1.6	4,140	4,710
Barley	476	302	2.6	2.7	1,890	1,140
Rapeseed	280	434	1.6	1.8	1,710	2,420
Potatoes	943	598	13.7	14.2	680	420
Oats	98	62	1.6	1.7	600	370
Soy beans	68	88	1.7	1.8	400	490
Subtotal					24,820	26,450
Other crops					7,280	
Total arable land					32,100	
Meadows and pastures	1,459/70 [a]	1,678/80 [a]	3.3/0.4 [a]	3.7/0.4 [a]	10,850	11,340
Total included agricultural land [b]					35,670	37,790
Forest					18,020	

[a] Cattle milk/beef

[b] Sum of the included crops and meadows and pastures

3.2.2 Step 2: Bottom-up assessment of measures

The four ILUC mitigation measures aim to reduce the demand for agricultural land and thereby make land available for the production of rapeseed for biodiesel. We used *low*, *medium*, and *high* scenarios for the measures to assess the range of the surplus land for a less or more progressive development in the agricultural sector in Eastern Romania. A *high*+ scenario was used to illustrate the variation in GHG emissions as a result of differences in the intensification method. The *baseline* scenario refers to the conditions that apply to the baseline as defined in step 1 and follow the MIRAGE model. For the low scenario we assumed only a little progress in the agricultural sector in Eastern Romania, which is comparable to the recent past, but slightly better than the MIRAGE projections. In the *medium* scenario we assumed that the level of the best county in the region can be achieved by the whole region. In the *high* scenario we assumed progress to the level of neighbouring countries, such as Poland. For the calculation of the surplus land, the *high*+ scenario is identical to the *high* scenario. However, for the GHG emission calculation, we assumed a more sustainable intensification pathway to achieve this potential than in the *high* scenario. For the above-baseline yield measure this was based on Gerssen-Gondelach *et al.* [118]. The *high* scenario is an optimistic scenario in increasing production potential, but assumes conventional intensification pathways in order to achieve this potential. Conventional intensification relies on increased application of fertilisers, pesticides and mechanisation without increasing efficiency [118]. Previous studies (e.g. [205,206]) showed unsustainable intensification can increase GHG emissions per unit of product. Intensification causing GHG emissions to increase to a level above the ILUC factors would make low-ILUC-risk biofuel superfluous. There are multiple methods for sustainable intensification such as precision farming [207,208], reduced tillage [118], new crop varieties with higher yield, improved drought or pest resistance [209], or better management [205]. An overview of the scenarios is presented in Table 3.3 in the Appendix.

In the GHG emission calculations we included the emissions that are required to achieve each measure (e.g. increase fertiliser use to raise productivity), or the savings that occur due to lower demand (e.g. when reducing losses). In addition, we included GHG emissions of land use conversion from former land use to rapeseed. For cropland-to-cropland conversion we assumed no land use change GHG emissions. Following the EU guideline, the land use change GHG emissions were divided over a twenty-year period to account for the fact these occur only once [210].

3.2.2.1 Above-baseline yield improvement

The current crop yields in Eastern Romania are low compared to the average European yields (see Figure 3.3). This is a result of the interplay among various elements of which poor mechanisation of agriculture [198], sub-optimal use of fertilisers [211,212] and low pesticide use [135,171] are three main factors. For the baseline scenario, the MIRAGE model projects only a small yield increase (seeTable 3.1). For each crop, this yield increase was applied to the current yield (average 2008-2012) in Eastern Romania [201] to calculate the baseline yield increase. The *low* scenario extrapolated the linear yield trend in Macroregion 2 in the period 1990-2010 to 2020 [201]. The *medium* scenario assumed that the current best yield for each crop of all the twelve counties of Macroregion 2 can be achieved in the whole region by 2020. The yield in the *high* scenario was calculated as the same yield level (as share of the maximum attainable yield, based on the agro-ecological suitability [164]) as is currently achieved in Poland (e.g. for rapeseed this is 52%, up from the current 37%). Increasing yields above the baseline ensures the 2020 baseline crop production requires less land. The difference between the projected agricultural land area and area after the yield increase is surplus land that is assumed to be available for the production of rapeseed for biodiesel.

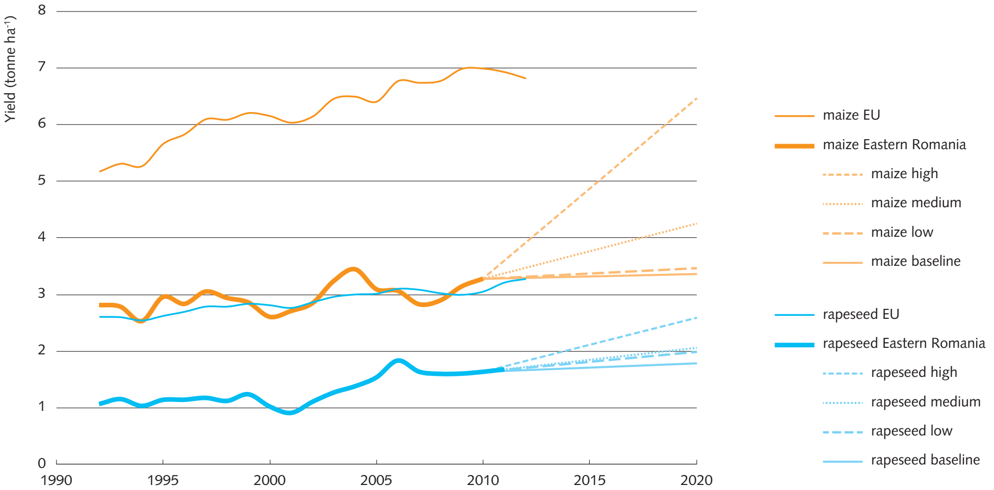

Figure 3.3 Rapeseed and maize yield development (five year moving average) in Eastern Romania and the EU27 (1990-2010) [40,41].

Livestock intensity in Eastern Romania is also low compared to the rest of the European Union, with only Greece, Bulgaria and the Baltic States having a lower density [171,202]. The index for livestock density was 1.0 livestock units per hectare (average 2008-2012). Livestock units (LU, as defined by EUROSTAT [213]) make it possible to compare the livestock density between countries with different compositions of the livestock herd. Here we included sheep (0.1 LU) and cattle (1.0 LU) as these are the two most land-demanding types of livestock in Romania. The density was based on livestock numbers (8.2 million sheep and 0.84 million cattle) from the national statistics office [201] and the sum of meadows and pastures in the region [201].

The intensification of livestock production follows the same logic as crop intensification. By increasing the productivity per hectare, less space is required for the production of the same quantity and the surplus area can be used for low-ILUC-risk biofuel production. For the increase in productivity in livestock production the same intensification pathways were used as for the crop yield increase in the *low* (extrapolating trend), *medium* (best county) and *high* (Poland) scenarios. Examples of measures to increase the production intensity are fertilising pastures, shortening of grazing periods and changing livestock diet towards less fibrous compositions [214].

GHG emissions of above-baseline yield improvement. Crop yield production intensification can lead to increased GHG emissions, -through higher agro-chemical application, diesel use in machinery or leaching resulting in nitrous oxide (N_2O) emissions. Still, by reaching a higher productivity, GHG emissions per unit product may decrease, but the net effect depends largely on how intensification is implemented. To calculate the GHG emissions of total agricultural production we used the BioGrace tool [56]. It is developed to calculate GHG emissions of different biofuel production routes and include the cultivation phase of eight different crops. BioGrace was selected as the tool follows the calculation rules for emission values (e.g. global warming potential, GHG emission coefficients) and system boundaries of the EU RED [37]. BioGrace is applied here to calculate the emissions of the cultivation of maize, wheat, rapeseed, soy and sunflower. Because the ILUC mitigation measures only relate to the cultivation phase and not the conversion to biofuel, only the cultivation part of BioGrace was used. Nine sources of emissions (diesel, N-fertiliser, manure, CaO fertiliser, K_2O-fertiliser, P_2O_5-fertiliser, seed and pesticide use, and the field N_2O emissions) and three additional variables (yield, crop moisture content, seed use and co-products as share of production) are available for this phase in BioGrace. For each crop, a default value is available for all of the twelve variables[56]. Each combination of these default values is part of the standard production route that corresponds to the default emission values for that specific biofuel production route in the EU-RED. This value is based on a typical production case set in a European country.

Table 3.5 in the Appendix presents the BioGrace input values for the *low*, *medium*, *high* and *high*+ scenarios. Five of the eight crops addressed in this study are also included in the BioGrace tool, i.e. maize, wheat, rapeseed, sunflower and soy. In 2020, these five crops cover 72% of the arable land or over 90% of the crop land in Eastern Romania that is covered in this study (seeTable 3.1). For the crops that are not included we used the following proxies: for the cereals barley and oats, we used the GHG emissions of wheat, and for potatoes we used the area weighted average of the emissions per hectare of the five included crops. As virtually all GHG emissions in the default set-up of BioGrace come from the NPK-fertilisers, the diesel use and the field N_2O emissions (99% of CO_2-eq emissions for rapeseed, over 90% for the others), only the values in these categories were adapted in the calculations for each scenario (see Table 3.5 in the Appendix). The other variables were not changed from their default values. The input values in the baseline were derived from current production in Romania [204,215]. The input values in the *low*, *medium* and *high* scenarios reflect the assumptions in the intensification pathways of these three scenarios as defined in the previous section. For the emissions in the *high*+ scenario we used the sustainable intensification pathway as described by Gerssen-Gondelach *et al.*, [118]. For the fertiliser application we used the highest nutrient use efficiency (NUE) for each crop and each fertiliser type. In the sustainable intensification pathway of Gerssen-Gondelach *et al.*

diesel use was 10% lower than in the case of conventional intensification [118]; this assumption was also used here.

For each scenario, BioGrace was used to calculate the emissions per cultivated hectare. Multiplying this by the production area (after the yield increase) gave the total emissions of crop production in Eastern Romania in the *baseline* and in each scenario. The GHG emissions of ILUC mitigation were then calculated as the difference between the emissions in the *baseline* and the emissions in each specific scenario in 2020.

Intensification of extensive livestock production can impact GHG emissions through changes in feed composition and energy use [216–218]. In addition, the conversion of grassland to cropland leads to land use change GHG emissions. To calculate the GHG impacts of the livestock intensification that was included in the scenarios we used the method developed by Gerssen-Gondelach *et al*. [118], who based it on multiple reviews [214]. As this method was already applied to the Eastern European context, only the Romanian-specific data differed from the previous study. The GHG emission calculations were limited to cattle as there are insufficient data available to include the effects of sheep production intensification. The GHG emissions for cattle include their most important emission sources: enteric fermentation, feed production, manure management and energy consumption, for both milk and beef production. The data on beef and milk productivity intensification in each scenario are presented in Table 3.2. Specific data on the emission sources of cattle production are presented in Table 3.6 in the Appendix. This shows the CH_4 emissions from enteric fermentation are responsible for the majority of GHG emissions; these rapidly decline with increasing intensification. The methane emissions of manure management, however, increase significantly with increased intensification. Sustainable intensification in the *high+* scenario was implemented using a 10% lower GHG emission impact compared to the *high* scenario, following the data of Gerssen-Gondelach *et al*. [118]. Multiplying beef and milk production by the respective GHG emissions per unit product gave the total emissions for each scenario. The GHG emissions of ILUC mitigation were then calculated as the difference between the total GHG emissions in each scenario and the baseline GHG emissions.

The land use change GHG emissions of converting meadows and pastures to crop land were calculated using the IPCC Tier 1 approach [219–221] and the EU guideline on the calculation of land carbon stocks [210]. The GHG emissions of the conversion of grassland to cropland consist of a decrease in soil organic carbon in the top soil (top 30 cm) and a loss in the above and below ground biomass. For the soil organic carbon content in the region, we selected the default value (38 t C ha^{-1}) for high activity clay soils in temperate-dry conditions from the EU guideline [210,222]. This was adapted by multiplying by factors for land use (1), land management (1) and inputs (1) that reflect nominally managed medium input grasslands. The carbon content of the cropland was calculated by multiplying the same reference soil organic carbon content of the region with factors for land use (0.8), land management (1) and inputs (1.04) that are in line with full-tillage, high input (without manure) agriculture in a temperate-dry climate [210]. For the loss in vegetation - in the form of above- and below-ground biomass - we took the default value for grassland from the EU guideline: 3.3 t C ha^{-1} [210]. In the *high+* scenario we adjusted the factor for land management to reflect a management system without tillage (1.1) that sequesters a higher level of carbon in the soil.

3.2.2.2 Improved chain integration

Expanding biofuel production also means an increased production of its co-products, which can have a positive indirect effect on land demand [223]. Crushing rapeseed to obtain rapeseed oil yields 59% rapeseed meal [224], which can be used as animal feed and thereby replaces other feed production. This reduces the demand for arable land for feed production and technically creates more space to produce biofuels. As the MIRAGE model already includes a reduction in crop production as a result of the use of rapeseed meal, there was a risk of double counting. We avoided this by increasing the crop production in 2020 (of Table 3.1) by the same amount that it was reduced in the MIRAGE model due to the use of the rapeseed meal as animal feed [194]. This amount was calculated by multiplying the rapeseed meal production and the replacement rate assumed by Laborde [123], following the description of Brinkman *et al*. [194].

In the *baseline* no chain integration was assumed to take place. In the *low* scenario we assumed the rapeseed meal to replace the marginal source of protein in feed, which is imported soy [225]. This alleviates the pressure on agricultural land in Brazil and Argentina, the two main soy-producing countries, but does not contribute to the domestic surplus land and low-ILUC-risk biofuel potential. In the *medium* scenario we assumed the current replacement rate in the Romanian feed mix, based on FAOSTAT data. In the *high* scenario we assumed rapeseed meal to replace the marginal source of energy in the feed; in this case, it was domestically produced barley [169]. The data for crop replacement by rapeseed meal are presented in Table 3.2.

As the land use savings in the baseline were assumed to be zero, we calculated the surplus land in 2020 for each scenario as the replaced crop production divided by the baseline yield (from Table1) of that crop.

GHG emissions of this measure came from the production of rapeseed meal and GHG savings were achieved through lower production of the displaced crops. Producing rapeseed meal from rapeseed requires energy for transport, drying and processing. This equates to 0.1 kg CO_2-eq kg^{-1} rapeseed meal [226]. The GHG emissions of the crop production that is displaced by the rapeseed meal can be counted as negative GHG emissions of this measure; the GHG emissions of processing of regular feed are neglected as it they represent only a small share of the carbon footprint of regular feed production [226]. To calculate this, the crop production reduction in Eastern Romania for each scenario was multiplied by the crop-specific GHG emissions (i.e. the baseline from the yield increase measure). The total emissions of this measure were calculated as the sum of the emissions to produce rapeseed meal and the negative emissions from the reduced crop production.

3.2.2.3 Reduced agricultural losses

Current pre-consumer losses in the agricultural chain for the eight selected crops range in Romania from 0.9% of the total domestic supply for wheat (EU average: 2.5%) to 8.9% for barley (EU average: 2.1%). These are country average data (2008-2012) from FAOSTAT as there are no region-specific data available [202]. Crop losses unnecessarily increase the land requirement to meet the demand; eliminating these losses would therefore make more land available for other uses [158]. The *baseline* assumption here was that the losses would not change. In the *low* scenario we assumed that the pre-consumer losses keep declining at the same pace as in the period 2000-2012. In the *medium* scenario the average losses in the Central and Eastern European member states of the EU were assumed to be achievable in Romania. The *high* scenario considered the losses in Poland to be achieved in Eastern Romania in 2020. The assumed losses for each scenario are presented in Table 3.2.

Following Gerssen-Gondelach *et al*. [118], we only included the GHG emission reduction from reduced crop production. Further savings from reduced transport and storage are expected to be negligible. The GHG emission effects associated with the reduced crop production as a result of the lower losses were calculated following the crop-specific emission factors as calculated for the yield increase measure.

3.2.2.4 Abandoned land

The agricultural land area utilised in Romania decreased after the fall of the communist regime as a result of low profitability, ambiguity of land ownership, lack of governmental support and poor mechanisation [227]. These lands have not been taken back into production, but doing so is an effective way to limit the risk of ILUC and high land use change GHG emissions. This is under the condition that these abandoned lands do not have high carbon stocks or other (conservation) value [112]. The amount of land classified as abandoned in Eastern Romania is presented in Table 3.4 in the Supplementary Materials. The data were derived from the national agricultural census of 2010. In the *baseline* we assumed no use of abandoned lands. The *low* and *medium* scenarios only included plots of abandoned land larger than 50 ha and 20 ha, respectively, as small plots are more difficult to take into production. The *high* scenario assumes all plots of abandoned land to be available for crop production (1100 km^2). To account for possible lower productivity of abandoned land, we assumed a yield of 50%, 75% and 99% of the *baseline* productivity in the *low*, *medium* and *high* scenarios, respectively. This range corresponds to the uncertainty range for yield on marginal lands as also used by Laborde [123].

Bringing abandoned land back into production, leads to GHG emission from the carbon stock lost due to the conversion of abandoned land to cropland. The carbon stock changes were calculated as in the case of grassland conversion. For abandoned land, the soil carbon content data were the same as those used for grassland [210]; the factors for land use (1), management (1.1) and inputs (1) were adopted to reflect abandonment. For cropland, the same factors were used as previously described for grassland to cropland conversion, including the higher management factor in the *high+* scenario. For biomass present on abandoned land, for vegetation we assumed shrub growth on the land (7.4 t C ha^{-1}). A part of the abandoned land can be in transition to forest, which would be associated with higher GHG emissions [159,160]. However, our analysis of the land use based on satellite images (see [203]) showed a continuous two-way conversion of lands in Eastern Romania, going from agriculture to forest and vice versa. This indicates that carbon stock growth in biomass on abandoned land is limited. Furthermore, as the abandoned lands were assessed on the ground by the statistics office during the land census of 2010 [228], it was assumed the conversion to forest land had not yet been started.

3.2.3 Step 3: Integration and comparison

In the third step, the total surplus land and the production potential of low-ILUC-risk biofuel were calculated. Figure 3.4 shows how the results of the four measures were integrated to calculate the total surplus land. Starting from the current agricultural land use, in seven consecutive steps the changes to land requirements as a result of increased crop demand and the application of the ILUC mitigation measures were included. The available abandoned lands were considered additional supply. As the measures also impact each other (e.g. more surplus land means higher availability of meal) a few iterative steps were made to also include these effects. As a result of these calculations, we obtained the total amount of surplus land in Eastern Romania after the implementation of each of the measures. This land was assumed to be available for low-ILUC-risk rapeseed for biofuel production. The amount of biodiesel produced was calculated assuming the average Romanian rapeseed crushing efficiency (2008-2012) of 39% [224] and a 98% biodiesel conversion yield [229].

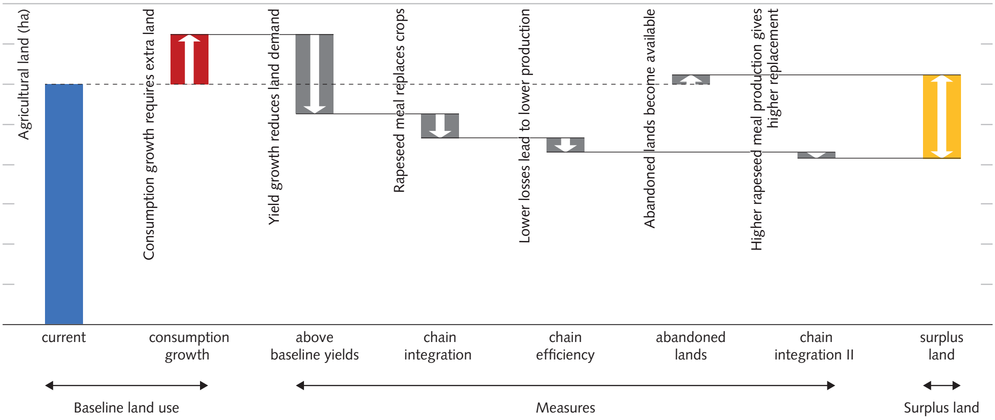

Figure 3.4 Schematic overview of the calculation steps to determine the surplus land. The current agricultural land (blue bar) and additional land to meet growing demand (red bar) give the baseline land use in 2030. The ILUC mitigation measures (grey bars) reduce this demand or increase supply of land. The surplus land (yellow bar) can be used for the production of biodiesel.

3.2.3.1 ILUC mitigation GHG emissions

The total GHG effect of ILUC mitigation was calculated similarly to that for land use by integrating the various measures. The GHG emission change in the *low*, *medium* and *high* scenarios was fully attributed to the low-ILUC-risk biofuel production in Macroregion 2. We compared the results for each measure and the integrated result (in g CO_2-eq MJ^{-1}) to the 55 g CO_2-eq MJ^{-1}, the ILUC factor for rapeseed biodiesel as reported by [123].

3.2.4 Data

Table 3.2 presents the data for the calculations of the surplus land of the four measures in Eastern Romania, in the baseline and *low*, *medium* and *high* scenarios. The data in S.4 in the Supplementary Materials are the input values to BioGrace for the calculation of the GHG emissions of the above-baseline crop yield increase. The data for GHG emissions of above-baseline livestock yield increase are presented in S.5 in the Supplementary Material.

We performed a sensitivity analysis on the most uncertain parameters of this study. For this we varied the value of the parameter to establish the effect on the low-ILUC-risk potential and ILUC mitigation GHG emissions.

Table 3.2 Input data for the calculation of the surplus land of the four measures in the baseline and the three scenarios. Surplus land in the high+ scenario is the same as in the high scenario. Assumptions for each scenario are explained in the previous sections and summarised in Table 3.3 in the Supplementary Materials.

ILUC risk mitigation measure			Scenario			
			Baseline	Low	Medium	High(+)
Above-baseline yield increase	Yields 2020 (t ha-1)	Maize	3.4 [a]	3.5 [b]	4.3 [c]	6.1 [d]
		Wheat	3.0	3.1	3	3.5
		Sunflower	1.6	1.5	2	1.6
		Barley	2.7	3.2	3	3.1
		Rapeseed	1.8	2.0	2	2.5
		Potatoes	14	12	15	17.0
		Oats	1.7	1.7	2	2.4
		Soy	1.8	2.0	2.1	1.6
	Livestock units (ha^{-1})		1.0 [e]	1.0 [f]	1.6 [g]	1.8 [h]
	Cow milk productivity (m^3 y^{-1})		3.7 [i]	3.6 [j]	3.7 [k]	4.9 [l]
	Cow beef productivity (kg)		173 [m]	178 [n]	176 [o]	226 [p]
Chain integration	Products replaced by one tonne of rapeseed meal (t)		none	soy meal: 0.89 [q]	maize: 0.63; wheat: 0.7; barley: 0.03; potatoes: 0.04; oats: 0.03; soy meal: 0.04 [r]	maize: 0.95; wheat: 0.98; barley: 1.1; potato: 3.8 [s]
Reduced losses	Losses 2020 as mass fraction (%)	Maize	1.4 [t]	0.94 [u]	1.4 [v]	1.4 [w]
		Wheat	0.9	0.37	0.9	0.9
		Sunflower	4.0	3.73	3.0	2.7
		Barley	8.9	8.70	3.7	3.8
		Rapeseed	1.5	1.49	1.5	1.5
		Potatoes	4.4	2.74	4.4	4.4
		Oats	2.1	2.08	2.1	2.1
		Soy	0.5	1.06	1.1	1.1
Abandoned lands	Assumed area available (ha)		0[x]	>50	>20	all
	Assumed productivity as share of average yield (%)		0[y]	50	75	99

[a] Calculated from MIRAGE baseline projections for the EU27 [123]. Growth percentages from MIRAGE were applied to the current (average 2008-2012) yields in Eastern Romania that were derived from the national statistics database [201].

[b] The linear yield trend per crop since 1990 in Eastern Romania (data from national statistics [201]) was calculated and extrapolated until 2020.

[c] Yield in the county of Eastern Romania with the highest yield for that crop, data from the national statistics office [201].

[d] The ratio between the maximum attainable yield and the current yield in Poland (FAOSTAT data, average 2008-2012 [202]) was multiplied with the maximum attainable yield in Eastern Romania. The maximum attainable yield was derived from the GAEZ data from IIASA [164] following the description in [203] and [194].

[e] The sum of the number of bovine animals and sheep in Macroregion 2 [201] multiplied by their respective livestock units (1 and 0.1) [213] divided by the sum of the meadows and pasture areas in Macroregion 2 [201]. Average for 2008-2012.

[f] Linear extrapolation of the trend (1995-2012) for livestock density in Macroregion 2, data before 1995 show a very rapid decline resulting from the reduction in livestock after the collapse of the communist regime.

[g] The density in the county with the second highest density (Botosani), because the county with the highest density, Braila, is an outlier (2.2) compared to the rest of the counties.

[h] Density in Poland, based on FAOSTAT data [202].

[i] Current productivity was calculated as the total milk production in Macroregion 2 (excluding consumption by calves), divided by the total lactating bovines [201]. This was increased with the projected increase in cattle productivity of 10% from MIRAGE [123].

[j] Extrapolating the trend of average milk productivity per cow in Macroregion 2 (2004-2012) to 2020.

[k] Highest average productivity in Macroregion2 is achieved in Galati.

[l] The milk yield per cow in Poland from FAOSTAT [202].

[m] Carcass weight in Romania [202] (average 2008-2012). As no macroregional level data are available, national data were used. This was increased with the projected increase in cattle productivity of 10% from MIRAGE [123].

[n] Extrapolating the national trend (2004-2012) in carcass weight to 2020.

[o] In 2015 the living weight of slaughtered animals in Sud Est was 313 kg [230]. Using national data for living weight of slaughtered animals [201] and FAOSTAT data for carcass weight [202] we calculated the average national ratio between living weight and carcass weight (0.56). Multiplying this ratio with the living weight in Sud Est gave the highest productivity in the region.

[p] Average (2008-2012) carcass weight in Poland [202].

[q] Protein content of rapeseed meal is 33%; for soymeal this is 48% [166]. Replacing it at equal rates and assuming 1.3 t soy is needed for a ton of soymeal [123] gave a replacement rate of 0.89 t soy t^{-1} rapeseed meal. All soymeal was assumed to be imported from Argentina and Brazil, the largest producers and exporters of soy to Europe [231].

[r] The current average feed mix is taken from FAOSTAT [202] (average 2008-2012).

[s] The digestible energy content of rapeseed meal is 13.8 GJ t^{-1}[169]. Replacement by energy content of barley (13.0 GJ t^{-1}), wheat (14.1 GJ t^{-1}), potato (3.66 GJ t^{-1}) and maize (14.6 GJ t^{-1}) [169]. Water content conversion data from [165]. Crop replacement in order of the lowest yield to maximise the surplus land.

[t] Current losses are reported by FAOSTAT, but are only at country level. Therefore, the average (2008-2012) losses for Romania as a whole were used to calculate the current losses in Macroregion 2. The losses were expressed as the share of the total supply (sum of production, imports and stock withdrawals) of the crop in Romania.

[u] The per-crop linear extrapolation of the losses, expressed as the share of the baseline production.

[v] Per-crop average losses found in the seven central and eastern European EU countries (Bulgaria, Czechia, Hungary, Poland, Romania, Slovakia, Slovenia), average FAOSTAT data 2008-2012 [202].

[w] Per-crop average losses in Poland (2008-2012) [202].

[x] For the availability of the abandoned lands (Table 3.4), we assumed in the *high* case all abandoned lands to be available, but for the *medium* case only those larger than 20 ha end in the low case only those larger than 50 ha.

[y] We assumed a marginal yield ratio for productivity on abandoned lands similar to the uncertainty analysis of Laborde [123], who used an uncertainty bandwidth of 50% to 99%, with an average of 75%.

3.3 Results

The surplus land that can become available from implementing the four ILUC mitigation measures in Eastern Romania, the resulting low-ILUC-risk biodiesel potential and the associated GHG emissions are presented in Figure 3.5 for a *low*, *medium* and *high* scenario. For the *high* scenario two variants are shown for the GHG emissions. These are the regular *high* scenario and a *high*+ scenario for which we assume the same low-ILUC-risk biodiesel potentials, but where we assume intensification takes place sustainably, reducing the associated GHG emissions. The potential surplus land of all four measures is between 2000 km^2 (*low*) and 18,000 km^2 (*high*). This corresponds to 6-43% of the current agricultural area in the region. In addition to the domestic surplus land, there is also additional surplus land abroad. This comes from the replacement of imported soy by rapeseed meal in the *low* and *medium* scenarios of the chain integration measure. This is a maximum of 400 km^2 and is not included in the calculations of low-ILUC-risk rapeseed biodiesel potential, as it is outside the region. Using all domestic surplus land for low-ILUC-risk rapeseed biodiesel production can yield a total potential production of 3 – 67 PJ. This is up to 30% of the 224 PJ projected total diesel consumption in Romanian transport in 2020 [171,198]. The low-ILUC-risk biodiesel potential is 15-340% of the NREAP biofuel target for the whole country, or 45-1000% when disaggregating the NREAP production to Macroregion 2 (disaggregation based on the region's share of Romanian arable land).

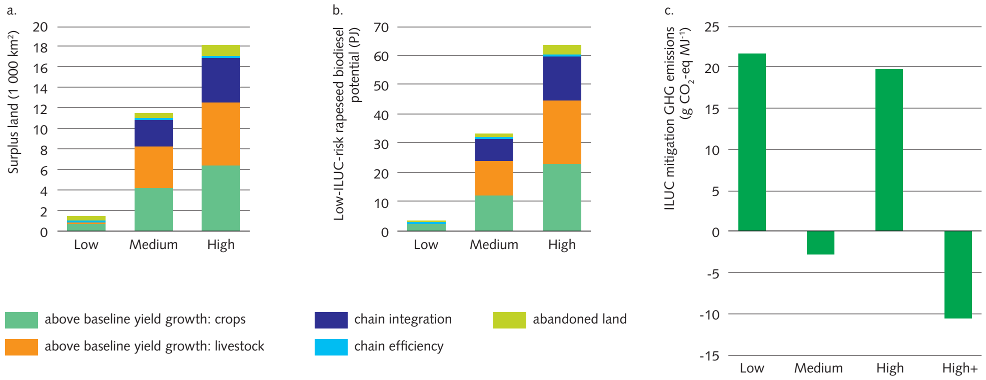

Figure 3.5 Surplus land in the low, medium and high scenarios as a results of the measures. (b.) Potential low-ILUC-risk rapeseed biofuel production. (c.) ILUC mitigation GHG emissions for the four scenarios. Note that the surplus land and low-ILUC-risk biodiesel potential in the high+ are the same as in the high scenario.

The GHG emissions to make the surplus land available are on average 28, -6 and 12 g CO_2-eq MJ^{-1} in the *low, medium* and *high* scenarios, respectively. In the *high*+ scenario that focussed on sustainable intensification, the GHG emissions are significantly reduced to -12 g CO_2-eq MJ^{-1}. This is mainly the effect of lower GHG emissions of above-baseline yield improvement because of lower fertiliser and diesel use. The ILUC factor for rapeseed biodiesel as calculated by Laborde is 55 g CO_2-eq MJ^{-1} [123]. This means making surplus land available for low-ILUC-risk rapeseed biodiesel can be done without additional GHG emissions compared to ILUC.

To put this in perspective, the complete life cycle GHG emissions for biodiesel produced from Eastern Romanian rapeseed, excluding the land use change emission, amounts to 30 g CO_2-eq MJ^{-1} in the most favourable case. The maximum emission to be able to meet a 60% reduction from the fossil reference (83.8 g CO_2-eq MJ^{-1}) set by the European Commission is 34 g CO_2-eq MJ^{-1} [37]. The small margin of 4 g CO_2-eq MJ^{-1} between the two means that when the ILUC-risk mitigation GHG emissions are included in the life cycle calculations, only those measures can be implemented that are associated with near -zero or negative GHG emissions. This would mean the low-ILUC-risk biodiesel potential decreases to 2.2 PJ in the *low* scenario to 15 PJ (*high*), 20 PJ (*medium*) or 59 PJ in the *high+* scenario. Thus, only the *medium* and *high+* scenarios can meet the national biofuel target of 20 PJ and fulfil the emission reduction criteria, as the *high* scenario has GHG emissions too large to be viable. This is also apparent from Figure 3.6, which shows the combination of the low-ILUC-risk potential and the associated GHG emissions. The negative GHG emissions for some measures indicate those measures that make land available through lower crop production (e.g. lower losses means lower required production) or where the production increases faster than the per-unit GHG emissions.

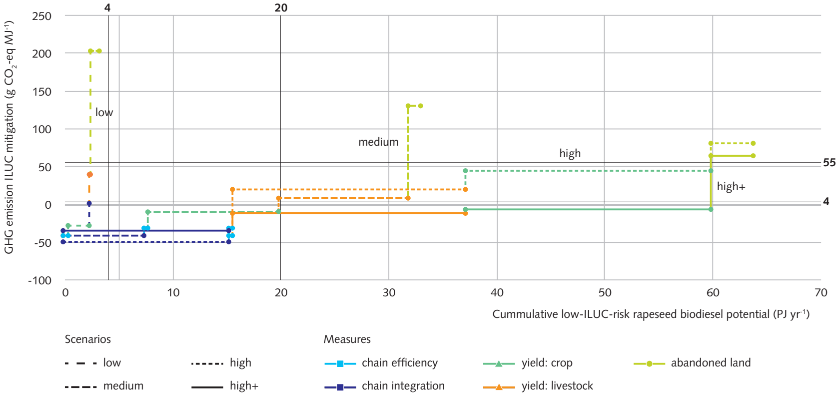

Figure 3.6 Potential and GHG emissions of the ILUC mitigation measures in all scenarios. ILUC GHG emissions of oilseeds are 55 g CO_2-eq MJ^{-1} [123]. The margin between total direct and indirect life cycle emissions of biodiesel production and the threshold value to achieve the mandated reduction compared to fossil fuels is 4 g CO_2-eq MJ^{-1}. The vertical lines indicate the NREAP [198] biofuel projected production in Romania (right) and disaggregated to Macroregion 2 (left).

Above-baseline yield development for crops and livestock is the most important measure in terms of surplus land and low-ILUC-risk rapeseed biodiesel potential in each scenario. Between 55% and 72% of the total surplus land comes from yield increases in the *low* to *high* scenarios. The yield increases in maize, wheat and livestock contribute most to the availability of surplus land. As the gap between actual and potential yields is large and only limited yield increases are projected in the baseline, the potential for above-baseline yield increase in crop and livestock production can lead to a large potential. The baseline yield development and above-baseline yield development are also the parameters most affecting the final outcome. A small change in yield can have a large impact on the low-ILUC-risk rapeseed biodiesel potential and the GHG emissions, as illustrated in Figure 3.7. It should be noted that a 20% change in the baseline yield can reduce the gap to zero and reduce the amount of surplus land from this measure to zero. A lower above-baseline yield for rapeseed amplifies this effect, as lower rapeseed yield means lower biodiesel feedstock production on the available surplus land. Lower yield increases would also mean the GHG emissions of crop intensification are spread over a smaller amount of low-ILUC risk biodiesel potential, thereby increasing the GHG emission per unit of low-ILUC-risk biodiesel.

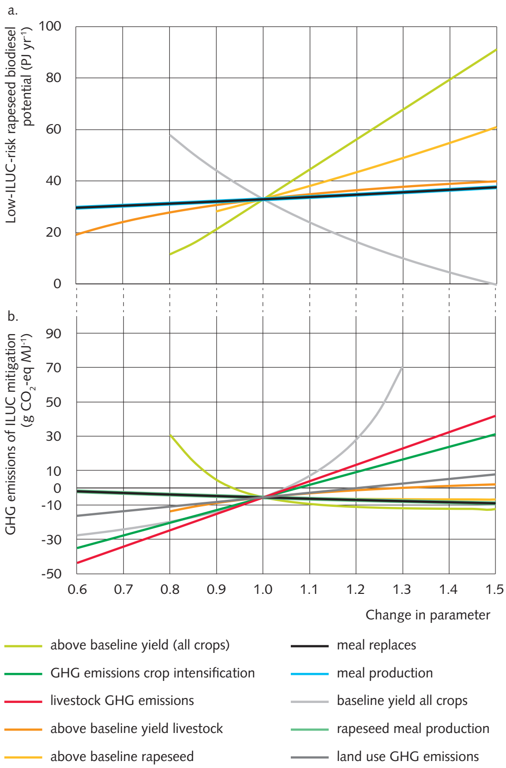

Figure 3.7 (a.) Sensitivity of the low-ILUC-risk biodiesel potential and (b.) GHG emissions of the ILUC mitigation measures to a change in various parameters in the medium scenario.

Although the GHG emissions of crop yield improvement are high (75% average increase in the *high* scenario) these are compensated by higher yields, leading to lower emissions per unit crop produced. The same is true for intensification of livestock production [118]. The GHG emissions of livestock intensification are higher as a result of the emissions of converting grassland to cropland. The conversion of meadows and pastures in Eastern Romania to cropland is associated with GHG emissions of 34-63 g CO_2-eq MJ^{-1}. These emissions are, however, partly compensated by the lower GHG emissions in livestock production, leading to lower net emissions of this measure. The LUC emissions of grassland to cropland conversion are allocated here to the low-ILUC-risk GHG emission factor, to account for the GHG emissions of reducing the ILUC risk. However, a problem of double counting occurs if these are included in the direct life cycle emission of biodiesel production.

3.4 Discussion and conclusions

Indirect land use change can have a severe impact on the GHG emission balance of biofuel production. In this case study, we calculated the potential to produce low-ILUC-risk biodiesel from Eastern Romanian rapeseed, and analysed the GHG emissions associated with the underlying measures to minimise the risk of ILUC (i.e. above-baseline yield increase, use of rapeseed meal to replace animal feed, reduced losses in the agricultural production chain, and the use of abandoned land). The results emphasise that ILUC mitigation is possible while still fulfilling a GHG emission reduction target of 60% compared to fossil fuels. However, this is only achieved when the entire agricultural sector is sustainably intensified, going beyond a focus on biofuel production alone. Key discussion points and conclusions are identified as follows:

Yield improvements of crops and livestock are crucial to reduce the ILUC risk. Yield growth is the most important measure in all scenarios and is responsible for up to three quarters of the surplus land. However, the extrapolation of current trends in crop and livestock yield, as is assumed in the *low* scenario, is insufficient to reach the regionally disaggregated NREAP target without a risk of causing ILUC. Thus, to be able to mitigate the risk of ILUC, crop and livestock yields have to grow faster than in the recent past. A comparison of the development in actual Eastern Romanian crop yields in the period 2010-2016 with the projected yields in the scenarios reveals yield increases are higher than in the past: in 2016 most crops are already above the yield levels projected in the scenarios [201]. Moreover, historic data on crop yield levels in Europe show that it is possible to achieve many continuous years of high yield growth. This high yield growth was even achieved when the yield gap was smaller than it is now [132,140,202]. An additional benefit of high yield growth is that higher yields for rapeseed also mean more biodiesel feedstock production on the surplus land.

Low-ILUC-risk biodiesel production is feasible with low GHG emissions of ILUC mitigation measures under specific conditions. ILUC mitigation requires intensification and modernisation of the agricultural sector and putting under-utilised land into production. It should be avoided that GHG emissions from these ILUC mitigation measures increase total GHG emissions compared to ILUC itself. Furthermore, emissions should be low enough that the total direct and indirect life cycle emissions of biodiesel production stay below the threshold value to achieve the mandated reduction compared to fossil fuels (i.e. 60% reduction in EU RED). We show this is possible in this case study. The mitigation measures with low GHG emissions can provide more than the regionally disaggregated biofuel target for Eastern Romania. To avoid high emissions, strict limitations apply. These limitations relate to the level of yield growth, need for sustainable intensification and consideration of the carbon stocks of the surplus land. Reducing crop losses and replacing animal feed with rapeseed meal can be qualified as no-regret options. These measures have a positive ILUC mitigation potential and, in all scenarios, reduce GHG emissions compared to the baseline.

Sustainable intensification of the whole agricultural sector is required. The *high* and *high*+ scenario result in the same amount of surplus land, but the lower emissions in the *high*+ scenario mean sustainable intensification can contribute towards meeting the 60% GHG emission reduction target for biofuel. In contrast, in the *high* scenario, the emissions from fertiliser use and the rest of the cultivation phase increase such that the GHG emissions of the ILUC mitigation measures are only just below those of ILUC itself, and far above the threshold value for GHG emissions reduction compared to fossil fuel. The optimal scenario is one where the agricultural intensification leads to faster yield growth than GHG emission growth, as that situation reduces emissions compared with the baseline.

To ensure low GHG emissions of the ILUC mitigation measures, the type and carbon stocks of the surplus land need to be considered. The conversion of abandoned land and grassland to cropland can have high associated GHG emissions. When abandoned land is covered by shrubs or vegetation with larger carbon stocks, the GHG emissions of conversion to cropland can offset the gains from mitigating ILUC. The abandoned land included in the surplus land calculations was recently abandoned, which means carbon stocks in vegetation will be limited [160]. As a result of the relatively low share of this measure within the calculated surplus land, the impact on low-ILUC-risk potential is limited. The conversion of grassland to cropland also has high associated

GHG emissions and is much more important than abandoned land in terms of ILUC mitigation potential. However, the intensification of livestock production that makes these surplus lands available is expected to reduce GHG emissions and thereby offset the land use change effects and related emissions.

ILUC mitigation requires a holistic approach to the agricultural sector. ILUC is an indirect effect of the expansion of biofuel production, which ripples through the agricultural sector and affects land use far outside the location of the biofuel production. Mitigating the ILUC risk therefore also works in this interplay of agriculture, land use and bioenergy: the combination of the ILUC mitigation measures aims at improving the whole agricultural sector and reducing its land use. This is not limited to biofuel feedstock production. As the GHG emissions of the ILUC mitigation measures also occur in the rest of the agricultural sector, it is important to consider this sector as a whole. This means evaluating and monitoring the progress of ILUC mitigation should focus on the broader agricultural sector to avoid underestimation of ILUC mitigation effects. Furthermore, as this study's results are based on a post-model analysis of the MIRAGE model results, the market-mediated effects of the ILUC mitigation measures are not included. Understanding the full implications of ILUC mitigation, including its own indirect impacts, is an important topic for future research. This helps ensure ILUC mitigation strategies are effective and contribute to lowering GHG emissions.

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Appendix

Table 3.3 Overview of the scenarios for the various measures. Table 3.2 in the main text shows the corresponding data for the calculations.

	Above-baseline yield increase (crops)	Above-baseline yield increase (livestock)	Increased chain integration	Increased chain efficiencies	Land zoning and biofuel feedstock production on underutilised lands
Baseline *Reference scenario form MIRAGE [123] with growing food, feed and fibre demand, but no additional biofuels compared to 2008-2012.*	Current ratio between EU27 average yield and yield in Macroregion 2 is applied to the projections from MIRAGE for the EU27.	MIRAGE projected productivity increase for cattle and non-cattle livestock in the EU27.	No chain integration assumed.	No change to the current (2008-2012) losses.	Identified abandoned lands will not be taken into production.
Low *Progress is low and will not rise above the current rate or the absolute minimum.*	Yields in Macroregion 2 keep increasing at the average linear rate of the period 1990-2012.	Yields keep increasing at the average linear rate of the period 2004-2012.	Replacement of marginal protein source of animal feed on basis of protein content of rapeseed meal (i.e soy imported from Argentina and Brazil is replaced). No use of straw other than current practice.	Losses keep decreasing at the linear rate of the period 2000-2012.	Only abandoned lands above 50ha will be taken into production, at 50% of the average productivity.
Medium *Counties in the macroregion will learn from others and yields and production methods increase to the current best in the country or CEE.*	The average yield per crop in Macroregion 2 reaches the yield level in the current (2008-2012) best county.	The average yield in Macroregion 2 reaches the yield level in the current (2008-2012) best county.	Replacement based on current feed mix data from FAOSTAT.	Gain the same level of chain losses (per crop) as the average for Central and Eastern Europe.	Only abandoned plots over 20 ha will be taken into production, at 75% of the average yield.

High(+) *Large progress in the agricultural sector. The country will catch-up with Poland*	The share of the maximum attainable yield in Poland that is currently achieved is extrapolated to Eastern Romania.	Current productivity in Poland.	Replacement on energy basis (i.e. domestic barley, maize and wheat).	Gain the same level of chain losses (per crop) as Poland.	All abandoned lands in Macroregion 2 are taken into production at a productivity of 99% of the future average yield.

Table 3.4 Abandoned lands by county and size in Macroregion 2, based on the data from National Agricultural Census in 2010 [201]

County	0 - 2 ha	2 – 5 Ha	5-10 ha	10 - 20 ha	20 - 30 ha	30 - 50 ha	50 - 100 ha	>100 ha	Total ha
Bacau	3,435	7,061	3,877	1,124	225	224	246	8,383	24,575
Botosani	1,468	2,867	1,077	381	115	216	119	5,870	12,113
Braila	231	227	141	51	32	27	183	7,044	7,935
Buzau	1,036	1,188	426	160	77	116	49	840	3,892
Constanta	387	572	641	199	156	157	197	7,282	9,591
Galati	1,381	1,794	947	266	59	84	217	2,740	7,488
Iasi	1,572	2,162	706	215	82	95	211	4,136	9,178
Neamt	1,051	1,070	352	266	78	48	24	2,390	5,280
Suceava	590	619	195	106	55	24	19	779	2,386
Tulcea	1,070	756	271	147	51	102	53	4,641	7,092
Vaslui	1,674	5,830	3,136	602	47	52	192	4,469	16,003
Vrancea	1,229	1,912	734	187	53	101	111	2,489	6,816
Total Macroregion 2	15,123	26,057	12,503	3,706	1,030	1,246	1,621	51,062	112,348

Table 3.5 Input values for the calculations with the BioGrace tool. Yields are taken from the scenarios (see Table 3.2). For the other variables default values from BioGrace were used.

		N-fertilisers (kg ha^{-1} yr^{-1})	K_2O-fertilisers (kg ha^{-1} yr^{-1})	P_2O_5-fertilisers (kg ha^{-1} yr^{-1})	Diesel (MJ ha^{-1} yr^{-1})[h]	Field N_2O emissions (kg ha^{-1} yr^{-1})
Baseline	Maize	69[a]	44[a]	33[a]	644[b]	1.2[c]
	Wheat	58[a]	39[a]	32[a]	664[b]	3.4[c]
	Sunflower	35[a]	52[a]	18[a]	530[b]	1.6[c]
	Rapeseed	49[a]	46[a]	37[a]	530[b]	3.7[c]
	Soy	39[d]	23[d]	35[d]	375[b]	0.9[c]
Low	Maize	59[e]	33[e]	24[e]	649[f]	2.0[c]
	Wheat	52[e]	29[e]	23[e]	684[f]	1.8[c]
	Sunflower	27[e]	35[e]	12[e]	482[f]	1.3[c]
	Rapeseed	46[e]	36[e]	28[e]	575[f]	1.4[c]
	Soy	37[e]	19[e]	27[e]	414[f]	1.2[c]
Medium	Maize	100[g]	109[g]	60[g]	950[f]	1.9[c]
	Wheat	56[g]	37[g]	32[g]	603[f]	1.7[c]
	Sunflower	45[g]	111[g]	28[g]	687[f]	1.1[c]
	Rapeseed	48[g]	44[g]	37[g]	484[f]	1.4[c]
	Soy	45[g]	27[g]	42[g]	407[f]	1.2[c]
High	Maize	124[h]	78[h]	63[h]	3284[h]	2.8[c]
	Wheat	110[h]	56[h]	52[h]	3607[h]	1.8[c]
	Sunflower	120[i]	64[i]	44[i]	3438[j]	1.5[c]
	Rapeseed	170[h]	56[h]	91.0[h]	3438[h]	1.4[c]
	Soy	134[i]	29[i]	86[i]	2437[j]	1.4[c]
High+	Maize	81[k]	35[k]	20[k]	2998[l]	3.6[c]
	Wheat	44[k]	18[k]	14[k]	3293[l]	3.0[c]
	Sunflower	57[k]	28[k]	21[k]	3139[l]	3.0[c]
	Rapeseed	83[k]	36[k]	25[k]	3139[l]	4.0[c]
	Soy	57[k]	28[k]	21[k]	2225[l]	3.1[c]

[a] For maize, wheat, sunflower and rapeseed national-level nitrogen, phosphate and potassium application rates per crop in 2010 were published by Romanian government [204]. To account for difference in fertiliser application between the whole country and Macroregion 2 we multiplied this crop-specifc fertiliser use with the ratio in average fertiliser use (kg ha^{-1}) between Romania and Macroregion 2. For each type of fertiliser the average consumption per hectare in Romania was compared with the average consumption per hectare in Macroregion 2 to calculate this ratio [201]. This was 0.96 for nitrogen, 1.02 for phosphorus and 1.04 for potassium (average 2008-2012).

[b] In Romania average mechanisation intensity (expressed as number of tractors per hectare of arable land) is only 26% of the rest of the European Union [137], and Eastern Romania only 66% of the rest of Romania [201]. For each crop Baseline diesel use was calculated by multiplying these ratios with the default diesel use in BioGrace.

[c] Field N_2O emissions were calculated using the field N_2O emissions module in the BioGrace tool [232]. This module follows the IPCC guidelines [233]. Here 1% of the nitrogen is directly emitted, 30% leaches into the environment and 10% is emitted as NH3. The calculation of the field N_2O emissions depends in the tool on crop type, crop yield, nitrogen fertiliser application and straw removal. As data inputs for this we used the yields from Table 3.2 of the main text and the nitrogen fertiliser application data came from column 3 of this table. The other variables were not changed from the default value present in the tool.

[d] Average fertiliser use per hectare for soy, as calculated by Rosas [215]. Average for the period 2006-2010 as more recent data is not available.

[e] The fertiliser use per hectare in Macroregion 2 is in decline since 1990 [201]. Extrapolating this trend

gives a fertiliser intensity (kg ha^{-1}) of 84% (nitrogen), 70% (phosphorous) and 72% (potassium) in 2030 as share of the average fertiliser intensity 2008-2012. Multiplication of the ratio between the yield in the *low* and *baseline* scenarios (Table 3.2, main text) with the fertiliser use in the baseline scenario gives the fertiliser use in the low scenario with a constant nutrient use efficiency (i.e. the production per unit of fertiliser used, kg kg^{-1}). Multiplying this with the fertiliser trend gave the fertiliser use in the *low* scenario.

[f] Multiplication of the diesel use of the baseline with the ratio between the baseline yield and the yield in the *low/medium* scenario.

[g] The counties with the highest yields are Neamt (maize, sunflower) and Braila (wheat, rapeseed, soy) [201]. The fertiliser use per hectare in Neamt is 1.2 (nitrogen) 1.4 (phosphorous) and 1.85 (potassium) times higher than on average in Romania [201]. In Braila this is 0.88 (nitrogen) 0.87 (phosphorous) and 0.81 (potassium) [201]. Multiplying this again with the fertiliser use under constant nutrient use efficiency (footnote e) gave the fertiliser use in the *medium* scenario.

[h] For maize, wheat and rapeseed, data of the official Polish technology inventory was used [234].

[i] No crop-specific data were available for soy and sunflower. To calculate the fertiliser application we calculated the ratio between rapeseed fertiliser use and sunflower/soy fertiliser use in the baseline and multiplied this with the rapeseed fertiliser use in the *high* scenario.

[j] Polish agriculture is 6.5 times more diesel intensive than Romanian agriculture (in MJ ha^{-1} arable land) [137,235], the diesel use from the baseline was increased in accordance.

[k] Total crop production divided by the nutrient use efficiency ($\text{kg}_{\text{product}}\ \text{kg}_{\text{fertiliser}}^{-1}$) from the sustainable intensification pathways of Gerssen-Gondelach *et al*. [118].

[l] The diesel use in the *high+* scenario was 10% below the diesel use in the high scenario taken from Gerssen-Gondelach et al. [118].

Table 3.6 Data and assumptions in the low, medium and high scenarios for the emissions of cattle intensification for beef and milk production, based on Gerssen-Gondelach et al. [118]. Data in kg CO_2 equivalent per kg of product.

	Management system	Enteric fermentation (CH_4)	Manure management (CH_4)	Manure management (N_2O)	Feed production (direct N_2O)	Energy consumption (CO_2)
Beef						
Baseline [a]	Extensive	20.7	1.2	1.5	6.57	0
Low [b]	Extensive	18.4	1.0	1.3	6.57	0
Medium [c]	Extensive/ mixed	14.6	1.8	1.1	4.96	0
High	Mixed	14.0	3.0	1.6	5.85	0.6
High+ [e]	Mixed	12.6	2.7	1.422	5.265	0.54
Milk						
Baseline [a]	Extensive	0.8	0.15	0.05	0.14	0
Low [b]	Extensive	0.75	0.14	0.05	0.14	0
Medium [c]	Extensive/ mixed	0.695	0.18	0.05	0.145	0
High [d]	Mixed	0.43	0.048	0.128	0.29	0.03
High+	Mixed	0.387	0.0432	0.1152	0.261	0.027

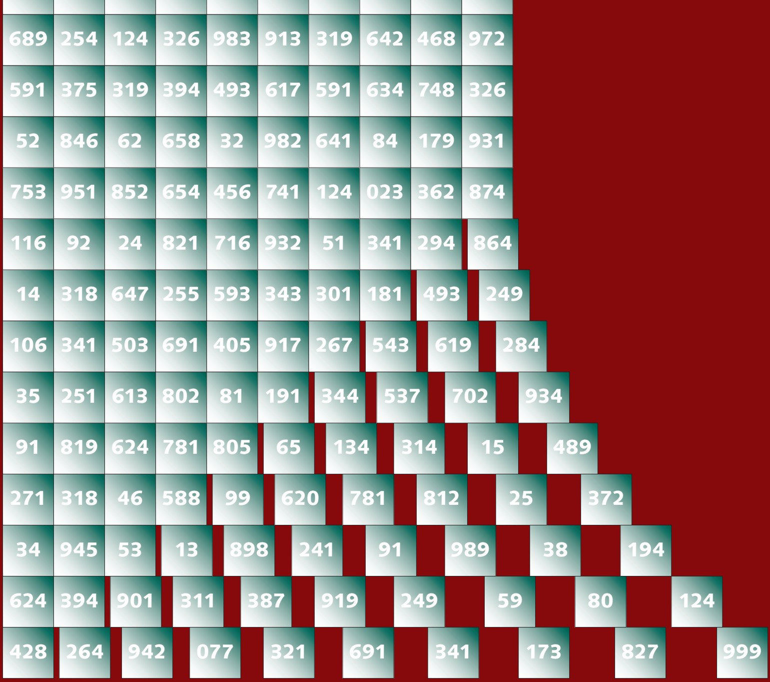
[a] Average for pasture in rest of Central and Eastern Europe (RCEU).

[b] Baseline data, but enteric fermentation, manure management and energy consumption corrected for rising productivity.

[c] Average data of pasture and mixed production systems in RCEU.

[d] Data for Poland (*low* scenario in [118])

[e] A 10% decrease from the high scenario, following the data of Gerssen-Gondelach [118].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753 951 852 654 456 741 124 023 362 874
116 92 24 821 716 932 51 341 294 864
14 318 647 255 593 343 301 181 493 249
106 341 503 691 405 917 267 543 619 284
35 251 613 802 81 191 344 537 702 934
91 819 624 781 805 65 134 314 15 489
271 318 46 588 99 620 781 812 25 372
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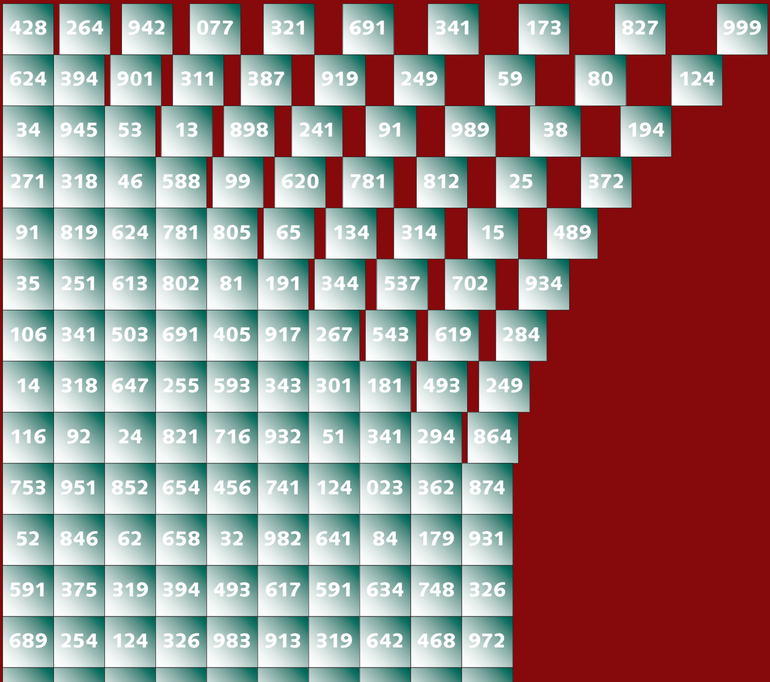
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4 Interregional assessment of socio-economic effects of sugarcane ethanol production in Brazil

Abstract

Brazil is the largest producer of sugarcane ethanol worldwide (28 billion litres in 2013) and its production is expected to increase substantially in the coming years. As the sugarcane ethanol sector contributes significantly to the national economy, an expansion of production impacts GDP, employment and trade; these impacts are not equally distributed throughout the country, nor between income classes. These differences between regions and income classes are not well understood since previous studies on socio-economic impacts used high aggregation levels. The objective of this study is to compare the distribution of socio-economic impacts of sugarcane ethanol production expansion in Brazil, including the interregional effects, across three microregions in the Centre South and different income classes. The spatial distribution of sugarcane for the supply of 54 billion litres of ethanol in 2030 was used as input for an interregional input-output model. Three scenarios for the quantity and location of sugarcane production are studied, based on measures to limit land use (i.e. second generation ethanol, higher agricultural yields). The results show that expansion of sugarcane ethanol production in Brazil in 2030 could increase the national GDP by 2.6 billion USD and employment by 53,000 fte. In general the microregional benefits of sugarcane expansion outweigh the downsides from displaced production of other crops and livestock. The microregions also benefit to varying extents from sugarcane ethanol expansion outside their borders. Additional employment is primarily generated in lower income classes. There are considerable differences in the impacts across the regions, these are related to the structure of the local economy and the scenario and not only dependent on the local potential for sugarcane expansion. Socio-economic impacts of biofuel production should thus be studied on lower aggregation levels to include these differences in benefits across regions and income classes.

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4.1 Introduction

Global energy security and climate change mitigation are important drivers for a shift towards alternative, renewable energy sources [236]. Bioenergy is currently the most important renewable energy source [180] and it is expected to play a substantial role in the diversification of the energy mix in the future [62]. A key role is reserved for biofuels that replace liquid fossil fuels in the transport sector in the short to mid-term [237]. Brazil has become one of the most prominent producers of renewable transport fuel in the world since the launch of the Pró-Álcool policy in 1975, in which the Brazilian government promoted and supported the development of the sugarcane ethanol sector [238]. Today, the country is the second largest producer and an important exporter of ethanol globally [150,239]. Production in the harvest year 2013/14 equalled just over 28 billion litres [240], and is expected to grow in the coming years [241,242].

In addition to its renewable character, the use of ethanol instead of fossil fuels is associated with environmental benefits, such as climate change mitigation and reduction in lead and sulphur emissions [243]. However, with increasing production, the sugarcane ethanol sector has come under greater scrutiny with regards to its sustainability. Despite only 1.2% of the total land surface in Brazil being occupied with sugarcane [244], concerns have been expressed about land use change and associated deforestation, risks of losing biodiversity and negative impacts on water quality and availability [58,82,112,243,245–247]. These problems could be exacerbated by the expected increases in demand for and production of ethanol.

It is not only environmental sustainability that is important for sustainable development, as socio-economic sustainability is also an important aspect [248,249]. This is also reflected in the United Nations Sustainable Development Goals (SDGs) that include goals such as poverty reduction, decent work, economic growth and improving rural livelihoods [30]. A literature review shows that biofuel feedstock production can also contribute to socio-economic development in rural regions [42,84,242,250–252]. These contributions to rural development can be made through investments in capital goods and additional demand for labour in the conversion plants and on the field. Furthermore, reduced dependency on (fossil) fuel imports, together with the export potential of biofuels, can strengthen national and regional economies [45,253]. Indirect contributions result from increased production in the sectors of the economy that supply inputs to the biofuel sector. Furthermore, increased employment can add household income and purchasing power which generates additional spending in the economy (also called induced impacts) [254]. With an increased role for biofuels in the future energy supply, positive effects are expected on the key socio-economic indicators GDP, employment and trade [246]. However, an expansion of biofuel production and the related impacts will not be evenly spread throughout the country [47]. Rather, the direction and the size of impacts in each region depend on specific dynamics and characteristics of the production region. Furthermore, employment will not be evenly distributed across all income classes and some will benefit more from sugarcane ethanol expansion than others [255,256]. Hence, it is important to understand not only the net economy-wide impacts of expanded biofuel production, but also the distribution of these impacts. This information can help to identify socio-economic opportunities and threats of biofuel expansion for different regions and income classes. This is especially relevant for Brazil where inequalities between regions and income classes in society are large [257].

The direct, indirect and induced socio-economic impacts of bioenergy production can be assessed ex-ante by input-output (IO) analysis. IO analysis has been applied in a number of studies as a tool to quantify the socio-economic impacts of biofuel production, but these studies are often performed on a national level [253,258–260]. Souza et al. used a hybrid method of IO analysis and social life cycle assessment to differentiate impacts on different stakeholders (e.g. workers, consumers, society), but focuses on the national level. Thereby, they overlook regional differences within a country, such as the heterogeneity of the structure of the economy, and they mask the (uneven) distribution of socio-economic impacts within a country. Other studies have used regional IO analysis to remedy this drawback [88,261,262]. Although these studies consider a more local level, their disadvantage is that the study area is analysed as a separate entity, not taking into account the economic connections with other regions or the country as a whole. This makes it impossible to analyse spillover effects and to compare impacts between different regions. In addition, these studies estimate only net employment effects of bioenergy production, and do not differentiate between different types of labour based on skills or remuneration, although this may vary and contribute to inequality – an effect that would counteract meeting the SDGs.

A number of inter-regional IO studies has been performed specifically for the Brazilian sugarcane ethanol sector. In these studies, different levels of aggregation can be found. Studies that are performed on a macroregional level are based on a division of the country into two to five regions [90,263–265]. Zooming in on one or more of the 26 states of Brazil, increased the level of detail. For example, Moraes et al. [266] consider São Paulo state, Herreras Matínez et al. [43] analyse the North East of Brazil, and Compeán and Polenske [267] make a comparison between the North East and South East regions. In this study, a next step is taken by adding an additional level of detail by including microregions, a sub-state administrative level in Brazil, in an IO model.

Thus, the aim of this study is to compare the distribution of socio-economic impacts of sugarcane ethanol production expansion in Brazil on a microregional level, including the interregional effects. This paper zooms in on Piracicaba, Presidente Prudente and South West Goiás, three microregions in the Centre South of Brazil and considers effects on GDP, employment and imports related to the increased sugarcane ethanol production in 2030. To capture the effects on different types of labour, the distribution of employment by income class will be analysed.

To calculate the socio-economic impacts of biofuel production expansion, we couple the outcomes of the macroeconomic MAGNET [268] model and the land use allocation model PLUC [269,270] to a new inter-regional IO model (modified from [271]). The combination of MAGNET and PLUC gives a spatially explicit distribution of sugarcane production and other land use in 2030. The region-specific characteristics of the economy are reflected in the inter-regional IO model that allows for variation between regions in the input and output of the economic sectors. These characteristics are further supplemented by region-specific cost structures of the sugarcane and ethanol industry, based on Jonker et al. [272].

4.2 Case study area

As a result of a policy-driven demand from abroad and a growing domestic market, Brazilian ethanol production is expected to expand significantly in the coming decades [241,243,273]. Within Brazil, sugarcane cultivation and ethanol production predominantly takes place in the Centre-South (CS) and to a lesser extent in the North East region (see also section 3). As the growth is expected to primarily take place in the Centre-South region of Brazil [273,274], therefore this study focuses on this region. The Centre-South is generally favoured by higher R&D investments, more advanced technologies, better soil and climate conditions and consequently a higher productivity than the North East [275].

Figure 4.1 Map of Brazil with macroregions, states and the three selected microregions, based on the administrative map of IBGE [276,277].

The effect of the sugarcane ethanol expansion is assessed for three microregions within the CS region: Piracicaba, Presidente Prudente and South West Goiás (see Figure 4.1). Microregions are legally defined administrative areas that consist of a number of municipalities, e.g. São Paulo state consists of 645 municipalities distributed over 63 microregions [277]. The choice for these microregions was made based on expected future dynamics with regard to sugarcane cultivation area. Piracicaba is the smallest of the three microregions, but is has been an important and stable producer of sugarcane in São Paulo state over the past decades [278]. However, due to its relative hilliness not all areas are suitable for mechanised harvesting as required at the latest by 2021 under the State Law [279] and Agro-Environmental Protocol [280]. Therefore, the total sugarcane cultivation area in this region is not expected to expand further. The planted area of sugarcane in Piracicaba peaked in 2010 with a total area of 1700 km^2, and decreased to 1530 km^2 in 2014 [244]. Presidente Prudente and South West Goiás are expansion areas where the area of sugarcane production rapidly increased over the past years. Presidente Prudente is considered as one of the last available regions in São Paulo state that is suitable for large scale sugarcane expansion [281]. The total cultivated area of sugarcane in this microregion increased by 545% between 2000 and 2014 [282]. South West Goiás is relatively new to sugarcane production. Between 2000 and 2014 it has witnessed an sevenfold increase in the sugarcane area, reaching nearly 2 500 km^2 [282], and a further expansion of sugarcane cultivation is expected to take place [283].

In addition to the variation in the sugarcane production and expansion potential, also the macroeconomic structure of the regions differs. For instance, in South West Goiás more than a quarter of GDP comes from agriculture, in contrast to Piracicaba where it is only 3%. These differences in the economic structure of the microregions will influence the effect of additional economic activity. Table 4.1 gives an overview of the characteristics of the microregions and their agricultural land use.

Table 4.1: General, economic, sugarcane cultivation and land use characteristics of the three selected microregions.

	Piracicaba	Presidente Prudente	South-West Goiás
General characteristics			
State	São Paulo	São Paulo	Goiás
Number of municipalities [a]	12	30	18
Total area (km^2)[b]	3700	18,000	56,000
Share of national population in 2012 (%)[c]	0.29	0.30	0.24
Economic characteristics			
GDP 2012 (billion USD)[d]	11	6.4	7.6
Share if national GDP in 2012 (%) [d]	0.37	0.28	0.32
GDP per capita 2012 (1000 USD)[e]	15	11	15
Contribution of agriculture to GVA in 2012 (%)[f]	3	8	28
Contribution of industry to GVA in 2012 (%)[f]	32	28	26
Contribution of services to GVA in 2012 (%)[f]	64	64	46
Sugarcane cultivation			
Planted area 2012 (km^2)[g]	1570	3140	1420
Average yield 2012 ($t\ ha^{-1}$)[g]	77.0	70.0	81.9
Production value sugarcane 2012 (million USD) [g]	408	646	330
Land use			
Crop land 2012 (excluding sugarcane) (km^2) [h]	80	890	19,220
Cattle 2012 (1000 heads) [j]	157	1544	2601

[a] The division of microregions in municipalities follows the administrative division by IBGE [277].
[b] 2010 Demographic Census of IBGE [284].
[c] Total population in Brazil was 194 421 853 in 2012, data from IBGE [285,286].
[d] Total GDP in 2012 in Brazil was 2.47 trillion USD (2012 prices), data from IBGE [287].
[e] Calculated by dividing the regional GDP of the year 2012 (d) by the regional population of 2012 (c)
[f] GVA = Gross Value Added (GVA + taxes on products - subsidies on products = GDP), data from IBGE [287].
[g] Sugarcane data from Produção Agrícola Municipal, IBGE [282].
[h] Crop area without sugarcane is calculated as the total planted area of temporary crops minus the planted area for the sugarcane (g), data from IBGE [282].
[j] Pesquisa Pecuária Municipal, IBGE [288].

4.3 Methods

The impacts of an increased sugarcane ethanol production in Brazil on the socio-economic indicators GDP, employment and trade were calculated using an interregional IO model (see Figure 4.2). This IO model was adapted for this study from the official IO tables from the Brazilian Institute of Geography and Statistics (IBGE) [288] and contains ten regions (section 3.1). Three scenarios and a reference scenario for comparison were applied to account for uncertainty in future sugarcane and ethanol production technologies (section 3.2). The scenarios were implemented in the IO model by changing the sugarcane and ethanol production technologies (section 3.2.1) and varying the size of the shock. The size of the shock in each scenario and each region was determined using to the macroeconomic MAGNET model and the land use model PLUC (section 3.2.2). The combination of these two models defined the agricultural production in each region, which served as an input to the IO model. In addition to the sugarcane production, the model shock also included the impact of the competition for agricultural land to accommodate the additional sugarcane production on the rest of the agriculture. A distinction was made between the direct effects (from the expansion of the sugarcane sector); the indirect effects (from those sectors delivering to the sugarcane and ethanol sectors); and the induced effects (from additional household income directly and indirectly earned from a sugarcane ethanol expansion and spent on consumer goods) [254]. The additional employment was disaggregated to twelve income classes.

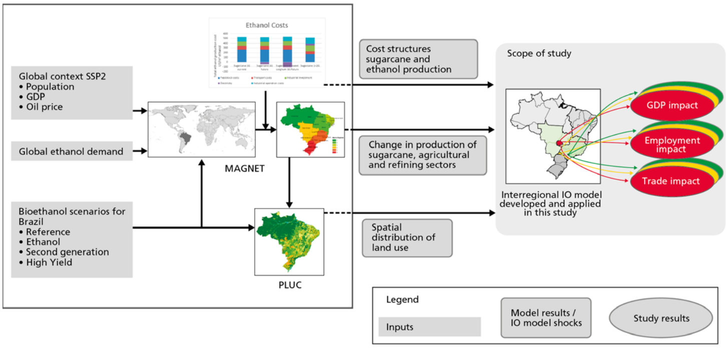

Figure 4.2 Overview of the inputs to the models and the connection between them. The left hand side of the figure shows the inputs to MAGNET [268] and the PLUC model [269]. Outputs of these models are inputs to the IO model that is depicted in the shaded area on the right-hand side of the figure. In each scenario the interregional IO model calculates the socio-economic impacts in Piracicaba, Presidente Prudente and South West Goiás.

4.3.1 Input Output model

This study used an initial inter-regional IO table for the year 2008 that was made available by the University of São Paulo (USP) [271]. In our IO model, the economies of the three microregions Piracicaba, Presidente Prudente and South West Goiás are disaggregated from the official national IO tables that are published by IBGE [289]. The method and the different data sources that are used to obtain an inter-regional IO table on state-level have been described by Guilhoto [290]. The three selected microregions were disaggregated from their respective states by estimating the monetary flows in the inter and intraregional matrices of the microregions. The estimation of these flows was based mainly on 1) statistical data on the level of microregions that are provided by IBGE: Produção Agrícola Municipal (PAM, municipal agricultural production) for the agricultural sector [282]; Pesquisa Industrial Anual (PIA, annual industry survey) for the industrial sectors [291] and Pesquisa Anual de Serviços (PAS, annual services survey) for the service sectors [292]); and 2) using cross-industry location quotients that are combined with the Relação Anual de Informações Sociais (RAIS, annual report of social information) [254].

The regional disaggregation that was used in this study distinguishes ten regions: three microregions we defined earlier (Piracicaba, Presidente Prudente and South West Goiás), the rest of their states (São Paulo and Goiás), the rest of the macroregions (South East and Centre West), and the other macroregions (South, North, and North East including Mapito). A description of the IO tables and the associated equations for the IO analysis, following the IO literature [254,265], can be found in the Appendix. The original IO table consisted of 56 sectors per region. However, for reasons of operability, the less relevant sectors with high similarities are grouped together, resulting in a total of 35 sectors in the final model (see Table 4.6 in the Appendix).

4.3.1.1 Technology differentiated sectors

An important deviation from standard IO models was the implementation of the technology differentiated sectors approach proposed by Cunha [293] and described in [265]. In classic IO models, each sector produces a single commodity and vice versa [254]. In this paper, we distinguished two variants: 1) a single commodity produced by multiple sectors (i.e. sugarcane from manual and mechanical harvesting) and 2) one sector producing multiple commodities (i.e. ethanol mills producing ethanol, sugar and electricity). This approach enabled us to include multiple inputs and outputs of the sugarcane ethanol industry.

4.3.1.2 Employment distribution

To explore the distribution of employment, different labour categories were distinguished in the IO model based on the level of income. This was done by dividing the total remuneration for each sector in every region into twelve income categories based on statistical data from the annual RAIS survey of 2008 of the Ministry of Labour and Employment [294]. The RAIS database was used to extract the number of employees and the average wages for each economic sector in each microregion specifically. The twelve income classes are expressed as the share of the minimum wage in Brazil (see Table 4.7, Appendix). Employees in the lowest income category receive up to half the minimum wage in Brazil, while those in the highest income category receive more than twenty fold the minimum wage [294].

4.3.1.3 Model runs

The IO model was shocked with varying sugarcane production values (X), expressed in monetary terms. Normally, the exogenous variable in an IO analysis defining the model shock is the final demand (Y), while the production value is determined endogenously. Here another approach was taken to account for 1) the production volume under competition for land with other agricultural sectors and 2) reduced demand for fossil fuels as a result of the expansion of ethanol production. For the latter, the shock to the sugarcane production was accompanied by a negative shock to the refining sector to account for the decrease in fossil fuel demand from an increase in ethanol production. For the former, the effect of the sugarcane ethanol expansion on the other agricultural sectors was also included as a positive or negative shock, depending on the scenario (see section 3.2.2).

The production values for sugarcane, agriculture and fossil fuels (see section 3.2.1) were determined for all ten regions. To calculate the socio-economic effects all regions were shocked simultaneously, which gave the total effects of the sugarcane ethanol expansion. Next, the regions were also shocked one by one to establish the spill-over effects from one region to the others. Shocking the regions one by one isolated the effect of sugarcane expansion on that single region without including the effect from expansion in other regions. This shows how much of the economic effect remains in the region and how much leaks away. To calculate how well a region absorbs the economic effects from outside its own borders, we shocked all regions except for the region of interest. All impacts in that microregion that has no sugarcane production are the spill-over effects from outside its own borders.

4.3.2 Scenario approach

To compare the effects of sugarcane ethanol expansion on a microregional level, it is important to isolate the effect of the increase in ethanol production. In order to do this we used a *Reference* scenario that assumed no increase in worldwide ethanol demand compared to 2012 and was used as a contrast to the production expansion in the other scenarios. The *Ethanol* scenario assumed a high increase in worldwide demand for ethanol, leading to an increase in ethanol production from 24 billion litres in 2012 to 54 billion litres in 2030 in Brazil. These two options are based on the forthcoming work of Van der Hilst et al. [270] and apply the same assumptions on socio-economic development in terms of population and economic growth, and the Brazil-specific issues such as mechanisation, yield growth, technological development etc.

As land resources are not unlimited, expansion of sugarcane can displace the production of other sectors and thereby influence the socio-economic impacts. Therefore, we also considered two additional scenarios that focus on the reduction of agricultural land demand in the case of extra ethanol demand. The *2G* scenario assumed a transition towards second-generation sugarcane ethanol production and twice as high yield growth in the sugarcane sector (1.6% per year instead of 0.8%) compared to the *Reference*. The *High Yield* scenario assumed productivity increases in the entire agricultural sector would develop twice as fast as in the other scenarios (1.4%-2.8% per year, depending on the crop). This reduces the competition for land between food, feed and fuels. In Table 4.2, an overview of the scenario parameters is provided. These parameters were assumed to be constant for the Centre South and the microregions, unless specified differently in this table.

Table 4.2 Input parameters and assumptions for the 2012 reference scenario and the four 2030 scenarios. The top presents parameters that are equal for all three microregions, the others are region specific.

	Unit	2012	Reference	Ethanol	Ethanol: 2G	Ethanol: High Yield
Ethanol production [a]	109 l yr^{-1}	24	28	54	59	55
Sugar production [b]	106 t yr^{-1}	38	67	67	70	68
Ethanol yield from cane [c]	l t^{1}	44-81	70-128	70-128	93-170	70-128
Ethanol technology [d]		1G 2012	1G 2030	1G 2030	1-2G optimised + use of trash	1G 2030
Annual sugarcane productivity increased	%		0.8	0.8	1.6	1.6
Annual livestock productivity increase (intensive/extensive)[e]	%		0.28 / 1.58	0.28 / 1.58	0.28 / 1.58	0.56 / 3.16
Livestock productivity 2030 intensive/extensive	Heads ha^{-1}		1.85 / 0.69	1.85 / 0.69	1.85 / 0.69	1.95 / 0.91
Annual productivity increase rest of agriculture [f]	%		0.7-1.4	0.7-1.4	0.7-1.4	1.4-2.8
Mechanical harvesting [g]	%	65	95	95	95	95
Net electricity production [h]	kWh t^{-1} cane	17.4	6.3	6.3	0	6.3

Microregion specific scenario assumptions and inputs						
Sugarcane area	km^2	PIR: 2100 PP: 800 SWG: 3300	PIR: 1975 PP: 775 SWG: 7450	PIR: 2125 PP: 130 SWG: 12,900	PIR: 2100 PP: 1125 SWG:1145	PIR: 1950 PP: 750 SWG:6800
Other crops	km^2	PIR: 0 PP: 450 SWG: 19,750	PIR: 0 PP: 480 SWG:19,000	PIR: 0 PP: 125 SWG:13,000	PIR: 0 PP: 477 SWG: 19,000	PIR: 0 PP: 375 SWG:14,500
Livestock area	km^2	PIR: 150 PP: 13,100 SWG:17,000	PIR: 0 PP: 13,500 SWG: 15,500	PIR: 0 PP: 13,500 SWG:15,500	PIR: 0 PP: 13,500 SWG:15,500	PIR: 0 PP: 13,000 SWG:15,400
Sugarcane yield	$t\ ha^{-1}$	PIR:77 PP: 70 SWG:82 PIR:	89 PP: 81 SWG:95 PIR:	89 PP: 81 SWG:95 PIR:	102 PP: 94 SWG:109 PIR:	102 PP: 94 SWG:109
Ethanol yield from cane	$l\ t^{-1}$	PIR /PP: 58 SWG: 73	PIR /PP: 92 SWG: 116	PIR /PP: 92 SWG: 116	PIR /PP: 123 SWG: 154	PIR /PP: 92 SWG: 116
Share sugarcane for ethanol	%	PIR /PP: 45 SWG: 73	PIR /PP: 31 SWG: 51	PIR /PP: 45 SWG: 73	PIR /PP: 47 SWG: 70	PIR /PP: 46 SWG: 74
Ethanol production	10^6 litre	PIR: 320 PP: 585 SWG: 623	PIR: 381 PP: 717 SWG: 1,781	PIR: 592 PP: 1736 SWG: 4454	PIR: 856 PP: 1578 SWG: 3699	PIR: 685 PP: 1760 SWG: 4632
Sugar production	10^3 ton	PIR: 864 PP: 329 SWG: 373	PIR: 1387 PP: 2609 SWG: 2612	PIR: 1159 PP: 3399 SWG: 2402	PIR: 2487 PP: 4586 SWG: 2801	PIR: 1386 PP: 3561 SWG: 2502

[a] Values from MAGNET model.

[b] 2012 data from UNICA for harvest season 2012/2013 [295], growth calculated from MAGNET model results.

[c] Reference 2012: for each state the sugarcane required for the ethanol production was calculated by multiplication of the sugarcane production and the share of the sugarcane that was used in 2012/2013 by the ethanol industry [296]. Dividing the ethanol production per state [295] by this number gave the ethanol yield in each region. For the macroregions in the North, where no division data were available, the national average of the equal division between sugar and ethanol was used. For the microregions, the average productivity of their state was used. Scenarios 2030: the productivity was assumed to increase similarly in each region (1.58% per year for the first generation scenarios; 2.1% per year for the second generation scenario).

[d] Terminology refers to the work of Jonker et al. [272]. For the cost structures we followed their default assumptions in which the size of a plant was 1230 t/hour for first generation and 156 for second generation. Adaptations were made to the sugarcane cultivation, where for each region the sugarcane yield was changed to the yield in this table, land prices per region were varied as a share of land prices in Sao Paulo, based on [297].

[e] We followed the assumptions that were used for MAGNET/PLUC [270].

f Following the assumptions for MAGNET/PLUC that use crop-specific yield growth percentages for the periods 2010-2020 and 2020-2030. The yield growth in the *High Yield* scenario was double the yield growth in the other scenarios.

[g] taken from the assumptions for MAGNET [270], here the mechanisation rate was assumed to increase to 95% in most regions, only in the North East this was somewhat lower.

[h] Derived from the outlook for sugarcane ethanol production of Jonker et al. [272] using the appropriate ethanol production technology for each scenario.

4.3.2.1 Implementation of technology differentiated sectors

To implement the scenarios in the model, we first adapted the IO model, to account for the changing technologies. The current and future cost structures of the sugarcane cultivation and harvesting, and of the ethanol sectors were based on the work of Jonker et al. [272]. They have estimated the development in production costs in the Brazilian ethanol sector. We used the cost structures of cultivation and manual and mechanical harvesting, including trash collection for second generation ethanol production, and the ethanol production technologies that were defined in Table 4.2. To align these cost structures with the rest of the IO model, the cost breakdowns from Jonker et al. were converted to the sectors of the IO model for each region, matching them to the 35 sectors in the ten regions of the original IO matrix. This was done by multiplying the cost structures with the technical coefficients of the original IO model.

We used region and scenario-specific parameters for the ratio between the different inputs and outputs in the two technology differentiated sectors (i.e. manual and mechanical harvesting, and ethanol, sugar and electricity production). The ratio between mechanical and manual harvesting was defined based on [270] and is presented in Table 4.2. To calculate the ratio between the outputs of the ethanol sector (ethanol, sugar and electricity), the production of each of the three products in each microregion was required. The first step was to disaggregate the ethanol and sugar production to the microregions. For 2012, the ethanol and sugar production per state were taken from UNICA [295] and disaggregated to the microregions based on their share in the sugarcane production of their state. To obtain the disaggregated ethanol production in 2030, we first calculated for each region the ratio between the share of the ethanol production in 2012 [295] and the share of the sugarcane production in 2012, this showed whether a region produces more or less ethanol than can be expected. Then the share of the sugarcane production in 2030 in each region was multiplied by the nationwide projected ethanol production in 2030 to obtain the expected ethanol production in each region. Finally, the results from the previous steps were multiplied to account for regional differences. A similar approach was used to calculate the 2030 sugar production. The electricity production per tonne sugarcane was derived from the model of Jonker et al. [272] and assumed equal for each region. The output parameters for the technology differentiated sector were then calculated as the share in the total revenue, based on basic prices (see Table 4.8, in the Appendix).

4.3.2.2 Model shock

The production value (X) with which the IO model is shocked in each scenario consists of three components: the sugarcane production, the reduction in the refining sector and the effect on the other crops and the livestock sector. The production value was calculated as the production in each sector multiplied with the basic price, to obtain the monetary value of the shock. All basic prices in this study are presented in Table 4.8.

The calculation of the sugarcane production in each region for each scenario started from the sugarcane area in 2012 per microregion from IBGE [282]. The growth until 2030 was derived from the land use allocation by the PC raster Land Use Change (PLUC) model [269]. The PLUC model used the output of the CGE model MAGNET, which calculates the worldwide macroeconomic responses to changes in the demand for ethanol considering competition for land and resources towards the future [187]. MAGNET reports the outcomes from Brazil on the level of the macroregions, the PLUC model then allocates the regional land use spatially-explicitly on a five-by-five kilometre grid cell level. Sugarcane productivity was extrapolated using the scenario assumptions by Van der Hilst et al. [270] with yield increases of 0.8-1.6% per year.

The rest of the agricultural sector consisted of two sectors in the IO model: other crops and livestock. To calculate the production value of the non-sugarcane crops for each scenario, we first calculated the crop area per region for paddy rice, wheat, coarse grains, oilseeds, fruit and vegetables, fibre crops, and 'other crops' based on the results of MAGNET and PLUC. Yield growth of these crops was expected to follow the assumptions for MAGNET of Van der Hilst *et al*. [270] (0.7-1.4% per year, 1.4-2.8% in the *High Yield* scenario).The production in livestock sector was calculated from the product of the livestock area the density. For livestock, both intensive (pasture) and extensive (rangeland) livestock areas in 2012 and 2030 were given by PLUC. Current densities, 1.76 and 0.52 heads per hectare, were assumed to be the same throughout Brazil [270]. The yield growth is presented in Table 4.2; resulting in densities of 1.85 (intensive) and 0.69 (extensive) in 2030 in the *Reference* and *Ethanol* scenarios. In the *High Yield* scenarios the livestock density increased to 1.95 (intensive) and 0.91 (extensive) in 2030.

The expansion of domestic ethanol consumption was 24 billion litres between the *Reference* scenario and the *Ethanol* scenarios in MAGNET. This additional consumption was assumed to replace an energetically equivalent amount of gasoline (i.e. 1 litre of ethanol replaces 0.66 litres of gasoline [37]). This was included as a negative shock to the refining sector.

The IO model was shocked with the production values of the sugarcane, other crops, livestock and refining sectors. These sectors are assumed to be directly affected by the expanding demand for sugarcane ethanol. For the other sectors no direct change, i.e. ceteris paribus, was assumed. This enabled us to isolate the effect of the sugarcane ethanol production expansion on the rest of the economy.

The production value of sugarcane in each scenario was applied as a shock. For the production in the rest of the agriculture and the refining sector, we applied another approach. For these sectors we calculated the shock as the revenue difference between the *Reference* and the three *Ethanol* scenarios in 2030, in order to isolate the effect of the additional ethanol production.

4.4 Results

Using the inter-regional IO model we calculated the impacts of an increase in Brazilian ethanol production from 28 billion litres in the *Reference* scenario to 54-59 billion litres on the socio-economic indicators GDP, employment and trade. The results include the effect of reduced fossil fuel production, the displacement of other agricultural land uses due to additional sugarcane ethanol production and the indirect and induced effects in the other economic sectors.

4.4.1 Overall results

The growth in sugarcane ethanol increases GDP and employment in Brazil. Table 4.3 shows the results for the three microregions and the whole country in 2012 and 2030 (full results are presented in Table 4.9 - 4.13 in the Appendix).

Table 4.3 Total contribution to GDP, employment and import of sugarcane in Brazil in the reference situation and in 2030, by region.

		Piracicaba	Presidente Prudente	Southwest Goiás	Brazil
Contribution to GDP (million USD_{2012})	2012	223	308	174	17,078
	Reference	326	464	579	24,514
	Ethanol	316	629	441	27,144
Contribution to employment (1000 full time equivalent, fte)	2012	11	20	14	988
	Reference	18	36	52	1524
	Ethanol	15	36	-19	1578
Contribution to imports (million USD_{2012})	2012	22	24	12	1886
	Reference	36	39	46	3107
	Ethanol	28	33	-23	2626

The low increase in ethanol production in the *Reference* scenario leads to a net GDP growth of 6.4 billion USD in 2030 or 0.25% of the 2012 GDP. All three selected microregions see an increase in GDP coming from sugarcane ethanol in 2030 compared to 2012. Despite a slight decrease in the sugarcane area in the microregions in São Paulo in the *Reference* scenario, the contribution to GDP increases. This is because technological progress in sugarcane conversion and increased yields lead to an increase in ethanol production in the microregion. South West Goiás is a growth region, and doubling the sugarcane area between 2012 and 2030 increases the contribution of sugarcane ethanol to the regional economy to 7% of the 2012 GDP in the *Reference* scenario.

An additional production of 26 billion litres ethanol in Brazil in 2030 in the *Ethanol* scenario compared to the *Reference* scenario increases the nationwide GDP by a further 2.5 billion USD. This includes the effect of displacement of other agricultural production and of fossil fuels, which reduces the economic benefits of sugarcane ethanol expansion. The GDP effect increases significantly in Presidente Prudente because of the additional sugarcane ethanol production. In South West Goiás the increase in sugarcane area in the *Ethanol* scenario leads to a decrease in other agricultural production. As a result the GDP growth in 2030 is 24% (138 M USD) lower in the *Ethanol* scenario than in the *Reference*. In Piracicaba no other agricultural activities are displaced as these were too small to be included in the land allocation of the PLUC model. The small decline in GDP growth between the *Reference* and *Ethanol* scenario can be attributed to a slightly increased spill-over effect. This means a larger proportion of the inputs for the sugarcane ethanol production is supplied from outside the region, so in the *Ethanol* scenario Piracicaba benefits less from the sugarcane and ethanol production in the region than in the *Reference* scenario.

The sectors that contribute most to the GDP growth of sugarcane ethanol expansion in 2030 are sugarcane, ethanol and sugar production (see also Figure 4.6). The only other important sectors in the three microregions are the transport sector and financial services. The importance of these sectors for the economy is region specific, and their contribution to GDP varies across regions.

The employment related to sugarcane ethanol production in Brazil, including the indirect and induced effects, grows from nearly 1 million in 2012 to around 1.5 million fte in 2030. In Piracicaba and Presidente Prudente, the effects on employment are comparable to those on the GDP. However, the large increase in the GDP effect in the *Ethanol* scenario in Presidente Prudente is not translated into an equivalent rise in employment. This can be explained by the labour intensity of agriculture. Ethanol and sugar production are less labour intensive per unit of GDP than the agricultural activities that are displaced. This is also well reflected in South West Goiás where employment falls (i.e. sectors outside sugarcane ethanol see a decline in employment that is not compensated by the increase from sugarcane ethanol production). The employment effect per unit of ethanol is lower in the three selected microregions than in the rest of Brazil (Table 4.4). The effect in South West Goiás is lower than in the two microregions in São Paulo as the decrease in other agricultural production is much larger in the former. The nationwide employment decrease resulting from the reduced demand for fossil fuels in 2030 is just below 7,500 fte. It is mostly concentrated in São

Paulo and the rest of the South East, where the refineries are situated. The effect in the three microregions is negligible at less than 100 fte.

Table 4.4 Net employment impacts (fte Ml^{-1} of ethanol produced) in each region. This also includes the effect on the rest of agriculture and fossil fuel production.

	Piracicaba	Presidente Prudente	South West Goiás	Brazil
2012	35	34	23	43
Reference	47	50	29	54
Ethanol	25	21	-4	29

In the *Reference* scenario, almost half of the additional nationwide employment is in the sugarcane sector. This is comparable in Piracicaba and South West Goiás; in Presidente Prudente it is 70% because a relatively large part of the supplies are from other regions and it supplies little to other regions. 75% of employment in the sugarcane sector is in income classes 2 and 3, this means most additional employment is in the lowest income classes (see Table 4.7 in the Appendix). Figure 4.3 shows the employment effect for Brazil, which is similar for the three microregions. The high share of employment in the lower income classes also means its benefits are mostly retained there. While additional benefits at this level are positive, this does not contribute to a reduction in income equality.

The *Reference* scenario includes a projected export of 2.9 billion litres of ethanol, increasing to 4.6 billion litres in the *Ethanol* scenarios. The imports to Brazil are presented in Table 4.3. The net trade balance is negative in the *Reference* scenario: -1.4 billion USD. In the *Ethanol* scenario the trade balance is slightly positive, at USD 39 million. The regional differences in the changes to imports show the same trend as the GDP effect. The negative effect of imports in South West Goiás is caused by the decrease in the other agricultural sectors that require fewer imports in 2030.

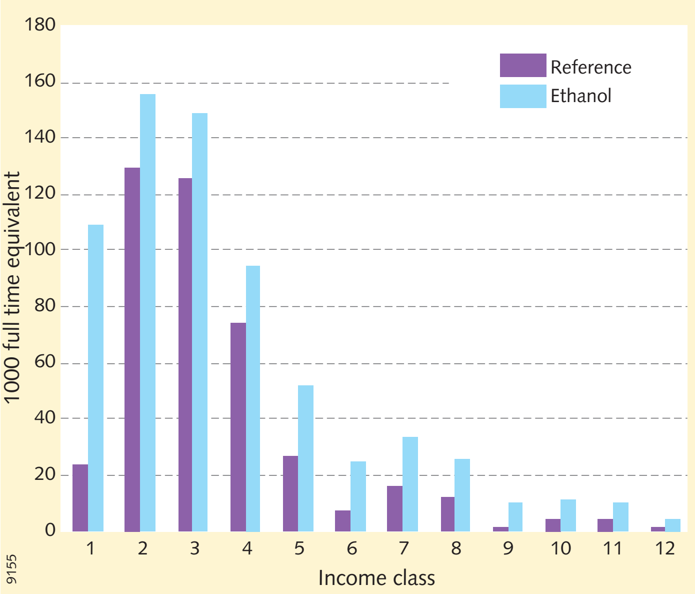

Figure 4.3 Total employment increase in 2030 compared to 2012 in each income category in Brazil for the Reference and Ethanol scenarios. The pattern is comparable for the microregions.

4.4.2 Direct, indirect and induced impacts

The majority of GDP and employment impacts in the microregions are directly related to the expansion of sugarcane and ethanol production (see Figure 4). The indirect effects, the additional economic and employment growth as a result of supply to the direct sectors, boost the GDP and employment further and are responsible for up to 25% of the impacts. The most important sectors where these indirect effects occur are commerce, transport, business services and the financial sector. These indirect effects on GDP and employment are substantially smaller than the direct effects, but the indirect employment is found in the higher income classes. In Piracicaba, the services and industry sector are much more important than in the other two regions (see Table 4.1) as a result, more indirect effects occur in this region, mainly in the commerce, transport and agricultural chemicals sectors.

Like the indirect effects, the effects induced in the rest of the economy are relatively small in the three microregions. These are mostly in services and intermediary financial services in Piracicaba and Presidente Prudente. In South West Goiás most effects are induced in commerce and transport. A disproportionally large share of the induced impacts in the selected microregions is in low earning sectors.

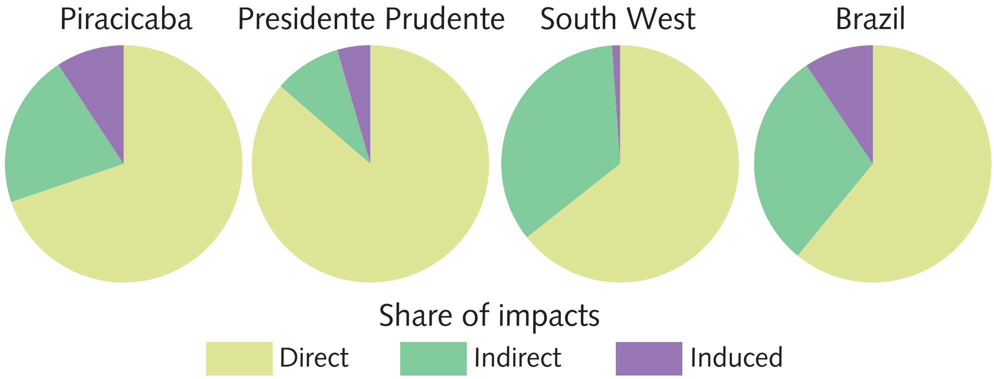

Figure 4.4 Division of the absolute direct, indirect, and induced GDP effects in the three microregions and Brazil in the 2030 Ethanol scenario. The picture is comparable for the other scenarios.

4.4.3 Spill-over

To quantify the economic interconnectedness of the regions, the spill-over effects from one region to another are assessed. Somewhat less than a third of the GDP effect in Piracicaba is the result of sugarcane production outside its own borders (Figure 4.5, right). In the *Ethanol* scenario, even without sugarcane expansion in Piracicaba itself, expansion in the rest of the country would add 98 million USD (or 1.3%) to the GDP and 4300 jobs (0.8% of total population) in the microregion. Especially the transport sector would benefit from this. The other two microregions benefit much less from the sugarcane ethanol expansion outside the region itself. This is because Presidente Prudente and South West Goiás are less traditional sugarcane regions than Piracicaba and will therefore have a less well developed industry for goods and services to supply the sugarcane and ethanol sectors.

The spill-over from the microregions to the rest of the country is similar for the three microregions. Around half of the total regional GDP effect and 60% of the employment effect of the sugarcane production in the region occurs inside the region where the sugarcane ethanol is produced, the rest spills-over to other regions (Figure 4.5, left). The largest share of the spill-over effect is to the rest of the state in which the microregion is situated. Despite being located outside São Paulo state, the amount spilled over from South West Goiás to the rest of Goiás is almost equal to the spill-over to São Paulo, where the sugarcane and ethanol industry are concentrated. The spill-over effect from Piracicaba and Presidente Prudente to South West Goiás is almost zero. In the state São Paolo mainly the transport (39%), financial services (33%) and machinery production (11%) contribute to the GDP growth.

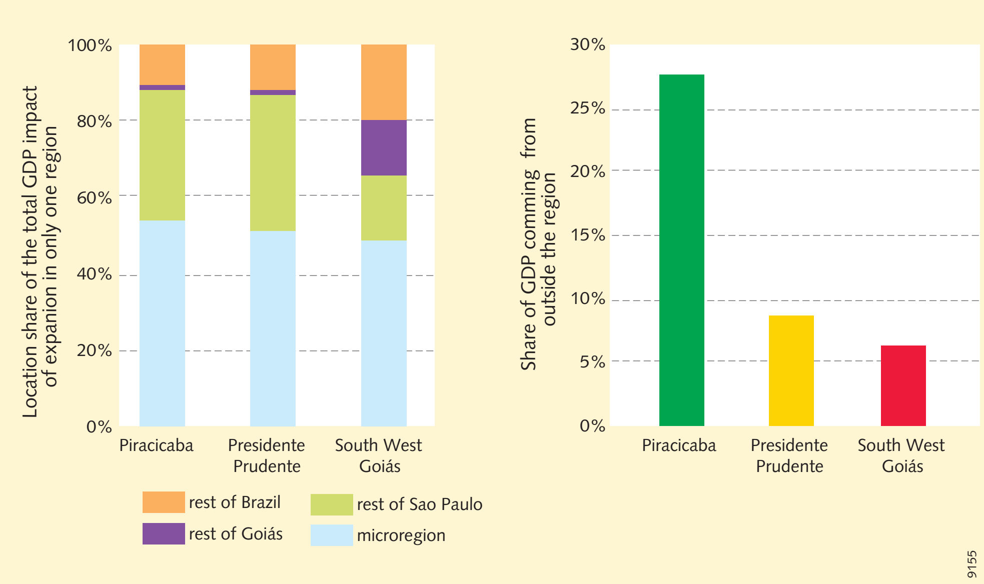

Figure 4.5 (left) Location of the total GDP impact if only that microregion would produce sugarcane (right) Share of the GPD effect (expressed as share of GDP in Table 4.3) that is spilled-over to the region from outside its borders. Results presented for the 2030 Ethanol scenario, similar patterns occur in the other scenarios.

4.4.4 Scenarios

Decreasing land use for sugarcane production in the *2G* and *High Yield* scenarios increases the GDP and employment growth compared to the *2030 Ethanol* scenario (see Table 4.5 and Figure 4.6). Higher yields in the sugarcane and ethanol production reduce the competition for land, which means the land can accommodate both an expansion in sugarcane and other agricultural products. This leads to higher employment and economic growth in Brazil.

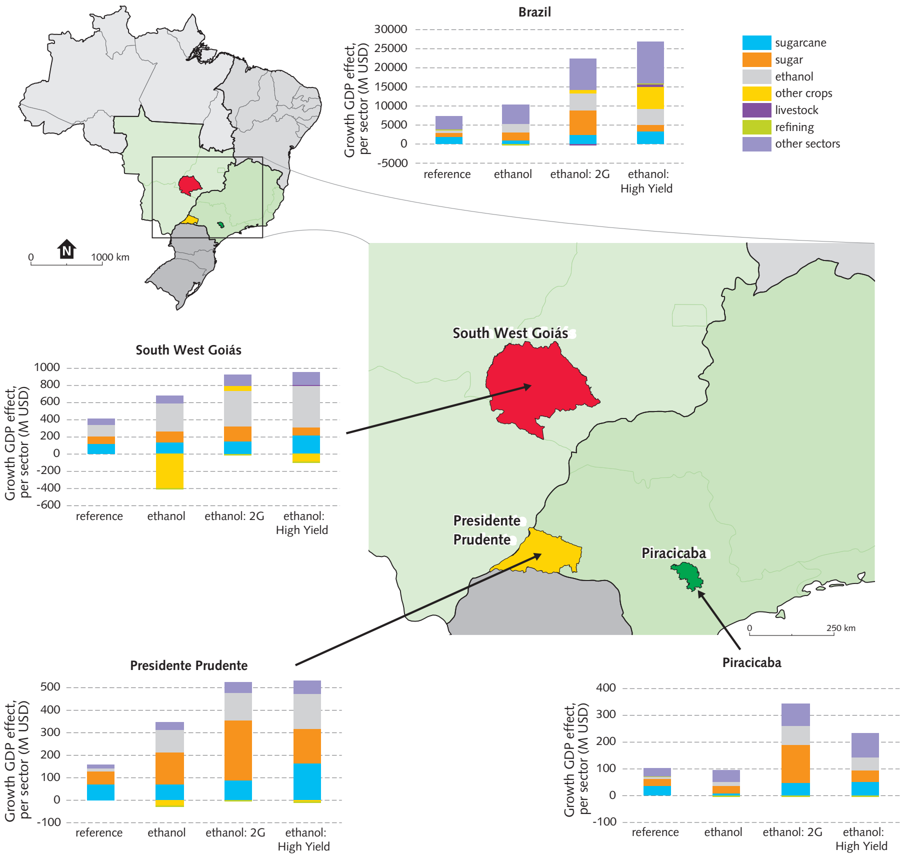

Figure 4.6 Contribution of the sectors to the GDP growth compared to 2012 in each region and each scenario in 2030.

The effects of the two scenarios differ for the three microregions. For GDP and employment, Piracicaba and South West Goiás see a larger increase in the *2G* scenario than in the *High Yields* scenario. In contrast, in Presidente Prudente and the rest of the country the impacts of the *High Yield* are larger than in the *2G* scenario. This means in the first two microregions an increase of ethanol from each ton of sugarcane is more profitable than a yield increase on agricultural land. The cause of these differences lies in the structures of the regional economies. Piracicaba has little non-sugarcane agricultural land, so increased productivity of other crops and livestock on these lands has little effect. Despite the ethanol and sugarcane industry in South West Goiás benefiting more in the *High Yield* scenario compared to the *2G*, the rest of the agriculture and the sugar sector perform well in the *2G*, making this the most profitable scenario. The allocation of the employment effect to the to the twelve income classes shows a similar picture in the 2G and High Yield scenarios as in the other two scenarios (see Figure 4.3). The majority of the employment effects remains concentrated in the lowest income classes.

Table 4.5 Results for the three Ethanol scenarios in 2030. The scenarios include an ethanol production of 55-59 billion litres and include different approaches to limit land use.

		Piracicaba	Presidente Prudente	Southwest Goiás	Brazil
GDP (million USD_{2012})	Ethanol	316	629	441	27,144
	Ethanol: 2G	563	829	1100	39,539
	Ethanol: High Yield	454	836	1031	43,993
Employment (1000 fte)	Ethanol	15	36	-19	1578
	Ethanol: 2G	32	59	81	2312
	Ethanol: High Yield	27	65	77	3695
Imports (million USD_{2012})	Ethanol	28	33	-23	2626
	Ethanol: 2G	45	46	57	3832
	Ethanol: High Yield	46	62	63	5163

4.5 Discussion

4.5.1 Comparison with literature

The previous section presented the outcomes of an IO-model that was used to calculate the socio-economic impacts in 2030 in Brazil of sugarcane ethanol production expansion. The results presented here on a microregion level cannot be compared directly with other studies as this is the first study that considers these microregions. It is however possible to compare our results to others on a higher aggregation level. This shows our results compare well to previous findings.

The ratio between the size of the shock to the sugarcane sector and the total GDP impact in Brazil is in the range of 1.4 *(Reference 2030)* to 3.0 (*2G*). Watanabe *et al.* (2014) [298] using an IO model for 2009 found an economy-wide impact in Brazil of USD 1.6 - 2.2 for each dollar increase in ethanol demand, considering various technological set-ups (first generation, optimised first generation and mix of first and second generation). The range we calculated is larger as we also included a shock to the rest of the agriculture and the refining sector, that were not included by the previous study.

Estimates on the employment in the sugarcane ethanol industry in Brazil in 2012 vary around 1 - 1.1 million [242,250,299]. This estimate is similar to our estimate of 0.99 million. Moraes (2013) [300] presented a separate estimate for the sugarcane sector of 365 thousand jobs in 2011, based on RAIS data. This is comparable to our 2012 result of 385 thousand.

Compared to other sources of bioenergy, the employment effect of sugarcane production for ethanol is quite high, in 2012 in Brazil we found 2000 fte PJ^{-1}, of which 1500 were included in the direct effects. This is outside the range of 80 to 800 jobs PJ^{-1} that Wicke et al. found in studies of other energy crops [253]. However, our high value is slightly distorted as it is for a multi-output system with the outputs sugar and ethanol. Deducting the employment for sugar production and the share of the sugarcane that is not for the ethanol production reduces the estimate to 825 fte PJ^{-1}. The estimate of 1500 fte PJ^{-1} is comparable to the analysis of Herreras *et al.* [43] for sugarcane ethanol in the North East of Brazil. Their results show an employment intensity of ethanol production of 1350 fte PJ^{-1} in 2010.

The results for the microregions showed a positive impact of sugarcane ethanol expansion on GDP growth and employment in Piracicaba, Presidente Prudente and South West Goiás. This corresponds with the finding of Walter *et al.* [246] who showed that, on average, municipalities in São Paolo State with sugarcane production score higher on the human development index (HDI) than those without sugarcane production. Furthermore, Machado Gerber *et al.* [301] performed a statistical analysis of the socio-economic development of the same three microregions between 1970 and 2010. This analysis showed that sugarcane production correlates positively with socio-economic development.

4.5.2 Input Output model

This research used a mixed-technology inter-regional input-output model to quantify the socio-economic impacts and their regional distribution, differentiated across income classes of biofuel expansion in Brazil in 2030. The use of an IO model has some inherent limitations [43,253,302]. These drawbacks include linearity of the model (i.e. the model works with fixed ratios; no economies of scale are considered), fixed prices and no competition for production factors. An IO model is a static model, and the linkages between economic sectors and regions are assumed to remain constant between 2008 and 2030, following the Ceteris Paribus principle. In reality, no changes in the economic sectors are unlikely, but it is inherent to the use of IO models. The advantage of not including structural economic changes is that the effects of sugarcane ethanol expansion can be isolated. To slightly remedy the effects of the rigid structure of the IO model, the technical coefficients of the sugarcane and ethanol sectors were variated between the scenarios, based on the work by Jonker *et al.* [272] to reflect technological progress and learning in these two important sectors.

As we use a mixed-technology IO model we can distinguish between manual and mechanical harvesting. However, there is only one labour category in the cost structures in the IO-model and the division to the 12 income classes is a post-analysis, following a fixed sector-specific ratio. Consequently, the agricultural employment in 2030 is still divided proportionally to the same labour categories as in 2012. This does not capture a redistribution of the income classes that is likely to occur with a switch to mechanical harvesting. Although a switch from manual to mechanical harvesting has a negative effect on employment, those employed need to be better skilled which affects the wage level [242]. Regional variation in wage level could also mean similar employment would be in different income classes in different regions; this is not included in the model. However, despite this, the pattern that most employment will be in the lowest income classes is still valid.

Although the IO model can capture the impacts on indicators that can be quantified, some not-quantifiable indicators are also important for the socio-economic situation. An example of these are the working conditions in manual harvesting that are currently very poor. It can be expected that banning sugarcane burning and technological development will improve working conditions and decrease accidents [242,250,303]. Currently many harvesters have almost no education [303], and as we see a decrease in the lowest income class in the *Reference* scenario, it remains to be seen to what extent these people can benefit from the additional employment in higher income classes as operating more advanced technologies requires better educated employees [304]. New initiatives such as the Renovação Project retrain sugarcane harvesters to other occupations in order to limit the negative employment impacts of the transition to mechanical harvesting [305].

The model does not include the effects of population growth and migration. As the supply of manual labour in São Paulo state is too small during the harvest season, it is common for people living in poorer areas, such as the North East, to move to São Paulo state to work as day labourer in the sugarcane sector [43]. This migration can put pressure on the local communities [246], which is not reflected in economic models.

4.5.3 Input data

The input output table that we used as a basis for our model was a disaggregated version of the Brazilian IO table in which we implemented new technical coefficients for the sectors related to sugarcane ethanol. These steps add detail to the analysis at a cost of increased uncertainty. The IO tables are based on data from 2008 as more recent data were not available. The cost structures of the sugarcane and ethanol sectors that were taken from the work of Jonker *et al.* [272] assume an average mill for sugarcane processing, whereas in reality there will be multiple types in operation. Furthermore, the assumed electricity output of the mills in 2030 in this study is relatively low compared to other studies (e.g. [306,307]). Higher electricity revenues would increase the total GDP and employment effects of the ethanol production expansion, but the effect here is negligible.

The final results are very sensitive to the sugarcane production in each region in the initial year. We used the area and production data from IBGE and calculated the growth in sugarcane area for each region from PLUC data for that region, starting in 2012. Although on macroregional level, the difference between PLUC and IBGE is small, on microregional level these changes are significant. Especially in Presidente Prudente the difference is large (800 km^2 in PLUC and 3 140 km^2 according to IBGE). This has a major impact on the final results as the impact of sugarcane in that microregion in the *Ethanol* scenario decreases by 72%. Despite the effect on the absolute economic contribution of sugarcane expansion, the relative economic growth in the *Ethanol* scenario compared to the *Reference* remains unchanged. However, the large differences between the official IBGE data and PLUC that based the baseline on satellite data emphasise the need for more reliable spatially explicit data on current sugarcane production in Brazil.

A majority of the effects of sugarcane ethanol expansion in Brazil are direct effects, this means the assumed location of the sugarcane expansion is important. The MAGNET model distributed the sugarcane area over the macroregions; the PLUC model in turn was used to calculate the spatial explicit distribution over the microregions. However, the MAGNET-PLUC framework only provides the regional distribution of the sugarcane production. It does not provide information on the ratio of sugar and ethanol production in a region, which is required for the IO model. This meant assumptions had to be made for this ratio. However, the impact of these assumptions on total GDP and employment are negligible, only the distribution between the sectors and income classes are affected.

4.6 Conclusions

The aim of this study was to analyse the distribution of socio-economic impacts of sugarcane ethanol production expansion in Brazil including the interregional effects on a microregional level. For this, we used an inter-regional mixed-technology input-output model and separated the employment effect for twelve income classes. We used a *reference* scenario with a small increase in sugarcane ethanol production in 2030 and three scenarios with a high increase (*Ethanol*) of which two additionally include the implementation of measures to reduce the competition for land (*2G* and *High Yield*).

The increase in 2030 sugarcane ethanol production from 28 billion in the *Reference* scenario to 54 billion litres in the *Ethanol* scenario results in a nationwide growth in GDP (2.6 billion USD) and employment (53,000 fte), despite a reduction in fossil fuel demand and displacement of livestock and other crop production. The three microregions show a more mixed picture: Piracicaba sees a small decrease in GDP and employment, whereas Presidente Prudente sees a large GDP increase, but no employment increase and both indicators decrease in South West Goiás. The effect of *2G* or *High Yield* is much more uniform across the microregions and impacts as it increases the GDP, employment and imports.

The mixed picture in the microregions is not only caused by the difference in potential to expand sugarcane production, but also by the structure of the economy. The sugarcane production in Piracicaba is well developed and has little room for expansion, but the microregion benefits most from expansions outside its own borders. Presidente Prudente and South West Goiás are projected to significantly expand sugarcane production, but as a result of displacement of other agricultural activities, the GDP and employment effects are negative in South West Goiás, and in Presidente Prudente only the contribution to GDP is positive. Despite a nationwide GDP and employment increase with increasing ethanol production these benefits are not uniform throughout the country.

The employment effects are not only unequally distributed geographically, but also unequally distributed over the various income classes, as over 60% of employment impacts from sugarcane ethanol production is found in the income classes lower than twice the minimum wage. This unequal distribution is similar for the three regions.

The socio-economic impacts of an expansion in sugarcane ethanol production that we presented here can be affected by policy measures. For example, the analysis of direct, indirect and induced impacts shows that GDP effects from sugarcane ethanol expansion in Presidente Prudente and South West Goiás are primarily direct. Indirect and induced impacts are very small. Similarly, the analysis of the spill-over effects shows that nearly 50% of the effects occur outside the region where the expansion occurs. Thus, regional policies to stimulate the economic sectors that deliver to the sugarcane and ethanol sectors (such as for machinery production) could help reap more of these benefits in the region.

The impacts and the ability to benefit socio-economically from the sugarcane ethanol expansion depend on characteristics of the economy of the region itself. This means that an assessment of the location of sugarcane expansion is not only important for sustainability from an environmental perspective, but also from a socio-economic perspective. These two types of distribution (spatial and over the income classes) are both important issues for sustainable development. Future research could point out the (policy) drivers in each region that caused the differences in the economic structure of the regions. This understanding can help steer sugarcane ethanol production towards more positive socio-economic effects. This can be important for industry and policymakers on national and subnational levels who want to increase the benefits of sugarcane ethanol expansion. The combination and trade-offs between environmental and socio-economic impacts can also be important for sustainability certification, where both pillars of sustainability are considered. The regional differences also mean that country level analyses of the socio-economic impacts of sugarcane ethanol expansion are not sufficient as microregional level analysis provides insights that remain hidden otherwise.

Acknowledgements

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Appendix

IO matrix

The interregional IO table (matrix Z) is built up from the inter- and intra-regional tables ($Z^{n,n}$) of these ten regions, and can be expressed as:

$$Z = \begin{bmatrix} Z^{1,1} & \cdots & Z^{1,10} \\ \vdots & \ddots & \vdots \\ Z^{10,1} & \cdots & Z^{10,10} \end{bmatrix}$$

Matrix $Z^{1,1}$ represents the intraregional flow of goods and services in region ‘1’. The interregional trade flows are accounted for by elements in the off-diagonal matrices. For example, the elements in the matrix $Z^{1,10}$ denotes a trade flow of goods and services originating in regio n 1 towards region 10 [254].

Dividing the monetary flows in each sector of each region (z_{ij}) by the total output (x_j) of that sector gave us the technology matrix (A). The elements (a_{ij}) then represent the technical coefficients. Estimations of the monetary flows are unique for every sector of each region in the model, and result in an estimation of region-specific intraregional and interregional technology matrices in which the regional differences in the economic structures are reflected.

The elements of the corresponding technology matrices are calculated as follows:

Intraregional: $a_{i,j}^{1,1} = \frac{z_{ij}^{1,1}}{x_j^1}$ where $A^{1,1} = \begin{bmatrix} a_{1,1}^{1,1} & a_{1,2}^{1,1} & \cdots & a_{1,n}^{1,1} \\ a_{1,1}^{1,1} & a_{2,2}^{1,1} & \cdots & a_{2,n}^{1,1} \\ \cdots & \cdots & \ddots & \vdots \\ a_{n,1}^{1,1} & a_{n,2}^{1,1} & \cdots & a_{n,n}^{1,1} \end{bmatrix}$

Interregional: $a_{i,j}^{1,10} = \frac{z_{i,j}^{1,10}}{x_j^{10}}$ where $A^{1,10} = \begin{bmatrix} a_{1,1}^{1,10} & a_{1,2}^{1,10} & \cdots & a_{1,n}^{1,10} \\ a_{1,1}^{1,10} & a_{2,2}^{1,10} & \cdots & a_{2,n}^{1,10} \\ \cdots & \cdots & \ddots & \vdots \\ a_{n,1}^{1,10} & a_{n,2}^{1,10} & \cdots & a_{n,n}^{1,10} \end{bmatrix}$

Following the basic equation of IO analysis (I – A) ▾ X = Y, where 'I' is the identity matrix, 'A' is the technical coefficients matrix, 'X' output and 'Y' the final demand, the inter-regional Leontief system for the IO model is [254]:

$$\left\{\left(\begin{bmatrix} \mathrm{I} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \mathrm{I} \end{bmatrix}\right| \left|\begin{bmatrix} A^{1,10} & \cdots & A^{1,10} \\ \vdots & \ddots & \vdots \\ A^{10,1} & \cdots & A^{10,10} \end{bmatrix}\right)\right\} \begin{bmatrix} x^1 \\ \cdots \\ x^{10} \end{bmatrix} = \begin{bmatrix} Y^1 \\ \cdots \\ Y^{10} \end{bmatrix}$$

The original IO model consisted of 56 sectors per region. However, for reasons of operability, the less relevant sectors with high similarities are grouped together, resulting in a total of 35 sectors in the final model (see Table 4.6).

The GDP, labour and import effects were determined by multiplying the total output per sector per region (X) by their respective coefficients (A). These coefficients were determined by dividing the total sectoral GDP, labour and imports (taken from the interregional IO matrix) by their respective output values [254]. The sectoral GDP accounts for the sum of the total net indirect taxes on domestic and imported intermediate consumption, labour remuneration, capital remuneration and direct taxes over this sector. To calculate the effect on the trade balance, the imports per scenario were deducted from the ethanol exports, which was determined in the MAGNET model (see section 3.2.2).

Table 4.6 Overview of the 35 sectors represented in the IO model.

	Sector	Translation
1	Agricultura, silvicultura, exploração florestal	Agriculture and forestry
2	Pecuária e pesca	Livestock and fishing
3	Petróleo e gás natural	Oil and natural gas extraction
4	Mineração	Mining and quarrying
5	Alimentos e Bebidas	Food and beverage products
6	Têxteis, vestuário e calçados	Textiles, clothing and footwear products
7	Produtos de madeira - exclusive móveis	Wood products, excluding furniture
8	Celulose e produtos de papel	Pulp and paper products
9	Jornais, revistas, discos, móveis e indústrias diversas	Newspapers, magazines, records, furniture and other industries
10	Refino de petróleo e coque	Coke and refined petroleum products
11	Produtos químicos	Chemicals
12	Outros químicos	Other chemicals
13	Defensivos agrícolas	Pesticides
14	Artigos de borracha e plástico	Rubber and plastics
15	Produtos minerais não metálicos	Non-metallic products
16	Aço e metalurgia	Iron, steel and metallurgy
17	Máquinas e equipamentos, inclusive manutenção e reparos	Machinery and equipment, including maintenance
18	Produtos eletroeletrônicos	Electrical and electronic products
19	Automóveis, camionetas e utilitários	Light vehicles
20	Peças e acessórios para veículos automotores	Car parts
21	Caminhões, ônibus e equipamentos de transporte	Trucks, busses and other vehicles and parts
22	Produção e distribuição de eletricidade, gás, água, esgoto e limpeza urbana	Electricity, gas and water supply
23	Construção civil	Construction
24	Comércio	Wholesale and retail trade
25	Transporte, armazenagem e correio	Transport and post
26	Serviços de informação, alojamento e alimentação, serviços prestados às empresas	Telecommunication, accommodation and food services, business services
27	Intermediação financeira, seguros e previdência complementar e serviços relacionados, atividades imobiliárias e aluguéis	Finance and insurance, real estate activities
28	Serviços de manutenção e reparação	Maintenance and repair
29	Educação mercantil e saúde mercantil	Private education and health services
30	Serviços prestados às famílias e associativas; serviços domésticos	Private households with employed persons
31	Educação pública, saúde pública e administração pública e seguridade social	Public health, education, public administration and social security
32	Cana total	Total sugarcane
33	Etanol total	Total ethanol
34	Açúcar total	Total sugar
35	Eletricidade total	Total electricity

Income classes

Table 4.7 lists the income classes that were used in this research. The classes were based on the level of income, as a share of the of minimum wage. For example, the first class receives up to half of the minimum wage, whilst class 12 receives more than 20 times the minimum salary per month

Table 4.7
The twelve income classes in Brazil, expressed as share of the minimum wage. Source: RAIS [294].

Income class	Wages as share of the minimum wage
1	< 0.50
2	0.51 - 1.00
3	1.01 - 1.50
4	1.51 - 2.00
5	2.01 - 3.00
6	3.01 - 4.00
7	4.01 - 5.00
8	5.01 - 7.00
9	7.01 - 10.00
10	10.01 - 15.00
11	15.01 - 20.00
12	> 20.00

Basic Prices

Table 4.8 Basic prices of the commodities used in this research.

Commodity	Basic price (USD_{2012})	
Ethanol (l)	0.58	
Sugar (ton)	442	
Sugarcane (ton)	16.2	The basic price of sugarcane was calculated using the national IO tables and agricultural production [282] of IBGE for 2008.
Electricity (kWh)	59.2	
Petrol (l)	0.61	The basic price was calculated from the output of the refining sector in 2008 from IBGE [282] and the consumption of national energy balance [308].
Paddy rice (t)	383	The basic price for each crop was calculated using IBGE data [282] for the production in physical and monetary terms in 2008. To align the crop categories from MAGNET with the IBGE data, we assumed maize (IBGE) to represent *coarse grains* (MAGNET); soy to represent oilseeds; *highland cotton* to represent *fibre crops; citrus fruits* to represent *fruits and vegetables* and for *other crops* we assumed a production weighted average of the other categories.
Wheat (t)	322	
Grains (t)	223	
Oilseeds (t)	393	
Horticultural products (t)	177	
Fibre crops (t)	651	
Other crops (t)	306	
Livestock (unit)	155	The production of cattle in monetary terms in Brazil was the sum of the sectors cattle and cow milk from the IBGE IO tables [288]. This was divided by the number of cattle in 2008 (IBGE) to get the basic price per unit of cattle. By combining this basic price with the yield and the livestock area, we calculated the production value of the livestock sector.

Table 4.9 Overview of socio-economic effects in Brazil in 2012.

		Piracicaba	Presidente Prudente	Rest of São Paulo	Rest of South East	South west Goiás	Rest of Goiás	Rest of Centre West	South	North	North East + Mapito	Total
Direct	GDP (M USD2012)	162	272	5,530	1,333	151	664	770	855	77	911	10,727
	Imports (M USD2012)	14	22	448	96	11	44	66	82	11	80	874
	Labour (fte)	8,157	18,066	265,107	70,441	12,643	52,810	76,046	57,449	11,275	151,345	723,340
Indirect	GDP (M USD2012)	52	24	3,100	1,315	15	176	220	553	86	611	6,151
	Imports (M USD2012)	9	2	839	186	1	21	24	155	19	130	1,386
	Labour (fte)	2,144	1,448	106,028	37,628	1,022	10,212	12,167	22,165	5,527	40,575	238,917
Induced	GDP (M USD2012)	8	12	618	-272	8	67	-54	-42	10	-155	200
	Imports (M USD2012)	-2	1	-215	-57	0	-3	-8	-41	2	-49	-373
	Labour (fte)	755	469	40,240	-7,075	620	4,613	-3,373	-742	744	-10,856	25,395

Table 4.10 Overview of socio-economic effects in Brazil in 2030 the Reference scenario.

		Piracicaba	Presidente Prudente	Rest of São Paulo	Rest of South East	South west Goiás	Rest of Goiás	Rest of Centre West	South	North	North East + Mapito	Total
Direct	GDP 234 (M USD2012)	409	8,105	1,133	519	1,228	1,756	519	74	863	14,840	
	Imports (M USD2012)	23	36	710	95	42	98	166	59	12	86	1,327
	Labour (fte)	13,332	32,301	437,075	64,554	46,559	105,997	199,613	31,276	9,174	166,514	1,106,394
Indirect	GDP (M USD2012)	62	30	3,662	1,441	33	298	368	529	101	603	7,125
	Imports (M USD2012)	11	2	1,011	203	3	38	39	157	23	132	1,620
	Labour (fte)	2,672	2,055	129,539	38,654	2,627	17,982	22,682	20,864	6,145	40,218	283,437
Induced	GDP (M USD2012)	31	25	1,914	124	28	209	12	127	37	42	2,549
	Imports (M USD2012)	2	2	119	7	1	9	0	12	8	0	160
	Labour (fte)	1,890	1,316	94,851	5,976	2,316	13,939	676	6,729	2,639	4,259	134,591

Table 4.11 Overview of socio-economic effects in Brazil in 2030 in the 2030 Ethanol scenario.

		Piracicaba	Presidente Prudente	Rest of São Paulo	Rest of South East	South west Goiás	Rest of Goiás	Rest of Centre West	South	North	North East + Mapito	Total
Direct	GDP (M USD2012)	227	593	9,023	1,075	806	1,438	2,742	861	442	1,437	18,645
	Imports (M USD2012)	18	42	626	71	49	87	226	96	41	106	1,362
	Labour (fte)	10,293	35,038	391,845	53,689	60,794	104,452	255,991	58,281	79,695	292,344	1,342,421

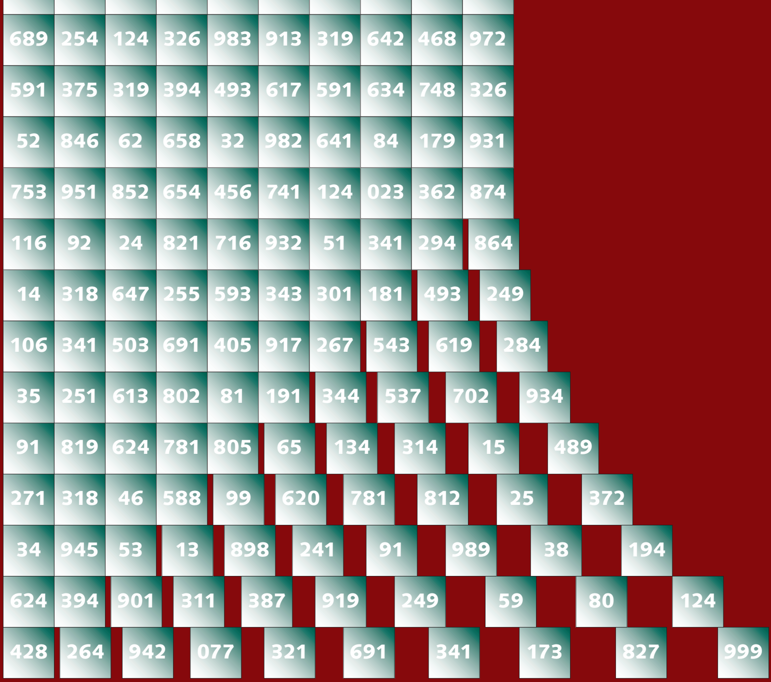
Indirect	GDP (M USD2012)	67	9	3,854	1,317	-374	88	391	650	111	684	6,798
	Imports (M USD2012)	10	-10	989	203	-71	-11	18	187	27	154	1,497
	Labour (fte)	2,742	-505	93,690	29,652	-79,875	-21,667	17,339	23,446	5,622	34,893	105,337
Induced	GDP (M USD2012)	21	27	1,447	-24	9	161	-73	111	68	-44	1,701
	Imports (M USD2012)	-1	2	-157	-28	0	6	-11	-16	9	-37	-234
	Labour (fte)	1,554	1,164	81,787	953	362	10,626	-2,323	12,740	9,502	13,489	129,855

Table 4.12 Overview of socio-economic effects in Brazil in 2030 in the Ethanol: 2G scenario.

		Piracicaba	Presidente Prudente	Rest of São Paulo	Rest of South East	South west Goiás	Rest of Goiás	Rest of Centre West	South	North	North East + Mapito	Total
Direct	GDP (M USD2012)	446	759	14,621	2,113	1,000	2,288	3,097	941	155	1,684	27,103
	Imports (M USD2012)	32	44	877	118	55	115	211	99	24	104	1,679
	Labour (fte)	26,152	55,463	826,044	128,582	71,022	146,975	268,171	48,470	14,698	213,827	1,799,403
Indirect	GDP (M USD2012)	74	34	4,418	1,881	51	339	383	667	46	683	8,576
	Imports (M USD2012)	10	-1	1,210	246	0	20	17	187	26	145	1,859
	Labour (fte)	3,299	2,224	163,353	52,006	4,990	18,377	23,683	22,886	-11,463	29,265	308,619
Induced	GDP (M USD2012)	44	35	2,719	305	49	313	54	195	58	87	3,859
	Imports (M USD2012)	3	2	198	25	3	13	4	26	13	7	294
	Labour (fte)	2,671	1,804	134,816	13,310	4,718	20,992	4,433	9,976	3,900	6,900	203,520

Table 4.13 Overview of socio-economic effects in Brazil in 2030 in the Ethanol: High Yield scenario.

		Piracicaba	Presidente Prudente	Rest of São Paulo	Rest of South East	South west Goiás	Rest of Goiás	Rest of Centre West	South	North	North East + Mapito	Total
Direct	GDP (M USD2012)	321	752	12,095	3,159	1,029	1,891	3,894	2,932	120	3,724	29,917
	Imports (M USD2012)	30	61	1,022	228	77	141	394	396	20	283	2,653
	Labour (fte)	20,402	59,674	701,214	246,814	87,567	154,245	443,800	340,338	14,104	1,130,026	3,198,183
Indirect	GDP (M USD2012)	84	40	5,083	2,105	-52	-451	530	984	46	611	6,151
	Imports (M USD2012)	13	-1	1,343	286	-17	-115	37	259	28	130	1,386
	Labour (fte)	3,704	2,741	170,274	58,075	-15,178	-139,573	32,510	43,009	-11,667	40,575	238,917
Induced	GDP 48 (M USD2012)	44	3,098	458	53	332	83	339	67	194	200	
	Imports (M USD2012)	4	3	276	52	3	38	9	55	15	23	-373
	Labour (fte)	2,957	2,388	151,953	21,298	4,571	21,089	8,055	26,336	4,784	36,277	25,395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116 92 24 821 716 932 51 341 294 864
14 318 647 255 593 343 301 181 493 249
106 341 503 691 405 917 267 543 619 284
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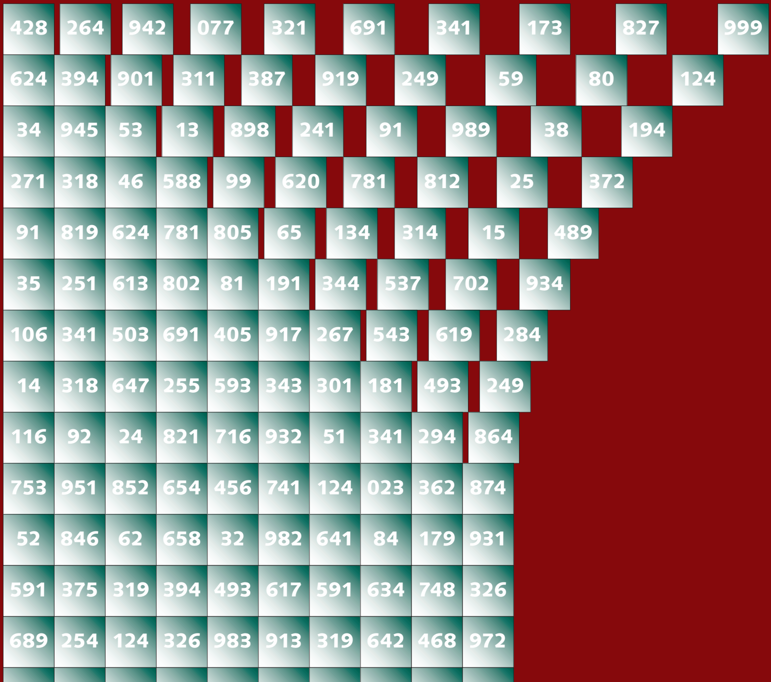
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5 Distribution of food security impacts of biofuels, a case study of Ghana

Abstract

In this chapter a novel method is used to determine the food security impacts of bioenergy for different households in a country. Previous studies assessed food security impacts for one or two dimensions and on national or higher aggregation level, thereby neglecting the complexity of food security and variation between different groups within a country. In this study, a computable general equilibrium model with a household and nutrition module is used to quantify the food security impacts of a 10% biodiesel and 15% ethanol mandate for rural and urban households in Ghana in 2030. The impacts are assessed for 13 indicators that cover all four pillars of food security: availability, access, utilisation of food and stability in the other three pillars. The results show largest effects are negative impacts on food prices and import dependency. However, the projected food security impacts of the biofuel mandate are relatively small compared to the projected effect of economic development in Ghana in the coming years. Our approach enables ex-ante quantification of the effects of biofuel on the four pillars of food security and the differentiation of the effects between urban and rural households. However, access and availability are best included in the model. To better ex-ante quantify the impacts for utilisation and stability at household level more research is needed. In addition, further disaggregation to households in e.g. different geographical regions or different income groups, is required to assess the variability of impacts across different groups in society. Furthermore, an integrated approach including all sustainability aspects would be required to assess potential trade-offs and support informed decision aiming on sustainable bioenergy production in developing countries. However, this methodical approach means a big step forward compared to the state of the art knowledge on food security impacts of bioenergy production and could contribute to identify options to minimise negative effects and optimise positive effects food security impacts.

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5.1 Introduction

Biofuels are an attractive alternative for liquid transport fuel, because of the renewable nature of the feedstocks and the potential favourable GHG emission balance compared to fossil fuels [57,309]. The combination of these benefits, with a large untapped feedstock potential [133,310,311], potential socio-economic benefits of rural development, increased energy access, reduced fossil fuel imports [84,312,313] and the possibility to benefit financially via the Clean Development Mechanism of the Kyoto Protocol [314] sparked interest in biofuel production in many developing countries [314–321]. However, in public, policy, and academic debates major question marks have been raised on the food security effects of biofuel production, particularly in developing countries. According to the definition of food security from the United Nations Food and Agriculture Organisation (FAO) food security consists of four pillars: *availability*, *access*, *utilisation*, and *stability* in the other three pillars. The definition considers people food secure when they have year-round access to sufficient and nutritious food [322,323]. Concerns on food security issues resulting from an increased biofuel demand are raised, because competition for land, water, labour and other resources could have a negative impact on production and prices of food products [85,319,324–327].

The rise in global food prices in the period 2007-2008 ignited the discussion on the food and fuel nexus [317,328]. An increased demand for bioenergy feedstock is thought to have contributed significantly to the price spike in global food markets [53,329,330]. Such an increase in global food prices negatively impacts *access* to food, especially in food importing countries and low income households [85,331–335]. However, the direct causation between increased bioenergy production and food prices is hotly debated as many interlinked factors (e.g. weather, energy prices) determine food prices on a global level [95,328,336–347]. Also on a local level, competition for land and resources can be connected to a reduction in food security [348]. Where farmers opted to produce more cash crops, such as bioenergy feedstock, *availability* and *access* to food has decreased [51,326,349]. Furthermore, a higher dependency of households on crop production for their income makes them more vulnerable to extreme weather events that also threaten food crop production, and therefore reduce *stability* [350]. Also, there are multiple documented cases of land-grabbing, where large tracks of land are purchased by international companies to produce bioenergy feedstocks. As a result farmers and production were displaced and their local food security was reduced [51,351,352]. As with land, in water scarce areas competition for irrigation water can reduce food security [353]. In addition, the competition for water can potentially reduce the possibilities for cleaning and cooking food, which negatively impacts food security [328,353].

In contrast, there are also positive impacts reported of bioenergy production on food security. Food *availability* and *access* have also been found to increase in areas with additional bioenergy production [54,354]. Investments can increase (fixed) employment, raise and stabilise rural income and act as a financial buffer for households. Thereby these investments contribute to increasing supply and *access* to food [54,85,326,334,348,354–359]. Furthermore, technology spill-overs from cash crop production can rise food crop yields, thereby increasing the food *availability* [55,326,360,361]. Furthermore, availability of bioenergy contributes to energy security and reduces energy price volatility. This positively influences the *utilisation* and *stability* aspects of food security, as because reduced energy security would affect reliable storage and cooking of food [85,332,362–364].

Given these diverse findings in the literature that show that the net balance of positive and negative effects depends on which and how crops are produced and how the land is managed [64], assessing the impacts on all the four pillars of food security is important. The need to understand the linkage between food security and bioenergy is emphasised by the Sustainable Development Goals' goal #2: "Zero hunger" and goal #7 "Clean and affordable energy" [30]. This attention for food security, combined with the projected growth in biofuel use, underlines the importance of avoiding negative impacts of the feedstock production on food security, the need to better understand and quantify its impacts and to search for synergies between food and fuel production.

Quantification of the impact of bioenergy on food security has mostly been based on studies of food *availability* and *access* [51,54,55,186,358,359,365–369]. Studies linking bioenergy and food security are generally based on specific case studies [51 ,54,55,326,349,354,356,358,359,370] that are not necessarily generalisable. These case studies often considered a single region [51,54,55,349,354,359,370] in a country where a bioenergy feedstock plantation was established and measured the food security impacts for employees or farmers [51,55,358] in that region. But they did not consider the effects on the rest of the country or on households not directly involved in bioenergy project [54,359], although they can be indirectly affected through e.g. higher food prices.

In addition, these case studies often investigate past (ex-post) performance [51,54,55 ,326,349,354,356,358,359], whereas ideally these analyses are made before starting (ex-ante) bioenergy production in an area to avoid negative impacts. The ex-ante studies that available mostly use macroeconomic models (e.g. [186,365,368,369,371,372]) that determine the effect of an increased demand for biofuel on the production and prices of other economic sectors and assess the food security impacts on basis of changes in these sectors. These effects are limited to those on *availability* and *access*. Most ex-ante studies that are available are on national [186,367,369,372,373] or higher aggregation level [102,365,368,374,375], obscuring the large differences in food security impacts within a country [376–378]. Regional differences within a country in e.g. economic development and agricultural suitability contribute to variation within a country [377,379]. Furthermore, rural households are in general poorer, less energy secure and more tied to agriculture than urban households in the same country. This means changes in the agricultural sector as a result of increased biofuel production affect rural and urban households differently [380]. Therefore it is important to distinguish between various groups within a country when assessing food security impacts [94,95,379,381–383], which is not possible when using highly aggregate models.

Given these knowledge gaps, we aim to ex-ante quantify impacts of biofuel production on all four pillars of food security (*availability*, *access*, *utilisation* and *stability*) for different household types in a developing country. We will illustrate this for Ghana in 2030, a country that has seen four different proposals to introduce a biofuels mandate of up to 20% biofuels in total transport fuel [1] consumption in 2030 [314,384–386]. Ghana also faces food security issues [137,376], making it important to ex-ante consider the effects of a biofuel mandate on the food security situation. To do so, we will use the macroeconomic model MAGNET as it can project food security impacts, including the nutritious value of food intake, and because MAGNET can disaggregate the results to rural and urban households [268]. Using this model we are able to make a comprehensive assessment of the food security effects of bioenergy in Ghana and show the distribution of the effects over rural and rural households.

We focus on first generation (food crop-based) biofuels in this study, because the link between biofuel production and food security is much more prominent in debates on first generation compared to second generation biofuels [387,388] and because Ghanaian biofuel policy proposals focus on first generation biofuels [385]. Furthermore, first generation biofuels can be much better represented in the economic models, as it is much further developed compared to second generation biofuels.

5.2 Case study description

Ghana is a West African country with about 27 million inhabitants and a GDP of

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[1] Although diesel and gasoline are called transport fuel, these are also used for other applications such as fueling generators and as household fuel [622].

approximately 38 billion USD, or 4,300 USD per capita at purchasing power parity [389,390]. About a quarter of the population lives below the poverty line. However, only 6% of the population is under-nourished [137,391]. This is significantly below the Sub-Saharan average of 23% [392], although the variation inside the country is large. For example, in the North East region it is as high as 34% [376]. Just over half of the Ghanaian population lives in cities [393]. Agriculture still provides employment for 44% of the population, and contributes 22% to the GDP [394]. Cassava, yams, plantains and rice provide nearly 60% of the consumed calories in the country (see Table 5.1). Two thirds of the rice is imported, while the other main crops are not traded in significant quantities [202]. Cocoa and timber are among the most important export products, after crude oil and gold. Until 2013, there was no sugar production in the country, which meant Ghana had to import all domestic demand.

Table 5.1 Food Supply in Ghana in 2011, derived from FAOSTAT [104]

	Food supply (kcal cap^{-1} d^{-1})	Share of total per capita daily calorie intake (%)
Cassava and products	708	23.6
Yams	407	13.6
Plantains	320	10.7
Rice (milled equivalent)	323	10.8
Maize and products	222	7.4
Wheat and products	139	4.6
Sugar (raw equivalent)	106	3.5
Groundnuts (shelled eq.)	85	2.8
Palm oil	65	2.2
Groundnut oil	61	2.0
Other	564	18.8
Total	2 436	100

Around two thirds of Ghanaian land area is classified as agricultural land, which is split evenly between crop land, and pastures and meadows for livestock [202] (see Table 5.2). Ghana's agriculture can be classified as extensive, and yield gaps are large, as is illustrated in Table 5.2 [395]. This suggest there is a potential for improvement in the agricultural sector and include biofuel production without displacing food production or expanding arable land area.

Table 5.2 Overview of crop production and land use in Ghana (average 2012-2016) [202,395,396]. Potential yield is yield that is already reached under optimal conditions in the country [395].

Crop	Area (km^2)	Production (kt)	Yield (t ha^{-1})	Potential yield (t ha^{-1})
Cocoa	16 504	858	0.5	1
Maize	9696	1778	1.8	5.5
Cassava	8976	16 669	18.6	45
Yams	4289	7114	16.6	52
Plantains	3517	3785	10.8	38
Oilpalm [a]	3506	2370	1.3	4.4
Groundnuts	3362	429	1.3	3.5
Pulses	2633	25	0.1	2.5
Sorghum	2283	258	1.1	2
Rice	2213	597	2.7	6
Cocoyam	1983	1287	6.5	20
Millet	1639	161	1.0	2
Other crops	13 440			
Total	74 040			
Meadows and pastures	83 000			
Forest	92 800			

[a] Production and area data for 2011-2015 [395]. Production and yield data for crude palm oil. Potential yield from IIASA [164].

The Ghanaian energy supply consists for a large part of traditional bioenergy (38% of primary energy supply, 150 PJ, mainly fuel wood) [397,398]. Other important energy sources are imported oil products (32%, 128 PJ), natural gas (7%, 29 PJ), crude oil (18%, 73PJ), and hydropower for electricity (5%, 20 PJ). A large majority of residential energy use is covered by traditional biomass [399]. Nearly 80% of the population has electricity access [390], but power supply cannot always match demand [400]. Oil is produced from the Jubilee field that was discovered in 2007 and taken into production in 2010. Current production is about 150,000 bbl d^{-1}. Although the country has one of only few African refineries, almost all crude oil is exported while the refinery operates far under capacity [401]. As a consequence, Ghana has to import nearly all of its transport fuels at a cost of 2 billion USD in 2015 (or 5% of GDP) [402]. This creates an incentive to consider alternative fuel sources.

Apart from the traditional use of fuel wood, no other sources of bioenergy are used in significant quantities in the country [397]. However, there have been initiatives in the past to produce jatropha biodiesel on a large scale [312,314,359,403], but all these projects failed [312]. In addition to the jatropha plans, Ghana has seen multiple proposals to implement a biofuels mandate. The national biofuel policy (2005) already aimed to replace 20% of diesel in 2015 by jatropha-based biodiesel [314]. The 2006 Strategic National Energy Plan wanted to introduce a liquid biofuels blending target of

10% for both biodiesel and ethanol in 2020 [386]. The proposed national bioenergy policy of 2010 increased the blending mandate to 20% biodiesel and ethanol in 2030 [384]. However, none of these three policies was ever implemented in law. In the context of ECOWAS, Ghana agreed in 2011 on national blending targets for biodiesel and ethanol of 5% in 2020 and 10% and 15% in 2030 [385]. At 2014 consumption levels, this is would be equivalent to 210 ML of biodiesel and 258 ML of ethanol.

5.3 Methods

To ex-ante quantify the impacts of increases in biofuel production on food security in Ghana in 2030 we used the computable general equilibrium (CGE) model MAGNET [268]. CGE models are considered as a suitable method to capture the food security impacts of bioenergy, as it includes competition for land and labour and the resulting effects on food production, prices and income [404]. The MAGNET model contains economic interactions of all sectors in the economy, a special household module that distinguishes a rural and urban household in Ghana, and a nutrition module to convert the household level food consumption to its nutritional value. The combination of these two additional modules to the MAGNET model, enable projections of food security impact on household level in Ghana (see section 5.3.1). We defined indicators for all four pillars of food security (section 5.3.2) and applied a scenario approach (section 5.3.3) to determine the effects of the biofuel mandate.

5.3.1 MAGNET model

The Modular Applied GeNeral Equilibrium Tool, MAGNET, is a computable general equilibrium (CGE) model, which includes 56 sectors in 140 countries and regions (see Figure 5.1). It was used here to calculate the food security impacts of a biofuel demand in Ghana for rural and urban households. The model is based on the GTAP model [405] and described in more detail by Woltjer *et al.* [268]. In order to assess the food security impacts of bioenergy for rural and urban households, we used the household module [406], which adds multiple household types in selected countries to the model and the nutrition module [407] to translate the food consumption per household from monetary terms to nutritional value. The relations between the modules to assess the impacts of bioenergy on the various food security indicators for the two types of households is illustrated in Figure 5.2.

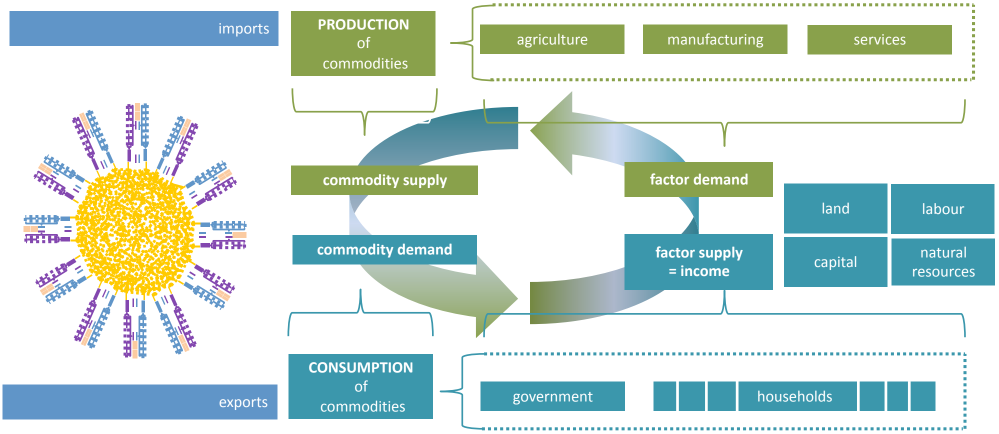

Figure 5.1 Graphic representation of the MAGNET model [408]. In this specific version two household types are distinguished [406] in Ghana, and nutritional module is added as post analysis [407].

The household module of MAGNET includes a rural and urban household type in Ghana. The characteristics of the two household types can be found in Table 5.5 in the Appendix. The social accounting matrix of Ghana, which is the overview of all domestic monetary flows between sectors, households, the government and abroad, was updated for the two household types based on the results of a national household survey of Ghana [406,409]. This builds on previous work of Breisinger et al. [410] who described the Social Accounting Matrix (SAM) for Ghana, made an overview of all domestic monetary flows between sectors and households, and included a rural and an urban household types. The nutritional module of MAGNET used a post-analysis to convert the consumption of agricultural products in households to the energy and nutrients they provide [407]. This enabled us to calculate the effects of the biofuel mandate on the level of energy and nutrient intake by each household. The set-up and functioning of the household module is further explained in Kuiper & Shutes [406] and the nutrition module in Rutten *et al*. [407].

For the size of the biofuel mandate (i.e. the shock) we used two scenarios (see section 5.3.3). For each scenario we examined the household level food security impacts from the increase in biofuel demand in Ghana.

5.3.2 Indicators

There are various indicators to measure the four pillars of food security. The FAO compiled a list of 30 food security indicators, based on expert judgement and data availability and monitor these on national level [411]. From this list, seven indicators (for *availability*, *access* and *utilisation*) can be assessed on household level using the MAGNET model, and an additional four indicators can be assessed on regional or national level (see Table 5.3) [406,407]. Other indicators of the FAO list (e.g. road density and political stability) cannot be represented in macroeconomic models.

In addition to these indicators from the FAO list, the nutrition module of the MAGNET model includes indicators for the household level consumption per capita of food energy and three macronutrients (protein, fat and carbohydrates). For *utilisation* the use indicators of dietary diversity (share of fruit and vegetables in total food consumption and share of cereals, toots and tubers in total food supply) were used. These indicators are not represented in the list of the FAO [411], as these focus on outcome indicators for *utilisation* (e.g. number of underweight children) that are not available in the MAGNET model. Therefore, the indicators mainly focus on the nutrition part of the definition of *utilisation* [2].

Energy and the three macronutrients are the main constituents of food items and therefore relevant when considering food security [412]. For these four indicators a minimal food security value or threshold was defined, because not only the direction of the change matters, but also the absolute values (e.g. 1% lower consumption is less of a problem for households with a high per capita consumption, than for households at risk of under nourishment). These threshold values were determined following the dietary reference intake. This is the minimum per capita consumption that is sufficient for 97.5% of a population without dietary deficiencies [413]. When this minimum is not met, it shows the food security is insufficient.

The results expressed in food energy or macronutrients in this chapter refer to primary agricultural products only. Processed foods contribute to the total food expenditure, but the composition of the category processed foods in the model is very heterogeneous and inclusion of its energy and nutrient composition would add a large uncertainty to the results.

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[2] *Utilisation* refers to the way food and the nutrients in it are taken up in the body. Various aspects play a role in this, such as hygiene, preparation and diversity [427].

Table 5.3 Indicators of food security from the MAGNET model and the nutrition module and their relation to food security [406,407]. A plus sign indicates a positive relation to food security, a minus sign a negative relation, i.e. an increase in the indicator reflects a negative effect on food security.

Pillar	Indicator	Unit	Level	Relation to food security	
Availability	Food energy consumption per capita [a]	kcal cap^{-1} d^{-1}	Household	+	A decrease in the food energy supplied to households is a sign of reduced food security in the area. The study of Maxwell *et al.* [414] put the recommended daily caloric consumption in Ghana at 2900 kcal for adults.
	Protein consumption per capita [a]	g cap^{-1} d^{-1}	Household	+	Protein is a macronutrient for which the dietary reference intake [b] is 45-56 g d^{-1} [413,415]. This is sufficient for 97.5% of the population. When this minimum is not met, it shows the food security situation in the country is insufficient.
	Fat consumption per capita [a]	g cap^{-1} d^{-1}	Household	+	Fat is a macronutrient of which an average person has to consume 64 g d^{-1} [415] [c]
	Carbohydrates consumption per capita [a]	g cap^{-1} d^{-1}	Household	+	The dietary reference intake of carbohydrates is 130 g d^{-1} (60-210) [415].
	Supply of protein from animal sources (excluding fish)	g cap^{-1} d^{-1}	Household	+	A supply of animal protein indicates sufficient feed is available to raise livestock to produce food consume this [416]. As peoples first reaction to food security issues is to reduce animal protein consumption, this is a good indicator for food security [381].
	Average value of food production per capita (in constant prices)	USD cap^{-1}	National	+	A higher value of food produced denotes a higher availability of food in the region. As it is presented in constant prices, price effects are excluded and this only includes production effects. This is not on household level as urban households do not produce food.
Access	Household income	USD cap^{-1} a^{-1}	Household	+	Because of the link between poverty and hunger, household income is a good indicator for access to food as increased income increases the households potential to purchase food.
	Food price index	index	National	-	Increased food prices result in lower accessibility of food, especially for lower income households. Households with a higher income are better equipped to buffer price increases.
	Share of food in total household expenditure	%	Household	-	Increasing the share of household income allocated to food purchases means food has become less accessible and therefore food security decreases.
Utilisation	Share of calories from fruit and vegetables	%	Household	+	High quality diets are associated with higher diversity in food sources. Especially for poor people in developing countries diet diversity can be an issue. Increasing diversity, increases the utilisation aspect of food security [417].
	Share of energy supply from cereals roots and tubers	%	Household	-	An increased reliance on staple crops as cereals, roots and tubers for food supply means dietary diversity and thereby food security decrease [417].

Pillar	Indicator	Unit	Level	Relation to food security
Stability	Share of food in total consumption imports	%	National	- A high share of food in total imports indicates Ghana needs to spend a significant share of its foreign exchange income on food imports and becomes vulnerable to exchange rate risks and price increases [411]
	Cereal import dependency ratio	%	National	- Price variations on the world market can translate to larger variation in domestic food prices endangering the food security of people. A high dependency on import makes a country more vulnerable to these price changes [85,335,411,418,419]. Cereals are specifically determined because cereals are proportionally more consumed by poor and food insecure people, the worst impacted by price increases.

[a] Results are only presented for primary agricultural products. The heterogeneity of the nutritious value of processed foods is too large for the results to be reliable.

[b] The dietary reference intake varies between women and men, the average value that was used here was based on a weighted average (regional data from Ghana household survey [420]) of the male and female daily reference intake.

[c] Based on the minimum food energy intake, the lower end of the suggested range of energy from fat [415] and the average energy content of consumed fat [421].

The indicators were derived from the MAGNET model as follows (as is also illustrated in Figure 5.2). Most indicators for *availability* were quantified in the nutrition module. The household level food consumption, expressed in monetary volumes for each food crop and animal product, was converted to the calories and macronutrients it contains in the nutrition module. Dividing the total household consumption by the total population per household type (see Table 5.5 in the Appendix) gave the food energy, protein, fat and carbohydrates consumption per capita. The supply of protein from animal sources was determined by dividing the per household type consumption of proteins from milk, beef and other animal products by the total per household type proteins consumption. The average monetary value of food production per capita was calculated by summing the value of all food produced in Ghana by the total population. The indicators for food *access* were determined on household level, with the exception of the food price index, which was determined at national level. The household income for each household was the sum of the income factors land (only rural), capital, natural resources and labour (divided into skilled and unskilled, with a special category for agricultural labour). Dividing by the household population gave the per capita income. The share of food in total the household expenditure was determined by dividing the expenditure for each household on all food products by the households total expenditure. For *utilisation* the two indicators were determined on household level. For the share of calories from fruits and vegetables, their total consumption (in caloric value) was divided by the total food energy consumption of the household. For the cereals

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and roots and tubers, the sum of rice, wheat, other grains, and horticultural[3] products was used. The cereal import dependency, an indicator for *stability*, was determined by dividing the household expenditure on imported rice, wheat and other grains by the total expenditure on these products. The share of food in total consumption imports was determined by summing the food imports and dividing these by the total consumption imports.

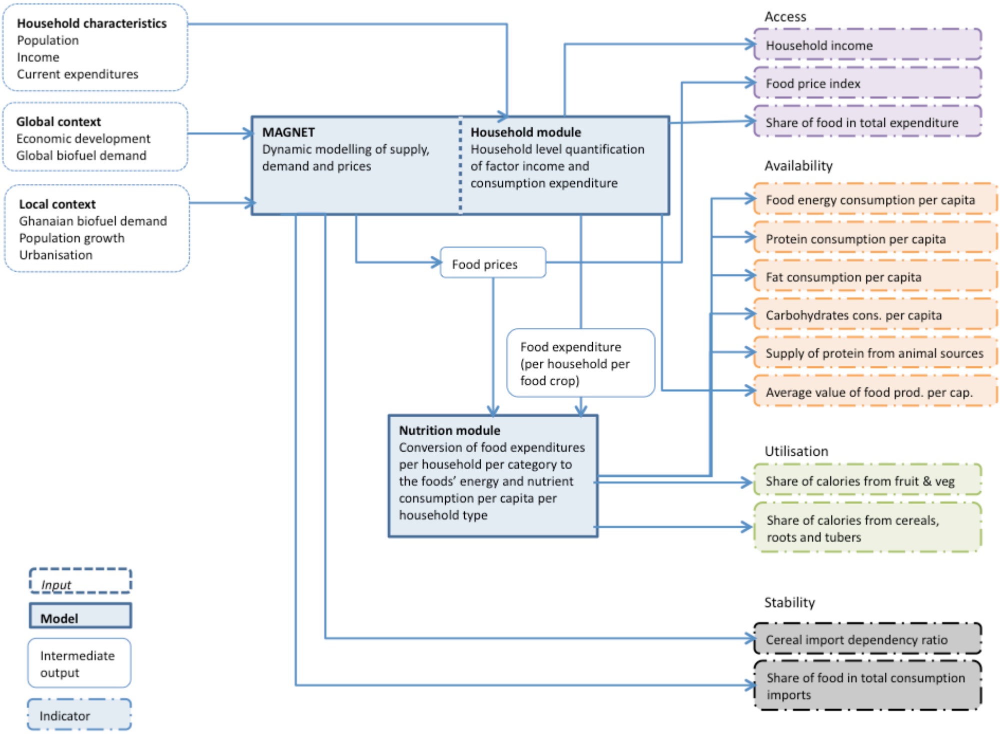

Figure 5.2 Relation between the MAGNET model and the household and nutrition module to assess the effects of the biofuel mandate on each of the pillars of food security at household level. The household module integrates the urban and rural households as two separate sectors in the CGE model. Thereby, the MAGNET model can determine the household income and food consumption. The nutritional module consists of an ex-post analysis to convert the household spending on each primary agricultural product (crop or livestock) into the food energy and nutrient consumption.

5.3.3 Scenarios

The MAGNET model was used to calculate the food security situation in Ghana in 2030 for two scenarios, a *baseline* scenario without biofuel production and a sce-

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[3] Both cassava and fruits and vegetable are aggregated in this category. The category was split based on the share of food energy from cassava in the sum of all horticulture products, based on FAOSTAT food energy for Ghana [202].

nario with a biofuels *mandate* [385]. Comparing the food security situation in the *mandate* scenario to the *baseline* scenario, shows the effects of biofuel production in Ghana. The *baseline* scenario included a business as usual development for the world economy (based on the Shared Socioeconomic Pathways SSP2 scenario [422] and includes projections for first generation biofuel for the rest of the world) and no biofuel production in Ghana. The *mandate* scenario was based on the most recent proposed biofuels mandate for Ghana in 2030 which consists of 15% ethanol and 10% biodiesel (E15/B10) [385]. The scenarios were implemented in MAGNET as targets for biofuel production in 2030 in Ghana. The additional costs of biofuel compared to regular fuel where assumed to be paid by government subsidies. This means that the government spend proportionally less on other sectors, reducing amongst others the direct transfers to households. Reducing energy costs corresponds to a goal of the Ghanaian biofuel policy that focusses on combatting energy poverty. Furthermore, increased fuel prices are a serious political problem in the country, which makes it unfavourable to place the burden on fuel producers. The land use is determined endogenously in the MAGNET model and assumes imperfect substitution between the various land uses. The potential to expand the total land use is limited and conversion to agricultural land becomes more expensive when closer to the total land supply [268]. The total land supply is equal to the country area, but not more than two thirds was used.

5.4 Results

5.4.1 Baseline

The *baseline* scenario shows strong economic growth in Ghana between 2010 and 2030, with the gross domestic product (GDP) quadrupling. In this period, labour productivity increases in the country, which results in higher production and lower agricultural prices. Demand for labour decreases in the agricultural sector by 28%, and demand for unskilled labour in services and manufacturing increases by 265% and boosts average wages. Land is a scarce resource and land prices increase in the country by 340%, while agricultural land use increases by 5%.

These economic developments results in large progress in the food security of the country, as nearly all indicators show an improvement for 2030, compared to 2010 in the *baseline* scenario (see Table 5.4 and Figure 5.3). Food *access* increases as household income increases both in urban (190%) and rural (162%) households. The higher income, combined with lower food prices, lead to a falling share of household income spent on food purchases in urban areas. In rural areas this share increases as the higher incomes lead to a switch to processed foods (increase of 435%), rather than primary agricultural products. As processed foods are relatively more expensive, the share of food expenditures in total spending increases. Despite the rise in the share spent on food in rural households, income available to spend on non-food consumption increases in absolute terms. The *availability* of food, expressed as primary agricultural food consumption per capita, grows as a result of the higher production, higher incomes and lower prices, despite an expanding population. The calorie consumption per capita increases by 17% (rural) to 34% (urban) in 2010 (see Figure 5.3). In addition to this, spending on processed foods further increases and becomes 32% in urban areas and 26% in rural areas, up from 27% and 17%. This explains why the energy and nutrient consumption from primary agricultural food consumption in the urban areas is lower than in the rural areas, see Table 5.4. The absence of the calorie and nutrition intake of processed foods in the model results is also the reason why the energy and macronutrient intake per capita are low compared to the threshold values from Table 5.3 and FAOSTAT data [202], which include processed foods. In 2030, the food energy from primary agricultural food consumption is about 75% of the recommended [414] daily caloric consumption; in addition 15% (rural) to 25% (urban) of the food expenditure of households is spent on processed foods. This would add to the food energy. In contrast to the indicators for *availability* which increase for both household types, the picture for the indicators of *utilisation* is more mixed. *Utilisation* improves as diets become less reliant on staples such as roots, tubers and cereals and more based on animal products. However, at the same time the share of fruits and vegetables in the food consumption decreases, indicating a decrease in food quality and *utilisation*. These effects are stronger in urban areas, which are generally richer. *Stability*, measured as the reliance on imported food, does not significantly change for the cereal dependency rate, as this remains nearly stable until 2030. The share of food in the total consumption imports is nearly halved.

Table 5.4 Household food security in Ghana in 2010 and 2030 for the baseline and mandate scenario.

Pillar	Indicator	Unit	2010		2030		2030	
					baseline		mandate	
			urban	rural	urban	rural	urban	rural
Availability	Food energy	consumption (kcal cap^{-1} day^{-1})^{a}	1660	1892	2223	2215	2222	2215
	Protein consumption	(g cap^{-1} day^{-1})^{a}	35	37	48	42	48	42
	Fat consumption	(g cap^{-1} day^{-1})^{a}	26	37	34	40	34	40
	Carbohydrates consumption	(g cap^{-1} day^{-1})^{a}	321	354	432	424	432	424
	Energy supply from cereals roots and tubers	(g cap^{-1} day^{-1})^{a}	968	776	1052	1096	1051	1096
	Supply of protein from animal sources (excluding fish)	(g cap^{-1} day^{-1})	4.24	2.44	6.05	2.95	6.04	2.95

	Average value of food production	(USD cap^{-1})	560[b]		834		853	
Access	Household income	(USD cap^{-1} yr^{-1})	2524	1729	7316	4532	7201	4527
	Food price index	(% change, compared to 2010)			-14.2%	-12.1%		
	Share of food in total household expenditure	(%)	19%	22%	12%	30%	12%	31%
Utilisation	Share of calories from fruit and vegetables	(%)[a]	16%	13%	16%	15%	16%	15%
	Share of energy supply from cereals roots and tubers	(%)[a]	51%	42%	52%	47%	52%	47%
Stability	Cereal import dependency ratio	(%)	5%	4%	5%	3%	5%	3%
	Food share in total consumption imports	(%)	27%		14%		14%	

[a] Only primary agricultural products are included

[b] In the MAGNET model, no agricultural production is assumed in the urban areas.

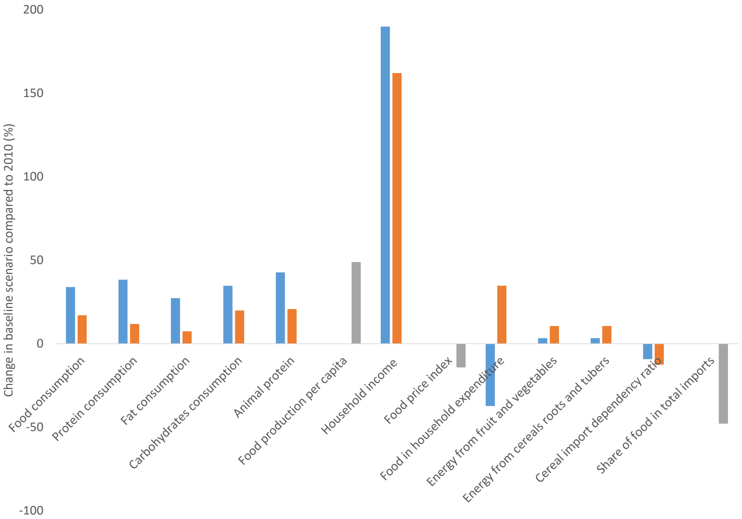

Figure 5.3 change in food security indicators between 2010 and 2030 in the baseline scenario (i.e. without biofuel mandate) for urban and rural households.

5.4.2 Mandate

To fulfil the E15/B10 mandate the MAGNET model projects grains (maize) to be the most important feedstock of ethanol and crude vegetable oil from oil seeds (in this case palm oil) as the major feedstock of biodiesel. The additional demand for these crops for biofuels result both in a higher production as well as a lower consumption and export, but the ratio is very different for both feedstocks (see Figure 5.4). Although total agricultural land use does not increase in the country compared to the *baseline*, but the land use for oil seeds production expands by 57%. The combined effect from this land expansion and a 4% yield improvement compared to the *baseline*, provides two thirds of the additional demand for oil seeds. In addition to this extra production, the demand for oil seeds for biodiesel production is met by reduced exports (27%) and from a reduction in consumption of food and other sectors (10%). The total grain production hardly differs between the *baseline* and the *mandate* scenarios, but grain consumption for food and the use in other sectors is lower compared to the *baseline*. The reduced consumption covers 95% of the demand for grains for ethanol, with the rest being provided by higher production. In general, the effect of the biofuel mandate is very small on most of the food security indicators (see Table 5.4 and Figure 5.5).

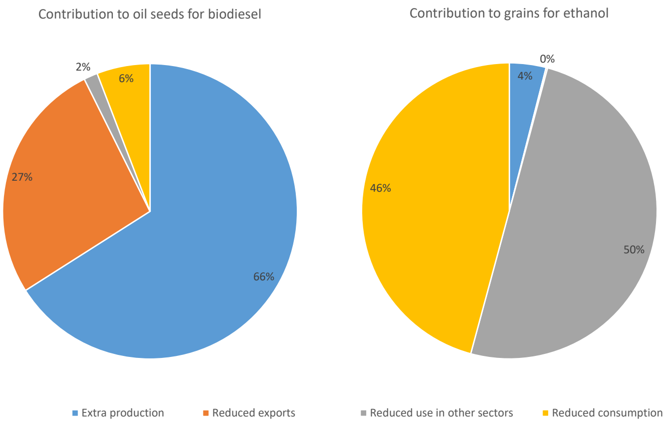

Figure 5.4 Contribution of additional production, changes in trade, and reduced consumption to cover the additional demand for oilseeds (mainly palm oil) for biodiesel (left) and grains (maize) for ethanol (right) in the mandate scenario.

The higher production of oil seeds and the reduced availability of maize for food, due to the demand for biofuel production, stimulate the agricultural sector. Demand for non-skilled agricultural labour and land for feedstock production increases significantly, leading to higher prices for land and labour compared to the *baseline*. This is beneficial for rural households as in the model they receive the payments for land and agricultural labour as income. The income from direct endowments increases as a result. As a part of the government expenditure is used for subsidising biofuel production, government transfers to households are lowered by approximately 7% in the *mandate* scenario compared to the *baseline* [4]. This cancels out the additional income

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[4] The low oil price of the last years made fossil fuels economically more attractive. As fuel prices are an important political topic in the country, it is unlikely biofuels will be mandated if these lead to higher fuel prices. This would mean biofuels need to be subsidised. If it would be assumed that fuel producers pay the higher costs for biofuel production, it would result in higher consumer prices, which would also lead to reduced disposable income.

rural households obtain compared to the *baseline*, and leads to a decrease in income in urban households. This means *access* to food is reduced in most households compared to the *baseline* (see Figure 5.6 in the appendix). Especially since the *mandate* leads to increased food prices (+2.4%) compared to the *baseline*, which showed decreasing food prices in 2030 compared to 2010. The share of household income allocated to food purchases also increases, with the highest increases in the urban areas. Comparing the country average food expenditure as share of the total income (23%) to current data of other countries shows Ghana would be comparable to countries as Mexico and China [423].

The *availability* pillar of food security is also affected by the biofuel mandate as calorie consumption in both household types decreases compared to the *baseline*. However, the decrease in consumption is limited to less than 1% for energy intake and for each of the macronutrients in both rural and urban households. At the same time, the diet also becomes less meat intensive, and use of fruit and vegetables decreases slightly, affecting the *utilisation* pillar of food security as well. In addition, the use of food crops to fulfil the bioenergy *mandate* means a larger share of the cereals and other foods have to be imported, reducing the *stability* pillar of food security.

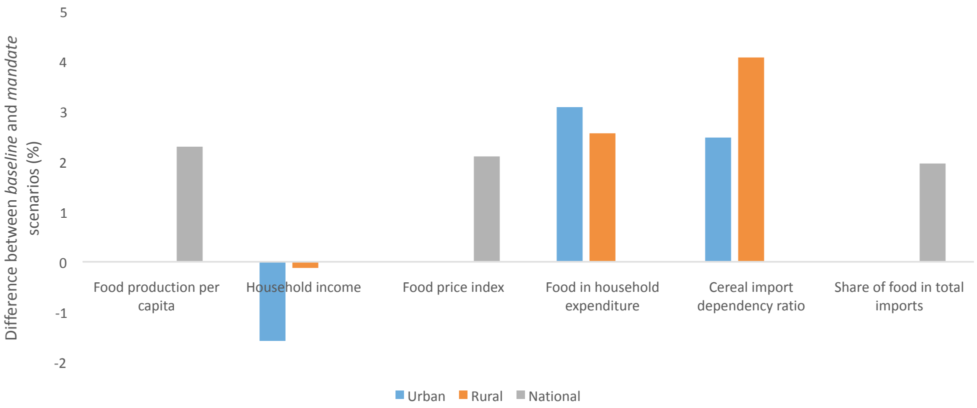


Figure 5.5 Differences in food security indicators between the baseline and mandate scenario in 2030 for the urban and rural households or on national level. Differences smaller than 0.5% are not shown in this figure.

5.5 Discussion and conclusion

In this chapter we projected the effects of a E15/B10 biofuel mandate in Ghana in 2030 on all four pillars of food security: *availability*, *access*, *utilisation* and *stability*. The food security effects were assessed for rural and urban households. In this study we develop and demonstrate a methodological approach to enable ex ante quantification of biofuel production on all four pillars of food security on a household level.

The projected food security effects of a biofuel mandate in Ghana are limited compared to the effects of the projected economic growth of the coming years. The increase in food production and consumption as a result of economic progress far outweigh the impacts of a biofuel mandate on the *availability* of and *access* to food. Although the introduction of a biofuel mandate slightly decreases the food security situation in the country in 2030, it would still mean strong overall progress from the current (2010) situation. Previous ex-ante studies on food security impacts of biofuel for other countries (e.g. [94,313,374,404]) confirm these findings, as these also show that the negative food security impacts of biofuel production are relatively small compared to the *baseline* and still show progress compared to the starting year, i.e. improving the food security situation. However, these studies did not consider all four food security pillars of food security and did not present the distribution of the results over the country, which means stronger effects may be obscured in the aggregated results.

The food security effects of biofuel are relatively small in Ghana, because a part of the effects will occur abroad. A large share of the oil seed feedstock for biodiesel is provided by reduced export. In addition, a larger share of the food consumption is imported. This means a part of the effects spill-over to other regions. The pressure on the world agricultural commodity market would increase slightly as a result of the trade effects of the biofuel mandate in Ghana. This analysis does not account for potential indirect land use change that can be caused by displaced food production. A cumulative effect of more countries implementing a biofuel mandate (in addition to those already included in the *baseline*) is likely to result in a larger effect on world agricultural commodity markets. The resulting price effects will probably impact low income countries disproportionately [424].

The extent of the food security effects of biofuel mandates also depends on the model assumptions on how the world develops. In this study, a SSP2 middle-of-the-road scenario was used as baseline scenario. Using a SSP1 (sustainable) or SSP3 (fragmentation) scenario can lead to very different results, especially in Sub-Saharan Africa [425]. The population projections in SSP3 are much higher, people have a large preference for animal products, yield increases are limited, which all adds up to larger pressure on agricultural land. As SSP3 also assumes a less globalised market, the effects in Ghana of a biofuel mandate in the country are likely to be higher. Conversely, in a SSP1 scenario with lower population growth, faster yield development, and more plant based diets, the effects of biofuels on food security are likely to be smaller. The assumptions on global developments would require more detailed analysis on their impact on food security.

It is possible to ex-ante quantify the four pillars of food security on household level, although *availability* and *access* are more easily and better addressed than *stability* and *utilisation*. As food *availability* and *access* are included in most previous studies on food security, they are well researched. In this study, nine indicators are available for these two pillars that together provide a broad picture of *availability* and *access* to food. The major aspect lacking in this study for the *availability* pillar, is a good representation of processed foods in the MAGNET model. The heterogeneity of this compound category means that the food energy and macronutrients content could vary much more for this category than for the primary agricultural products that are included in the assessment, which are much more homogenous.

Ex-ante quantification of the pillars *utilisation* and *stability* is in general less comprehensive and more research is needed. In this study, *utilisation* is quantified based on the shares of staple foods and fruits and vegetables in the diet to reflect the dietary diversity, because more diverse diets, which are less dependent on staple foods are considered healthier [426]. Other nutrients than the macronutrients that were used in this study (such as fibres, vitamins) are also important for healthy diets and utilising the nutrients in the food [427]. Other aspects of *utilisation*, such as cooking and food preservation are not represented in the MAGMET model and therefore not included. Integration of these indicators in the model would increase the quality of the assessment. It is likely that increased energy access as a result of bioenergy expansion has positive effects on *utilisation* as it can help to improve food quality through better storage and preparation.

The *stability* in the *availability*, *access* and *utilisation* of food is in this study assessed by the share of the consumed food that is imported. This is however only one aspect of *stability* of the three pillars, but as can be sees from Figure 5.5 it is the indicator a biofuel mandate has the largest impact on. The *stability* in food *availability* can for example be affected by extreme weather events which are not included in the *stability* indicators of the MAGNET model. The period 2005-2014 showed two years in which the maize harvest was 10% lower than the previous year [202,395]. A 10% decrease in availability of a staple crop, could lead to food security issues in Ghana. Extreme weather events are more likely to occur with climate change [14] and as biofuels lead to a higher dependency on agriculture, the vulnerability to harvest failure increases [350].

World food prices are volatile [428] and assuming an average price for a commodity in a country, neglects the variation in prices over space and time. Historical market price data from Ghana shows a variation of 50% in food prices within the country as well as over the year [429]. This intra-annual and intra-country variation in food prices is not captured in the food price index indicator [337,428]. In addition, this indicator focusses only on the economic access to food. In developing countries, characterised by less developed distribution infrastructure, the physical access can play a role as well. Market access for both buyers and sellers may depend on access to a road that is blocked. Leaving the people unable to reach the market to buy or sell food [98]. This type of indicators of *access* to food is not included in food security models.

The variation in food *availability* can also have an impact on the *stability* in the *utilisation* pillar. If a stable supply of a specific food type is substituted by a food type with only a short seasonal availability and the rest of the year depends on staple crops, the *stability* in the *utilisation* pillar would decrease.

The indicators for food security that have been used in this research are those that can be quantified using the MAGNET model. Future research has to lead to quantification of the food energy and macronutrients of processed foods. In addition, extra indicators for the *utilisation* and *stability* pillars on household level need to be developed that can ex-ante quantify the food security effects of biofuel.

Our approach enables the differentiation of food security effects of biofuels between urban and rural households. However, further disaggregation to households in e.g. different geographical regions or different income groups, is required to assess the variability of impacts across different groups in society and to assess which groups in society are effected most. Previous studies only considered one aggregate household for a country. In this study, the household food security impacts are presented for an urban and a rural household. This is a strong improvement, as rural and urban households tend to differ in their food security responses. Our results show that that rural households tend to benefit more from biofuel expansion, whereas the urban population is only confronted with negative food security impacts. Nevertheless, overall urban households are still better-off on all indicators.

Although relevant, the disaggregation in urban and rural households this study is still crude. Further disaggregation would increase the level of detail and show better where impacts accrue and which groups in society are confronted with negative impacts. Suggestions for further disaggregation would be to include various income groups to differentiate between richer and poorer households, distinguishing between rural households with and without land ownership, or further regional disaggregation. Disaggregating to various income classes can be useful, as increased income can mitigate the effects of increased food prices. Higher prices are most likely to benefit those who own land and already have a relatively high income[430]. Further geographical disaggregation can provide additional insight as Ghana contains various agro-ecological zones, which vary in suitability to produce various crops, but also in socio-economic status, and food security situation. The distribution of the food security impacts is likely to be impacted by such aspects as well.

Even household level assessment of food security impacts masks some differences. It assumes that within a household food is shared equally, according to the needs of each household member. However, especially in periods of food scarcity, households are confronted with an intra-household distribution question [380,431]. In sub-Saharan countries this can be a gender issue where women are likely to be the least food secure [431].

In order to consider biofuel production sustainable, other potential sustainability effects need to be considered as well. Food security is one of the most prominent potentially negative sustainability impacts of biofuel production. This study showed that the impacts of biofuel expansion on food security in Ghana are likely to be limited. However, there are also other aspects that determine the sustainability of biofuel production in a country. As there are likely to be trade-offs between the various sustainability impacts, it is important to consider them in an integral manner. This relates not only to food security, but also impacts such as on GHG emissions, energy access and rural development.

Increasing energy supply and in Ghana without dependence on imported fossil fuels can offer clear socio-economic benefits compared to the current reliance of fuelwood for cooking and heating and can be an important reason to expand biofuel production in the country. In addition, this study shows that an introduction of biofuel in Ghana stimulates the rural economy as it leads to an increase in demand for agricultural land and tempers the *baseline* effects of reduced employment in agriculture.

Another reason to opt for biofuels is that these can reduce GHG emissions compared to fossil fuels [385]. However, this means the direct and indirect GHG emissions need to be assessed as well in order to verify that the production chain emissions provide a GHG emissions reduction compared to the fossil fuel reference. The results of this study show the implementation brings a risk of indirect land use change. Although the land use in Ghana does not expand between the *baseline* and *mandates* scenarios, the biofuel production brings a risk of land use change outside the Ghanaian border. In the current setup not all effects are contained within the borders, as oil seed exports decrease and food imports increase. This may mean land use change can take place elsewhere, indirectly caused by the expansion of the biofuel production in Ghana. This indirect land use change can potentially have high associated GHG emissions [58]. This needs to be further investigated and mitigation measures (e.g. [115]) should be taken in order to avoid the production of biofuel the cause additional GHG emissions. Due to the weak institutional environment in the country, it is unlikely to implement strong sustainability safeguards and meet the demands for sustainable production [432].

The method presented in this chapter enables the assessment of various scenarios including the effects of more sustainable agricultural production on the food security indicators. For example, assuming higher yield increases may show a reduced competition for land and therefore smaller impacts on *availability* and *access* of food.

Appendix

Table 5.5 Households characteristics of the two households in Ghana included in the MAGNET model.

Household	2010 Population (million)	Income (USD cap^{-1} yr^{-1})	2030 Population (million)
Urban	12.5	2524	16.3
Rural	16.3	1729	17.1

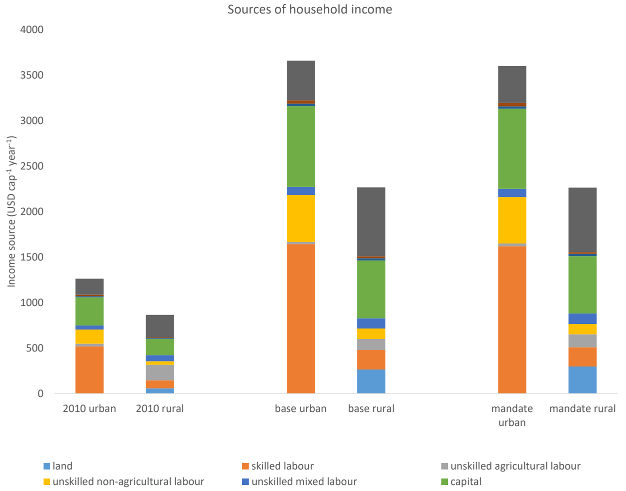
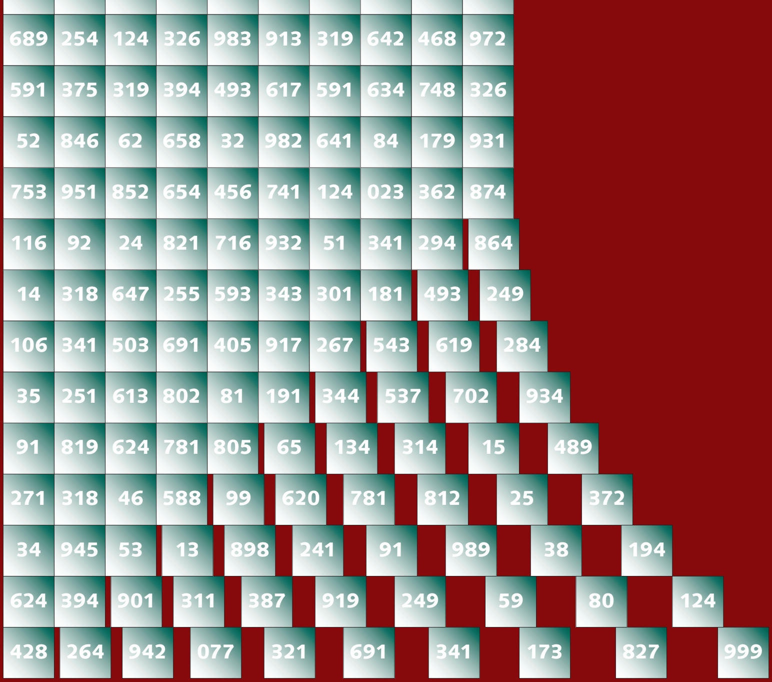


Figure 5.6 Sources of household income in rural and urban areas in Ghana in 2010, baseline (base) and mandate scenarios.


689 254 124 326 983 913 319 642 468 972
591 375 319 394 493 617 591 634 748 326
52 846 62 658 32 982 641 84 179 931
753 951 852 654 456 741 124 023 362 874
116 92 24 821 716 932 51 341 294 864
14 318 647 255 593 343 301 181 493 249
106 341 503 691 405 917 267 543 619 284
35 251 613 802 81 191 344 537 702 934
91 819 624 781 805 65 134 314 15 489
271 318 46 588 99 620 781 812 25 372
34 945 53 13 898 241 91 989 38 194
624 394 901 311 387 919 249 59 80 124
428 264 942 077 321 691 341 173 827 999

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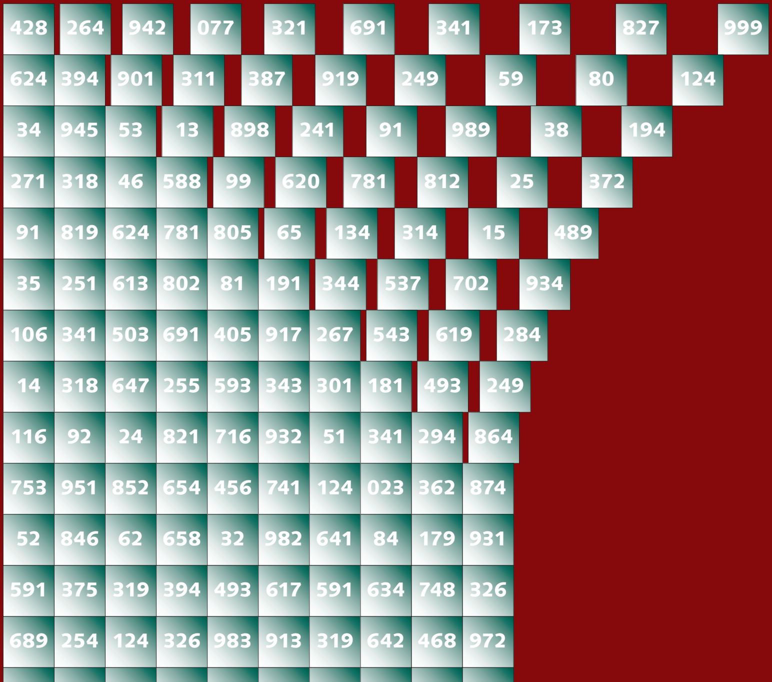
428 264 942 077 321 691 341 173 827 999
624 394 901 311 387 919 249 59 80 124
34 945 53 13 898 241 91 989 38 194
271 318 46 588 99 620 781 812 25 372
91 819 624 781 805 65 134 314 15 489
35 251 613 802 81 191 344 537 702 934
106 341 503 691 405 917 267 543 619 284
14 318 647 255 593 343 301 181 493 249
116 92 24 821 716 932 51 341 294 864
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6 Projecting socio-economic impacts of bioenergy: current status and limitations of ex-ante quantification methods

Abstract

The potential socio-economic benefits of bioenergy are one of the main arguments for its expansion the last decades. However, the socio-economic effects are not unequivocal positive. In order to determine the balance between the positive and negative impacts, the impacts need to be quantified. This is preferably done ex-ante. In order to account for the geographic distribution of the effects, this should take into account the various spatial levels at which the impacts occur. Quantification requires methods and tools, therefore we map the status, limitations and options of improvements in quantitative research on socio-economic impacts of bioenergy. For this, we perform a literature review to identify relevant indicators and analyse the state-of-the-art of ex-ante quantification methods and tools and their ability and suitability to assess these indicators at different spatial scales. The review of the ex-ante quantification methods showed that not all relevant indicators are ex-ante quantified, for community impacts and public acceptance no ex-ante was found. In addition, blind spots such as the low-aggregation level food security impacts where quantification does not match the level of impacts were identified. From the review of the methods, it was shown much more can be done and disaggregation of models and model collaboration make it possible to extend the scope of the socio-economic analysis. It is demonstrated how model collaboration between different methods and disaggregation of macroeconomic methods could provide low aggregation level quantitative ex-ante assessment of the food security impacts of bioenergy.

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6.1 Introduction

In recent decades, modern bioenergy has been promoted to contribute to climate change mitigation, increase energy independence and stimulate the economy [46,62,433]. Scientific and political debate has primarily focused on climate change and other environmental impacts of bioenergy (e.g. [58,59]). Socio-economic development is an integral aspect of sustainable development and needs to be considered in this context as well [434–436]. Although countries with a bioenergy mandate expect bioenergy to contribute to a number of socio-economic goals, such as domestic energy security, job creation, and rural development [46,312], socio-economic impacts of bioenergy are not unequivocally positive [44,47,73,243]. Previous studies have identified negative socio-economic impacts such as competition with food production and poor respect for local land rights [51,60,312,437].

To avoid negative impacts of bioenergy, principles and certification schemes for sustainable bioenergy feedstock production and conversion have been introduced [75,103,104]. Certification schemes such as the Roundtable on Sustainable Biomaterials (RSB) [438–440], Roundtable on Responsible Soy (RTRS) [441] and Bonsucro [442], have set sustainability standards that need to be met by producers. Although these certification schemes include socio-economic impacts of bioenergy, the focus is more on environmental impacts [75,106,443–445]. Furthermore, the principles on socio-economic impacts are often formulated as general principles that are vague and cannot always be quantified [44,67,106,443,444]. For example multiple certification schemes (e.g. [442,446]) set employees' freedom from discrimination as one of their criteria. This is to be demonstrated by the availability of a company policy document against discrimination, without a requirement for actually measuring whether or how often discrimination takes place. However, quantitative information can help to understand the scale of an effect and to transparently weigh the positive and negative aspects of bioenergy implementation [44,65,447]. Based on objective measurements of the socio-economic impacts, the quantitative information on the socio-economic effects of bioenergy can then help facilitate and inform decision-making processes [67–69].

Studying present and past bioenergy projects to determine success factors and barriers can help to improve sustainability of bioenergy. However, to avoid negative impacts or overly optimistic expectations [46,448], the direction and magnitude of the socio-economic impacts of the possible future development of bioenergy need to be assessed in advance of actual production. Ex-ante knowledge on the positive and negative impacts of bioenergy and the balance between those enables decision-makers to steer bioenergy development to minimise undesirable impacts.

Although there is consensus on the key socio-economic areas of concern regarding bioenergy [44,75,103,105], there is less agreement on the indicators that could and should be used to measure the socio-economic performance of bioenergy supply chains [67,73–76]. As the impacts of bioenergy are diverse and cannot be characterised by a single comprehensive value, each potential socio-economic impact is described by multiple indicators. The indicators account for the various dimensions of each socio-economic impact [32,44,449,450]. Having consensus on clear indicators of the potential socio-economic impacts of bioenergy can help to formulate widely supported sustainability criteria and measure compliance [76]. This helps to promote the overall sustainability of bioenergy [67,76,451].

Socio-economic impacts of bioenergy are not equally distributed geographically. In order for an assessment to be able to include the variation in socio-economic impacts, it is important to consider the spatial level at which the impacts take place [44,95,452–454]. Assessing socio-economic effects at a high aggregation level can obscure regional variation in impacts, because the average for the whole area smoothens out the regional differences, making it impossible to consider the distribution of the effect [455,456]. In contrast, only zooming in on the effects of a specific bioenergy project in the production region would neglect the effects that occur outside the production area [90]. As nearby communities, the surrounding region, whole country or the rest of the world can be affected as well, this would miss a significant share of the potential socio-economic impacts. Furthermore, a focus on only the region with bioenergy ignores effects that are indirectly caused by bioenergy (e.g. reduced demand in sectors supplying to the fossil fuel industry) and the cumulative effects of multiple bioenergy projects in a country, such as effects on food prices. To be able to comprehensively capture the socio-economic impacts of bioenergy, potential effects need to be analysed at various spatial scales. Information on the spatial distribution of the socio-economic effects can help to avoid disproportionate occurrence of negative impacts in a specific area.

Ex-ante assessment of the socio-economic impacts of bioenergy requires the use of methods and models that translate scenarios and assumptions on bioenergy implementation to effects on the various indicators. The selection of a method or combination of methods is important for the quantification of the impacts as all methods have their specific strengths and weaknesses, which affect their ability and suitability to quantify the socio-economic indicators. Methods vary on aspects such as in the indicators that can be quantified, the inputs that are required, the inclusion of indirect effects, and the spatial scales that can be included. All this means the selection of a method can also affect the final outcome of an assessment [457]. An overview of the available methods for quantitative ex-ante assessment of socio-economic impacts at different spatial scales and an assessment of their suitability and ability are currently not available, but these are relevant to identify the blind spots of current methods and the associated knowledge gaps.

The shortcomings identified above hinder agreement on appropriate indicators of the socio-economic impacts of bioenergy at various relevant scales and the underlying methods for their quantification. Therefore, the aim of this paper is to map the status, limitations and options of improvements in quantitative research on socio-economic impacts of bioenergy. For this, we perform a literature review to identify relevant indicators, analyse the state-of-the-art of ex-ante quantification methods and tools, and assess their ability and suitability to assess these indicators at different spatial scales.

6.2 Methods

The approach for this literature review consisted of two parts. In the first part we selected relevant indicators of socio-economic impacts of bioenergy. In the second part we identified available methods and their ability and suitability to quantify the relevant socio-economic impacts at different spatial levels.

The first step was to make an overview of the socio-economic impacts of bioenergy. This was done based on previous reviews of sustainability criteria for bioenergy [44,46,462,67,73,75,434,458–461]. This overview made it possible to later cluster the indicators per impact and to potentially identify blind spots where no relevant indicators are available for an identified impact. We included all impacts that were mentioned at least in two different studies as the list was meant to be exhaustive, but not too disaggregated.

We considered indicators of socio-economic impacts of bioenergy relevant for ex-ante quantification if these reflect effects [5] of bioenergy are included in certification schemes or agreed upon in stakeholder consultation processes, and a numerical value can be assigned. Certification schemes and stakeholder consultations represent the indicators that public, policymakers, companies and other stakeholders see as most important [463]. To come to the list of relevant indicators, we made an overview of

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[5] This is analogous to the categorisation of Meyer *et al.* [104] who assessed the environmental indicators of bioenergy certification schemes. As some studies and certification schemes are designed to assess the sustainability of an ongoing project, these contain indicators that reflect properties of management or production (e.g. the availability of a management plan), rather than impacts of bioenergy.

all indicators of the socio-economic impacts of bioenergy that were identified in the previous step. This overview was based on the previously mentioned review studies, as well as the certification schemes and standards for good practice that were reviewed [32,439–442,446,464–467].

We merged similar indicators into one indicator to avoid duplication in slightly different form. To get from the long-list of indicators to the list of relevant indicators, we removed those indicators that did not meet the following criteria for relevance:

1) We removed the indicators that reflect an attribute of the bioenergy project, rather than an impact, conform Meyer *et al*. [104].
2) We removed the indicators that require a qualitative assessment.
3) We removed the indicators that were not included in a certification scheme or named by stakeholders in a stakeholder consultation process.

These steps are illustrated in Figure 6.1.

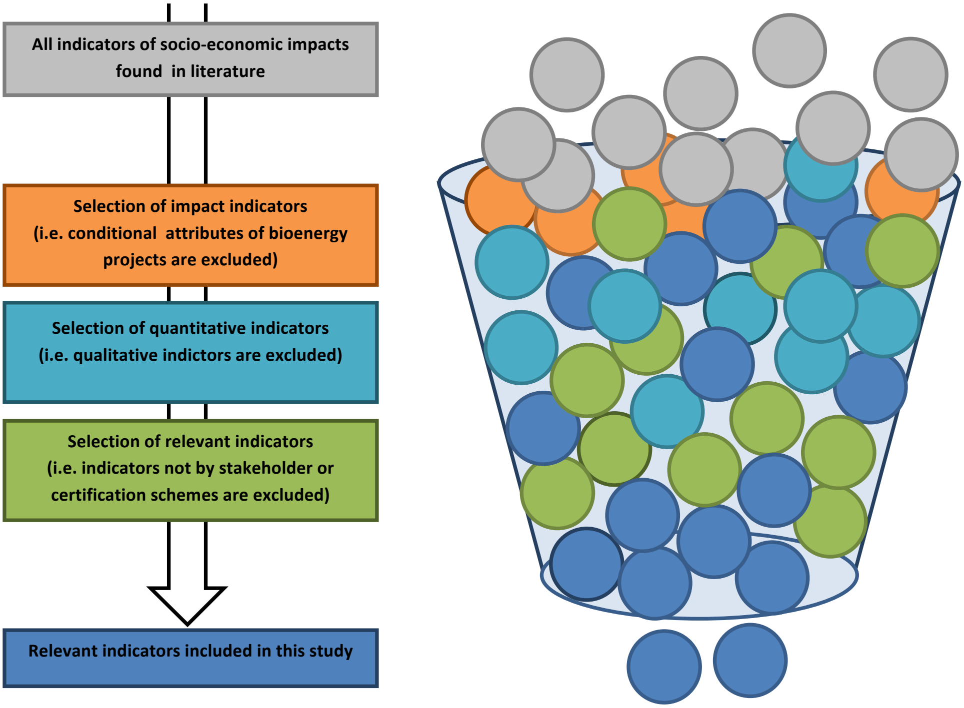

Figure 6.1 Funnel with three selection criteria in order to arrive at the list of relevant indicators of socio-economic impacts.

In the second part, we reviewed studies that ex-ante quantify socio-economic impacts of bioenergy in order to get an overview of available methods and tools that are and the spatial level at which these methods are applied. The studies quantifying one or more socio-economic impacts of bioenergy were selected using the search engine Scopus. We searched for studies in the scientific literature after 2014 in order to include only the most recent literature. As search terms we included the name of each impact and terms related to the list of relevant indicators (for a complete overview, see Table 6.3). We combined this with the terms "bioenergy", "biomass", "biofuel", "biodiesel", "ethanol", and "charcoal". This yielded around 400-2700 papers per impact category (see Table 6.3). If, we judged a paper from its title and abstract to not be related to our research, it was discarded from further examination. We then narrowed down the selection of sources by excluding all studies that did not focus on ex-ante assessment. From the remaining papers, we recorded the assessed indicators, the applied method and the spatial scale of the study. Based on the method and discussion sections of the selected studies and previous reviews studies, we then discussed the potential, limitations, strength and weaknesses of the methods, i.e. their suitability to ex-ante quantify the socio-economic impacts of bioenergy. This discussion also included opportunities to improve the ex-ante quantification methods.

6.3 Results

6.3.1 Relevant indicators

We identified 13 socio-economic impacts categories related to bioenergy: employment & income, food security, macroeconomic development, rural economic development, energy access, energy independence, economic feasibility, health & safety, land right, working conditions, social acceptability, equal opportunities, and community impacts. For these impacts we found 236 indicators that are mentioned in reviews, certification schemes and guides of good practice. Table 6.5 in the appendix gives an overview of all indicators. Of these 236 indicators, 46 are considered relevant, this means they reflect effects of bioenergy, are included in certification schemes or agreed upon in stakeholder consultation processes, and a numerical value can be assigned. We arrived at this list (see Table 6.1) by removing those indicators that either a) not reflect impacts (78), b) are not quantifiable (32) or c) that are not included in certification schemes or mentioned by stakeholders (80), as is illustrated in Figure 6.2. Table 6.1 gives an overview of the 46 indicators that are considered relevant.

The highest number of relevant indicators was found for employment & income, which has nine relevant quantitative indicators that provide insight in the effects on this impact category. These relevant indicators contain the whole spectrum of impacts: from the amount of jobs created and lost in other sectors to information who benefits from these jobs (e.g. local workers or migrants) and the income that is generated for the employees. The indicators for employment & income are also the indicators that are mentioned most in the literature sources, and are often mentioned as important by stakeholders (e.g. [32,468,469]), reflecting the prominence of this bioenergy impact. For food security effects the indicators reflect the four pillars of food security, availability, access, utilisation and stability that are identified by the FAO which means all aspects of the issue are included [322]. For the categories land rights, working conditions, economic feasibility, community impacts, energy access, and equal opportunities only two to four relevant indicators are identified, but in general there is high consensus on each of these indicators, illustrated by the large number of sources that include them. For health & safety four relevant indicators were identified, but none of these was named more than three times. Although macroeconomic impacts, rural economic development and energy independence are often mentioned as reasons to implement bioenergy, few relevant indicators are available and these are not mentioned often.

Social acceptability is the only impact category for which we did not find a relevant indicator as the indicators that have been found (e.g. commitment to ethical conduct [446], effective stakeholder participation [73,434], transparency [434,470]) are either qualitative or not included in a certification scheme or mentioned in a stakeholder consultation process.

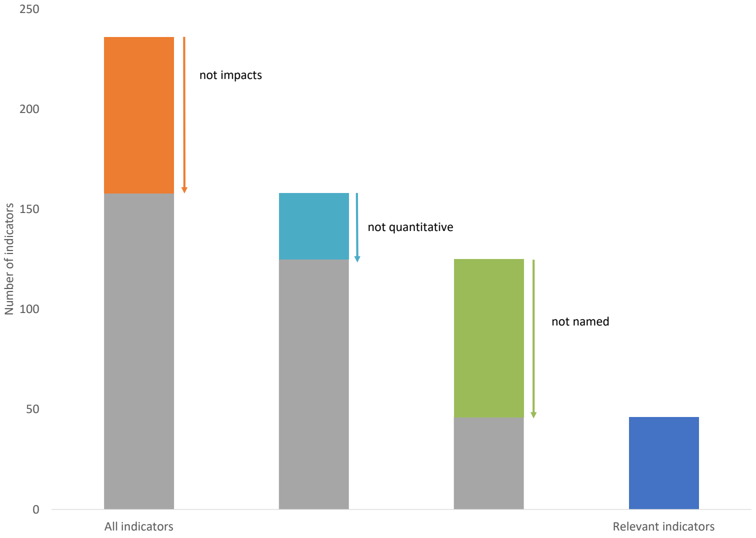

Figure 6.2 Selection process to come from the long-list of 236 indicators to the list of 46 relevant indicators.

Table 6.1 Overview of the relevant indicators for socio-economic impacts of bioenergy and the units in which these can be expressed. The certification schemes and stakeholder consultations in which the indicators are included, as well as previous studies that mentioned these indicators are prevented.

Impact category	Indicator	Unit	Stakeholder	Certification	Source
Employment & Income					
	Household income	€ dy^{-1}	[471] [e]	[439]	[33,64,84,434,439]
	Job loss of other activities	#		[439]	[33,439]
	Ratio between local/migrant workers	%		[464]	[44,460–462,464,472]
	Contribution of feedstock sales to household income	% / € dy^{-1}	[32] [b]		[32,44,73,470]
	Job creation (in the bioenergy sector or company)	# / # MJ^{-1} / fte / # ha^{-1}	[32,468, 469] [a,b]	[441,464]	[32,44,434,459,473] [46,64,441,464,470,472]
	Ratio permanent/temporary (casual/daily) jobs	%	[32]		[32,44,460,461]
	Ratio skilled/unskilled jobs and availability thereof	%	[32]		[32,44,459,461,473]
	Total wages in the sector	€	[468]		[44,473]
	Wage levels at bioenergy company, compared to minimum or median wage	% / € dy^{-1}	[32,469]	[441,446, 464,467]	[32,44,467,472,67,441, 442,446,461,462, 464,466]
Food security	Change in area of food crops	ha / %		[440]	[44,440]
	Change in calorie/nutrient deficit score	gr cap^{-1} day^{-1} / kcal cap^{-1} day^{-1}		[440]	[440,459,474]
	Change in yields of main staple crops	t ha^{-1}		[440]	[44,440]
	Lowest monthly calorie deficit / seasonality of hunger	kcal cap^{-1} dy^{-1}		[440]	[440]
	Price of national food basket	Δ% / Index / € /€ cap^{-1} dy^{-1}	[32,74] [c]		[32,44,73,440,459, 473,474]
	Supply of national food basket	t / % /kcal	[32,74]		[32,44,459,474]
Macroeconomic development	Change in GDP	€	[468]		[44,73,473]
	Sector contribution to GDP or GRDP	€ / %	[74]		[44,472,474]
	Trade volume	€ yr-1	[468]		[84,434]
Rural economic development	Gross value added	€ MJ^{-1} / %	[32]	[442]	[32,44,442,460]
	Change in share of people below the poverty line / number of poor people	Δ%	[74,468]		[33,44,64,73,474]
Energy access	Bioenergy to expand access to modern energy services	l yr^{-1} / MJ yr^{-1}/%	[32]	[464]	[32,44,73,464]
	Share of population that has increased access to energy	Δ %	[32]		[32,44,46]
Energy independence	Change in fossil fuel imports	MJ yr^{-1} / € yr^{-1} / t yr^{-1}	[74]		[46] [33]
	Energy diversity/diversification of the energy mix	(Herfindahl) index/ MJ bioenergy in TPES	[32]		[32,44,46,84]
	Change in consumption of fossil fuel and traditional biomass	MJ yr^{-1} / € yr^{-1}	[32]		[32,64]
Economic feasibility	Productivity / resource efficiency	t ha^{-1} / MJ ha^{-1} / € MJ^{-1}	[32,471]	[442]	[32,44,84,434,442,462]
	Capacity of infrastructure and logistics for distribution of bioenergy	# / MJ yr^{-1}	[32]		[32,33,64,439]
	Total investment	€	[471]		[44]
	Profitability (yearly, net present value, return on investment, payback period, internal rate of return)	€ yr^{-1} / € / % / year	[468,471]		[44,434,474]
Health & Safety	Crime rate	%		[439]	[73,439]
	Indoor wood cooking	Δ %		[440]	[33,64,440]
	Change in mortality and burden of disease attributable to indoor smoke	%	[32,470] [f]		[32,44]
	Risk of HIV/aids and other diseases	%		[439]	[73,439]
	Traffic safety	# accidents		[439]	[439]
Land rights	Expansion of biofuel feedstock over other crops	ha / %	[32]	[439]	[32,44,439,472]
	Loss of natural resources and grazing land	ha		[439]	[73,439]
	Number of land conflicts	#		[446]	[44,73,446,460,472,475]
	Share of land acquisitions that comply with formal or socially accepted procedure regarding absolute numbers and area	%	[469]	[446]	[44,73,441,446,459]

Working conditions	Number of work related accidents and health issues	# yr^{-1} per 1000 employees / time lost to accidents		[442]	[44,442,460,461,466]
	Incidence of occupational injury, illness and fatalities	# / % / # ha^{-1} / # MJ^{-1}	[32]		[32,44,472]
	Training and/or education provided to employees	% / # yr^{-1}	[32,468,471]	[465]	[32,44,73,460,461,464,465]
Equal opportunities	Change in unpaid time spent by woman and children in collecting biomass	hrs $household^{-1}$ $week^{-1}$	[32]	[440]	[32,44,440]
	Female participation (in a type of work, sector, company, management)	%		[441]	[44,441,461]
	Share of women wages comparted to men's	%	[468]	[441,464]	[44,67,441,464,472]
Community Impacts	Access to water supply	%		[439,440,446]	[73,439,440,446,462,466,472,474]
	Community investment	€		[464]	[44,464]

[a] The indicators that were used in the final indicator list of Vaidya & Mayer [471] were those supported by the stakeholders.
[b] GBEP [32] is a tool designed for stakeholders, therefore all indicators are included.
[c] Gaitán-Cremaschi et al. [468] determined the importance of issues based on a stakeholder consultation. Issues were considered important when at least 65% of the respondents rated it at least 4 out of 5 on a Likert scale.
[d] Manik et al. [469] the indicators with the highest weight were selected as relevant.
[e] The indicators considered as “most relevant” or “very relevant” in Van Dam *et al*. [74].
[f] From the study of Baudry et al. [470] those indicators were included that were named by at least half of the stakeholder groups.

6.3.2 Ability to quantify

In total, 218 studies were reviewed that contained an ex-ante quantification of relevant socio-economic indicators. As some studies quantified multiple indicators, we analysed in total 474 ex-ante quantifications of indicators. The indicator that is quantified the most is profitability, which is included in over 50 of the selected studies.

From the actual quantification of the indicators in the various studies (Table 6.4 in the appendix), we see the ability of the applied models to quantify macroeconomic impacts, employment & income and rural development is high: these impact categories are quantified most often and at almost all spatial levels. For the macroeconomic impacts a wide range of methods is available to quantify the four indicators (see Table 6.1 and Table 6.4); although most studies use input-output modelling in combination with other methods.

We did not find a study that ex-ante quantified the community impacts of bioenergy. Although the community impacts are not an attribute of company management, management has a strong influence on the outcome of this indicator. This means the uncertainty in an ex-ante assessment is very high, making projections of this indicator less valuable.

Other indicators that have not been found to be quantified are: ratio between local and migrant workers, ratio between permanent and temporary jobs (employment & income); seasonality of hunger (food security); capacity of infrastructure (economic feasibility); crime, indoor wood cooking, risk of HIV and other diseases (health & safety); education provided to employees (working conditions). For the impact categories rural development, equal opportunities and health & safety this means only two indicators are ex-ante quantified and for working conditions just one. For employment & income the lacking quantification of these two indicators means that two of the three indicators for the social distribution of employment are not quantified, with only the ratio skilled/unskilled employees being quantified. This indicates that the insight from the ex-ante quantification of employment and income impacts is currently not comprehensive.

Most indicators are quantified using a regional or national level method. There are exceptions to this. For example, profitability and total investment are almost only quantified at project level, as that is where these impacts occur and the method that is most often applied, i.e. cash flow analysis, is able to quantify the profitability at project level. Food prices and trade, in contrast, are mostly quantified at national or higher level although impacts range from local to global level [33]. This means lower aggregation level impacts are not well included in the current methods and geographic distribution of these effects have not been ex-ante quantified in the reviewed studies.

6.3.3 Suitability

In this section we discuss the suitability of the methods that have been applied most often for the ex-ante quantification of socio-economic impacts of bioenergy. A focus will be on the macroeconomic models (input output, computable general equilibrium models and partial equilibrium models), because studies employing a macroeconomic model either alone or in combination with other methods, cover almost the entire spectrum of socio-economic impacts (see Table 6.4 in the appendix). The suitability of the methods are evaluated based on the operation and the limitations of the method, the indicators it addresses, the spatial levels it can be applied at, and how the suitability of the method to ex-ante quantify socio-economic impacts of bioenergy can be further extended and improved by combining various methods.

6.3.3.1 Input output models

An input-output (IO) model consists of a static overview of all deliveries to and from each economic sector in a single geographic area; linking additional demand proportionally to extra production in all supplying sectors [254,260]. IO models are applied to calculate the socio-economic impacts of bioenergy because they can differentiate between direct, indirect and induced effects [6]; they are relatively easy to apply compared to CGE and PE models; and they are able to include multiple impacts [101,260,455].

Applied on national level, an IO model is generally used to determine the effect on GDP [101,260,483,484,455,476–482] or regional added value [455,478,480,484–488]. The IO approach can be extended to other socio-economic impacts by relating the economic activity in a sector to the socio-economic impact (e.g. employment per million dollar) [260]. Examples of this are job creation (e.g. [455,480,484,487,488]), job loss in other sectors [489], educational level [304], occupational accidents [490] and traffic safety [491]. To apply this method, sectoral data on these impacts are required. Such data can be provided by the social hotspots database [466], which contains sectoral data on socio-economic impacts that can be coupled to the outcomes of an IO model [304,445,466].

An IO model is based on the economic interactions between sectors specified in the social accounting matrix (SAM) for a specific area, meaning socio-economic impacts can only be calculated for that area and spatial level without interaction with the rest of the world. Multi-region IO models can broaden the scope of the IO approach to include the interaction between the sectors in various countries (e.g. [101]) or regions within a single country (e.g. [455,478]). This extension can help to identify where the effects of bioenergy materialise (e.g. where is employment increased) and show which activities generate economic activity elsewhere (i.e. cause the largest spill-over effect) [101,455,478,481,484,492]. The downside of the additional information on the distribution of the socio-economic effects over the different regions or countries, is the reliance on generally poor quality trade data and the effects of exchange rate dynamics [493].

A limitation of IO models is the time lag in the availability of the data. Due to the data intensity to produce SAMs and the infrequent updates, they are always a few years old when they are published. This means new developments, such as new or rapidly expanding sectors (e.g. bioenergy) and their interactions with other sectors, are not well covered. Furthermore, due to their static nature, IO models cannot endogenously incorporate technical progress (e.g. more efficient production methods) or structural changes to the economy [265,488]. Changing the technical coefficients of the model

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[6] direct effects are from the expansion of the bioenergy sector; indirect effects are those that occur as a result of additional economic activities in the supplying sectors, including the suppliers of the suppliers; induced effects are from spending the additional income that households earned from the direct and indirect activities [260,455]

can help to include technical change and thereby make the IO model more accurate and suitable to project socio-economic impacts [494]. Updating the technological coefficients can for example, show the effects of mechanisation in feedstock production on employment [455].

Although in practice additional demand for bioenergy leads to effects in other sectors through price dynamics, competition and substitution, this effect is not included in IO models [253,302]. This may result in overstating the size of the socio-economic impacts of bioenergy [302]. By linking the IO model to other models (e.g. CGE or land use) or using the outcomes of these models, the IO model can take into account price dynamics, competition and substitution effects. These other models can help determine the size [495,496] or regional distribution [455,485] of future bioenergy demand as input to the IO model [497]. This improves the quality and, when combined with a multi-regional IO model, the spatial detail of the calculated socio-economic impacts.

6.3.3.2 Computable general equilibrium models

Computable General Equilibrium (CGE) models are a type of macroeconomic models that include a global coverage [7] of all sectors of the economy and the economic interactions of supply, demand and competition between the sectors that lead to a state of equilibrium [498]. CGE models are applied for studying the socio-economic impacts of bioenergy because of their ability to include indirect effects, and their global scope matches the effect chain of bioenergy [128,372,499–502]. CGE models are most suitable for mid-term analysis, typically 10-20 years in the future.

For socio-economic impacts of bioenergy, CGE models are mostly applied to calculate change in GDP [97,313,507,508,372,404,501–506], price and supply of food [102,372,404,498,501–503,507,509], trade volume [498,501,502,505] and wages [372,502,503,505,507] as a result of bioenergy expansion (see Table 6.4). The effects that are calculated directly by the model are changes in price and production volume of economic sectors and the interactions between the sectors. CGE models are limited to monetary interactions that do not correspond well with physical volumes [128]. This means that for example food is only included by its monetary value, although the nutritional intensity (i.e. nutrients per $) can variate significantly. This leads to high uncertainty in results as it is difficult to assess indicators solely based on the monetary value of a sector, especially in aggregated sectors. A key other example is land use, for which the competition between bioenergy and other sectors is very important. To in-

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[7] disaggregated in multiple countries or continents

clude other effects (such as job creation) it is possible to use the same method as in an IO model, i.e. relating the impact to the economic intensity of a sector [407,503,510].

Most CGE models use data for the interaction between the various sectors, aggregated to national or higher level. As a result, the calculated effects do not account for variations in the socio-economic impacts on lower spatial levels. The same holds true for the sectoral aggregation; variation within sectors cannot be detected with a CGE model, even though there will also be winners and losers within a sector. In order to provide more detailed results, including the social or geographical distribution of effects, it is necessary to adapt the CGE models. Whereas most CGE models contain only one household for each region, it possible to derive household level results by splitting that single household into multiple households in a specific area [406,502]. By differentiating the households according to region, income [511,512], or location (urban/rural, [511]), additional information on the social and geographical distribution of the effects of bioenergy can be derived. Another option is to extend the analysis with microsimulations, an approach that does not rely on the disaggregation of the top-down SAM to various households, but uses the bottom-up data from a household survey to simulate the effects of e.g. price and income changes on thousands of different households [96,97,313,502]. This approach is well-equipped to show the distribution of the socio-economic effects for multiple households [513]. Using microsimulations impacts can be determined at household or local level and can include e.g. household income and the poverty rate [97,313,372,502].

CGE models are dynamic, meaning the relations between the sectors can change over time in response to changes in the economy, based on the models' elasticities [506]. Therefore, projections can include the effects of developing technology. However, as these effects are based on historic data, the adaptations to the model's elasticities are confined to what has happened historically. The time lag between the base year and publication year for SAMs is even longer for application in CGE modelling than for IO, as its production is a more data intensive process. Bottom-up technology assessment [514] or adaptations from the structure of the sector in other areas [512] can be used to include bioenergy expansion to new areas in a CGE model. However, this does not account for all structural changes to the economy in general and agriculture in particular. More sustainable production methods and potential for faster progress in the agricultural sector are not included in the CGE models, although these are important for sustainable bioenergy production, for example by limiting competition for land (e.g. [194,515]). Including the potential to reduce negative impacts, either via technology or policy interventions, in the CGE models would enable higher quality assessment of the sustainability impacts. For example for the effects on food security the competition for land plays a major role.

A basic assumption of CGE models is that economy tends to equilibrium. However this is a theoretical concept that does not exist in practice [510]. In addition, disregarding the adjustment path towards equilibrium, might mean overlooking periods of extreme food price volatility, food shortages or other potential negative effects of bioenergy in the short run [516]. The equilibrium assumption has implications specifically for the projections on employment, because labour is not a normal commodity [508,510]. This is because employees are not as easily transferred from one sector or region to another as capital would. Thus additional employment in a specific sector does not necessarily compensate for job losses in another sector or region [510]. This means unemployment from displacement of production (e.g. in the fossil fuel sector) is likely to be underestimated in a CGE model, especially in the short term because labour markets require time to adjust. These limitations have smaller impact, the longer the time-frame applied in the CGE model [128]. In addition, an option to address this issue is to distinguish different skill levels in employment and thereby make labour a less homogeneous good in the model [97].

Linking a CGE model to other types of models can help to overcome the lack of detail in the relations between the sectors in the global model. For example by linking a CGE to an energy sector model such as MARKAL [508], a biophysical model [372,517], a land use model [455,518] or detailed technical modelling of biofuel production chains [517], the modelling outcomes of the CGE can be more spatially explicit or better account for the variation within economic sectors, which is not included in the economic model itself.

6.3.3.3 Partial equilibrium

Partial equilibrium models (PE) are similar to CGE models, in that they also use the laws of supply and demand to establish a new equilibrium after an economic shock has been introduced. But, instead of the highly aggregation of all economic sectors that is used in a CGE model, only a limited number of sectors is included in a PE model, and these are represented in much more detail. Modelling of the sector or sectors that are included in the PE model is much more extensive, with many products and interrelations between the sectors included. PE models are typically used for longer-term analysis (up to 2050).

PE models are most commonly used to calculate the impacts on trade [519–527], food prices, and food supply [347,495,521,522,527–532]. Most studies present the results on national [495,508,530,531,533–536,519–526] or higher [347,496,527–529,532] spatial aggregation levels. The increased detail in the energy sector compared to CGE or IO models can help to provide projections on e.g. the role of bioenergy in the energy mix [524,537,538], change in fossil fuel imports [496,522,535,537] and changes in the use of traditional bioenergy [531,538]. In addition, a PE model can be adapted to include spatially explicit land use modelling, to reflect the competition between various land uses (e.g. [539]). As the competition takes into account local suitability, the projections of land use is more detailed than in a CGE model. PE models are for example use to project reduction in land for food production [529,536], or to determine where current agricultural land is replaced by bioenergy feedstock [534,535,540].

PE models include only a partial representation of the economy and assume fixed prices and income in other sectors (i.e. ceteris paribus). This means the socio-economic effects for the other sectors are not included. Although in reality, the effects of bioenergy are not limited to the few sectors that are included in the PE model. This problem can be partly mitigated by combining the global modelling of a CGE model with the detailed analysis of a PE model [508], or combining several PE models [527].

6.3.3.4 Bottom-up & process modelling

Bottom-up models are a heterogeneous group of various analytical and process models. The methods have in common that these start with a detailed representation of the relevant process interactions between inputs and outputs and that they do not contain explicit modelling of interactions outside the production chain, such as market-based effects [128,541,542].

Starting from the technical performance of the bioenergy supply chain and its energy and mass balance, the social-economic impacts are analysed. The technical model can then be used to project the total investment (e.g. [415,543–545]) and profitability (e.g. [546–548]) of a project. Some studies use special process modelling software such as ASPEN (e.g. [546,549]), or a spreadsheet model [546,550,551] to assist in the modelling and cost estimation. Using the share of labour in the total cost, or extrapolating the labour requirement can be used to estimate job creation at project level (e.g. [552–554]), the ratio between skilled and unskilled employees [553] and wages [555,556].

These bottom-up models are almost exclusively used for project level projections for the near future. Although the methods are rigorous and includes all aspects of the production process, they are not able to account for indirect effects of the investment on the rest of a region or country, neglecting the effects of competition and of additional production in the rest of the economy [259,457].

To be able to account for indirect effects, bottom-up modelling can be combined with macroeconomic modelling such as IO or CGE analysis [259,557]. In the latter case, also dynamic changes to the economy can be included. In such a combination of approaches, the detail of the analysis of the process modelling can be combined with the potential of the macroeconomic models to calculate indirect effects.

6.3.3.5 Cash flow analysis

Cash flow analysis is a method that makes an overview of all expected monetary incomes and expenditures and calculates the profitability, taking into account the opportunity costs and interest rates for capital. It is mostly used in combination with bottom-up and process modelling (e.g. [272,558–561]). It is relatively easy to use, and the method is transparent. Depending on the depth of the process modelling the data requirement can be low, although for new processes the availability can be low and the data itself uncertain. Cash-flow analysis is mostly applied at project level. Combining cash flow analysis with a Monte Carlo simulation can provide information on the uncertainties of the outcomes [562].

6.3.3.6 Social LCA

Another distinctive set of methods are life cycle assessment (LCA) and social LCA (sLCA) [93,563]. LCA is a standardised method that provides an inventory of all physical and energy input and output flows of a specific production process and calculates their environmental impacts. In the context of socio-economic impacts of bioenergy only the impacts relating to fossil fuel use and its reduction [564–566] and human health effects for employees [468] or the general public are relevant. An example is respiratory diseases caused by SO_2 and NO_x emissions from using biofuels in the transport sector [481,565,567,568].

Social LCA is an extension of the LCA framework that relates the input and output of a production process to social impacts instead of environmental impacts [93,569]. Not all studies quantify the impacts, but rather use a narrative to indicate the risk of negative impacts [93,466,569,570]. In the context of bioenergy, job creation [304,490,571], wages [304,490,571] and occupational accidents [304,490,571] have been ex-ante quantified using sLCA. The impacts are connected to the production chain, but as no region-specific data is available yet, the results present them without specification of the location [461]. (s)LCA focuses on a specific production system, with clearly defined boundaries. This means cumulative effects or indirect effects on other systems, for example arising from competition for land, are not included.

Some studies use a hybrid input-output (s)LCA approach [260,304,478,490,491,572,573]. Here the detailed modelling of the production system is replaced with the more general approach of IO modelling [563,574]. This sacrifices detail in the exact inputs and location of production and reduces spatial detail. However, it makes it possible to include indirect effects in a (s)LCA [574]. In addition, the process information that is gathered for the LCA can also be used as an input for the technical coefficients in the IO model.

6.3.3.7 Other methods

A few additional methods have been applied to ex-ante quantify socio-economic impacts of bioenergy. For impacts at a low spatial level, system dynamics models [476,575–577] and agent based modelling [578,579] have been applied. These types of models represent a bioenergy systems based on the actors and their interactions [580]. However, these are mostly applied to explore cases ex-post and explain the present state of a system, rather than project future responses. Spatially explicit methods (e.g. [455,581–583]) have mostly been applied in combination with macroeconomic models. In those studies the macroeconomic effects calculated using CGE or IO were translated to spatial effects using land use allocation methods (e.g [455]. To determine impacts at a global level, integrated assessment models [425,584–586] and biophysical [587] models have been applied, calculating mostly land use change effects that are especially relevant for food security. Game theory is relatively new and only one study has been found that used this approach in the context of socio-economic impacts of bioenergy, here to determine the trade impacts [588]. Game theory is generally applied to analyse situations of competition and cooperation and in this sense could be relevant to analyse the interactions between bioenergy and other agricultural sectors [589,590]. Also a number of studies applied different types of optimisation models [586,591,600–603,592–599], mostly as an extension to bottom-up/process modelling in order to determine the best achievable outcome. These models can be used to explore the socio-economic effects in an optimal situation [601].

6.4 Discussion/Conclusion

Socio-economic impacts are an integral aspect of the sustainability of bioenergy. They preferably require ex-ante quantification to enable informed decision-making in order to stimulate the development of sustainable bioenergy. This study systematically reviewed the state-of-the-art in ex-ante assessments of socio-economic impacts of bioenergy. Based on a review of previous studies, guidelines of good practice and certification schemes, we identified and analysed the relevant indicators and the ability and suitability of methods to quantify these indicators at various spatial levels. The review showed gaps and limitations in the ability to ex-ante quantify the relevant indicators of socio-economic impacts of bioenergy at the specific spatial levels at which these impacts occur. The gaps identified in this study are discussed in more detail below (section 6.4.1). This is followed by the main conclusion in section 6.4.2.

6.4.1 Gaps and limitations

Ex-ante quantification for social acceptability and community impacts has not been found, but most other socio-economic impacts of bioenergy are ex-ante quantified. The review showed that for most socio-economic impacts of bioenergy relevant indicators and methods to ex-ante quantify them are available. However, for social acceptability no relevant indicator was found and for community impacts no ex-ante quantification methods for the indicators were found. This is likely a result of the importance of the local context and the performance within (local) projects [44,62]. As this may play a large role in the effects of bioenergy on this indicator, the uncertainty of a projection would be large.

Although these impacts are not quantifiable, it does not mean these should not play a role in decision-making processes. However, neither of these impacts has attracted enough support during stakeholder consultations, even where the subject has been explicitly addressed [468,469,604]. Only in Dale et al. [66], public opinion has relatively modest support as a sustainability indicator that stakeholders want to see included in decision-making.

One important aspect in the quantification of socio-economic impacts is the inability to include the social context in ex-ante quantitative models. Together with aspects that can be included in the models, such as the biophysical situation, economic situation, technological and feedstock choice, the social context also influences the magnitude and importance of the socio-economic impacts of bioenergy [44,107,605]. The social context contains aspects such as the cultural norms, strength of government and the local institutions [98,106,319,606,607]. These factors influence which sustainability criteria are set for bioenergy production, and their enforcement [106,107]. Although many certification schemes demand compliance with local laws, for example for land acquisition or labour rights, for countries with weak legal frameworks or low demands in these areas, this will not lead to positive effects for the population [106,319,608]. Integrating this social context in ex-ante modelling is a challenge. For models that are calibrated to historic data, such as CGE, PE and land use models, the effects of the social context are implicitly included. During the model calibration phase, the model is benchmarked and adapted to reflect past outcomes [539,609]. The real-life data (as opposed to model outcomes) to which the models are calibrated, indirectly reflect the choices that people made within their respective social context. As a consequence of adapting the models to fit these actual outcomes, the elasticities, that represent the market responses to changes, reflect these choices. However, the effectiveness of a calibration procedure depends on the availability of high quality datasets for the calibration of the model [91,302]. Therefore, future work in the form of monitoring of e.g. agricultural performance is needed to improve data availability and model outcomes. This data can also help to better include technological progress in the models.

Qualitative information (e.g. opinions of people) can be included in quantitative models by aggregating the information. For example, qualitative information such as personal opinion can be converted to quantitative information by counting the number of people that share that opinion. This conversion to quantitative information makes it possible to include this qualitative information as a variable in a model. An example where this is used is in agent-based modelling, where actor preferences are modelled as a dependent variable based on changes in their environment such as characteristics of the agent and changes in biomass cost [610]. Agent-based modelling can be used to explicitly include the social context when assessing the socio-economic impacts of bioenergy [611].

In the context of the environmental performance of bioenergy, Davis et al. [63] apply the term management swing potential to indicate how much impact management can have on the environmental impacts of bioenergy. It can be hypothesised that the management swing potential for socio-economic impacts differs between various impacts, depending on the importance of the management compared to biophysical and social context factors on the specific socio-economic impacts [44,64]. For the socio-economic impacts where the management swing potential is relatively large, making projections becomes more difficult. This can be partly overcome by varying potential management strategies using scenario analysis to reflect the range in outcomes. This may also be applied to make projection on community impacts, for which no other quantification methods were found.

Indirect effects are not always captured by the models. As some of the most prominent impacts of bioenergy are indirectly caused by bioenergy (e.g. food security), it is important to consider these indirect effects when analysing the socio-economic impacts of bioenergy. However, only few methods are able to include these indirect effects. As the indirect effects are often the result of competition or substitution between economic sectors in the model, macroeconomic models can include effects outside the bioenergy sector. However, as the spatial detail of these macroeconomic models is relatively low, the indirect impacts are determined at a higher aggregation level. This means that the impacts are not specifically calculated at the low spatial level where these impacts occur. Inclusion of multiple households in these models or lower aggregation level analysis would be required to increase this level of detail (see also Figure 6.3).

Additionally, not all socio-economic impacts that can be quantified by the methods are actually presented as results in the studies. For example, IO studies that present the net employment effects of bioenergy can also calculate the job loss in other sectors [455,489]. However, this is often not included, missing this important indirect effect. Another example of indirect effects that are not presented by the studies are the health and safety aspects of indoor smoke resulting from use of traditional bioenergy. Increasing household income leads to switch to other fuel sources [612,613] and thereby to better indoor air quality and lower health impacts [614,615]. Other aspects that are linked to income are the time spent by women gathering fuelwood [616,617]. These aspects are not directly included in studies on bioenergy use, but by explicitly linking these impacts to the income effects of bioenergy this would become possible.

A key blind spot in terms of availability of ex-ante quantification is the lack of methods to assess the local effects of bioenergy on food supply and price. Smith and Bustamante [33] showed food security impacts of bioenergy range from local to global. However, to our knowledge no local or household level assessment of the effect of bioenergy on the availability or price of food has been published so far. The only sub-national food security impacts that were found to be structurally ex-ante quantified are effect on agricultural land use [575,582,618,619]. Although this is a useful proxy to show impacts of bioenergy on food availability, it does not include the effects of additional income or a potential switch to a higher yielding crop. As no low aggregation level ex-ante quantification has been found, it is hard to assess the distribution of the food security effects of bioenergy at a lower aggregation level.

Current methods for ex-ante assessment of socio-economic impacts of bioenergy can provide more information than what is currently obtained, but more work remains necessary to include the effects on all relevant spatial levels. From the review that was performed in this paper, it appears not all socio-economic effects of bioenergy are so far ex-ante quantified at the spatial levels where the impacts occur. However, the analysis can be extended beyond what has already been done. Analogous to the work of Wicke et al. [128], here we show how a combination of different methods can be applied to extend the analysis of the socio-economic impacts of bioenergy beyond the current state of the art. Here we address the blind spots in the assessment of the geographic distribution and illustrate how the distribution of the food security impacts of bioenergy can be determined for a specific case.

The six relevant indicators of food security that have been identified in section 6.3.1 are area of food crops, food prices, food supply, calorie/nutrient deficit score, yields of main staple crops, lowest monthly calorie deficit/seasonality of hunger. The connections between the models that can help to ex-ante quantify these impacts on a low spatial aggregation level are discussed below and illustrated in Figure 6.3. This also shows on which spatial level each of the pillars of food security is quantified (Figure 6.4).

Scenarios for socio-economic development at macro level (population, global economic growth, etc. [425]) and the bioenergy demand for which the food security effects are to be assessed are the starting point for the analysis of the food security impacts of bioenergy on household level. A macroeconomic model (1, in Figure 6.3) such as a CGE or PE model (e.g. [268]) can account for the dynamics in demand and supply of all sectors that change in response to the bioenergy demand. This includes the indirect effects in the rest of the economy of this increased bioenergy demand. The economic dynamics that are included in the macroeconomic model lead to national or higher-level projections on the development in food demand, supply and prices as well as information on household income. In order to gain insight in the distribution of these effects, a disaggregated macroeconomic model (2) can be used (e.g. [406]). The use of a macroeconomic model with sub-national sectors enables the inclusion of the selected household types in the economic dynamics of the model[8]. Disaggregation to household types for specific regions or income groups can provide information on the distribution of the food security effects within a country.

The land use of each crop that is determined in the macroeconomic model can be spatially disaggregated using a land use allocation model (5) that is able to operate at the desired spatial level (e.g. [134,187]). Inputs for the land allocation model are maps on the current land use and infrastructure, information on local suitability and yields, for example from biophysical model (4), and the total land demand in the future scenarios. The biophysical models use information on climate, local conditions and technological

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[8] In chapter 5 of this thesis a case is presented where the food security impacts of bioenergy in Ghana are disaggregated to rural and urban households. This is comparable to part 1-3 from Figure 6.3.

development and intensification to determine the suitability and potential yields in each location (see e.g. [165]). The outcomes of the land allocation model can be used to determine the land use in the regions of the disaggregated macroeconomic model. Integrating the macroeconomic model and the land allocation model can create the opportunity to include feedback mechanisms between the economic demand for land and the physical supply. In addition, this can help to better project yield development and competition for land between various agricultural demands by including both biophysical and economic dynamics that determine yield development. Specific local conditions can be factored in the cost structures for agriculture or bioenergy conversion in the macroeconomic model using bottom-up technology projections (6) that are dependent on e.g. local prices, management practices and yields (e.g. [514]).

A nutritional module (3) added to a CGE model, for example through post analysis [407] or microsimulations [620], can project the consumption changes resulting from changes in income, prices, and production. Combining these model outputs with information on the energy and nutrient content of the food products can then give the household calorie and nutrient consumption. Comparing this to the recommended nutrient and energy intake gives the deficit in food consumption. The seasonal variation in calorie intake can be determined in an uncertainty analysis (7), where the information on the total food supply, in combination with household survey data and for example Monte Carlo simulations are used to determine the likelihood of the food supply dropping below the required level.

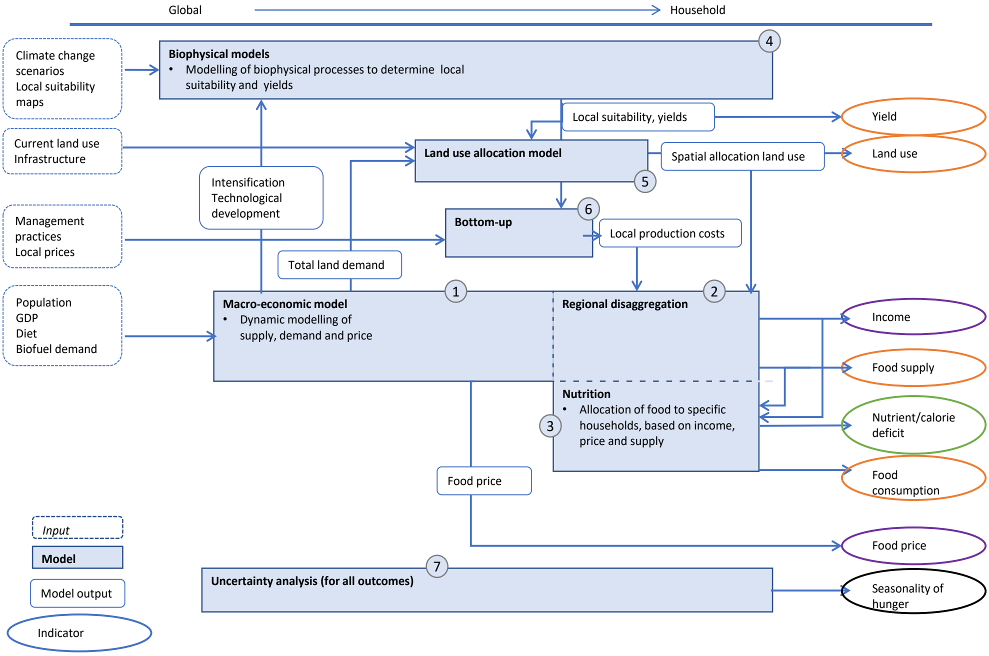


Figure 6.3 Model collaboration in order to overcome the identified blind spots of food security impacts on low aggregation level. A macroeconomic model (e.g. CGE) accounts for the global context, dynamics and (indirect) interactions (1). This information can be disaggregated to a lower level (2) for example by distinguishing multiple households within the country, and used to determine the effects on food consumption and nutrition (3), based on the changes in income, prices and production. The local context is included through a link with a land use model (4) that provides spatial explicit allocation of the land use. A bottom-up model can be used to determine local agricultural and bioenergy processing costs, which can be converted to cost structures to be used in the macroeconomic model, for example by including local input prices and management practices. The land use allocation is dependent on the local conditions such as the current biophysical conditions (4). To account for the seasonal variation uncertainty analysis (7) can be applied to provide information on the variations in food supply throughout the year. The colour of the indicators on the right had-side of the figure relate to the pillars of food security: availability (orange), access (purple), utilisation (green), and stability (black). The levels at which the pillars can be ex-ante quantified is presented in Figure 6.4.

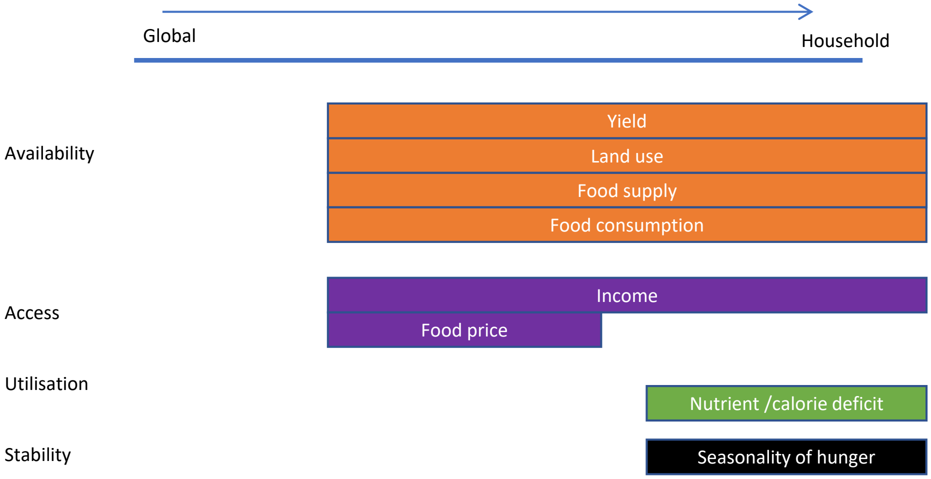


Figure 6.4 Aggregation level at which food security indicators can be ex-ante quantified, following the description in Figure 6.3. The indicators are classified based on the four pillars of food security (availability, access, utilisation and stability) as defined by the FAO [322].

6.4.2 Final remarks

The ex-ante quantification of the socio-economic impacts of bioenergy is important for the sustainability of bioenergy. This is because it can help to present the socio-economic effects in a transparent and objective manner, providing insight into the trade-offs between the positive and negative impacts. Based on lessons learnt from the review of the state of the art of ex-ante quantification of socio-economic impacts of bioenergy there are some final remarks.

In order to be able to present a comprehensive ex-ante assessment of the socio-economic impacts of bioenergy, more efforts need to be made to improve the quantification of those indicators relevant indicators for which no quantification method has been found yet. This may require development of new methods, or as is illustrated for food security in Figure 6.3, collaboration of already existing methods to provide insight in the distribution on lower aggregation levels. Another option is to explore indicators that can be ex-ante quantified and can be used as a proxy for the missing indicator.

Extending the analysis to a lower spatial aggregation level in order to show the distribution of the socio-economic impacts is not yet feasible for most cases as data is not available. As the most likely option to ex-ante assess the socio-economic impacts of bioenergy at a lower spatial aggregation level is to use a CGE, PE or IO model, or a combination of these, timely availability of social accounting matrices is required. Disaggregated models are only available for specific situations. The data intensity makes it unfeasible to disaggregate a macroeconomic model for each specific study. For low aggregate spatial levels, high-quality data is difficult to obtain and depends on the quality of the data collection. In countries with a large informal economy and few resources for the gathering, the data collection is more difficult and data quality is often lower. But these countries are also the most likely to be confronted with negative impacts of bioenergy, which is why it is even more important to have high quality data and ex-ante assessment of socio-economic impacts. This need for better quality data is also extended to technological development that is only included in models with a delay, but can have significant effects on the socio-economic impacts of bioenergy.

Also, the availability of spatial land use information is crucial. Land use dynamics are important to determine the competition for land and other resources. Land use allocation can be a way to increase the spatial detail of the socio-economic impacts (e.g. [455]), but it depends on the availability and the quality of spatial data of current land use and local suitability in order to be able to properly model the land use dynamics [518].

Ex-ante assessment of the socio-economic impacts of bioenergy is important as it can help to promote positive impacts and avoid production where negative impacts dominate. This does not mean certification becomes unnecessary as it remains equally important to verify the actual production practices that are applied by producers.

6.5 Appendix

Table 6.2 Socio-economic impact categories connected to bioenergy.

Impact category	Scale of impacts [33]
Employment & income	Local to regional
Food security	Local to global
Macroeconomic development	Local to national [a]
Rural economic development	Local
Energy access	Local
Energy independence	Local to national
Economic feasibility	Local to national
Health and safety impacts	Local to national
Land rights	Local to global
Working conditions	Local to national
Equal opportunities	Local to national
Social acceptance	n/a
Community impacts	Local to national

[a] [33] only includes increase in economic activity and market opportunities, but disregards e.g. trade.

Table 6.3 Search terms in Scopus and number of hits for that search term. For each query was the combination of the bioenergy search term combine with the specific search term for that impact category.

Impact category	Search terms	Results
Bioenergy (this term was used for each search and combined with the terms below)	TITLE-ABS-KEY (bioenergy OR biofuel OR ethanol OR biodiesel OR biorefinery OR biomass OR charcoal) AND TITLE-ABS-KEY (model OR project OR predict OR modelling OR scenario OR ex-ante) AND PUBYEAR > 2014	
Employment & income	TITLE-ABS-KEY (employment OR job OR wage OR salary OR income OR socio-economic)	639
Food security	TITLE-ABS-KEY (“food security” OR food OR “staple crops” OR calorie OR nutrient OR basket OR hunger OR malnutrition AND access OR supply OR price OR volatility OR area)	1429
Macroeconomic development	TITLE-ABS-KEY (GDP OR trade OR import OR government)	1166
Rural economic development	TITLE-ABS-KEY ((rural AND development) OR community OR gini OR equality OR smallholder)	2624
Energy access	TITLE-ABS-KEY ((energy AND access) OR (modern AND energy) OR electrification)	367
Energy independence	TITLE-ABS-KEY ((energy AND security) OR (fuel AND imports) OR (energy AND mix) OR (energy AND independence))	514
Economic feasibility	TITLE-ABS-KEY (npv OR roi OR pbp OR irr OR (economic AND feasibility))	465
Health and safety impacts	TITLE-ABS-KEY (smoke OR cooking OR HIV OR traffic OR crime)	930
Land rights	TITLE-ABS-KEY ((land AND rights) OR (crop AND expansion) OR (suitable AND land))	511
Working conditions	TITLE-ABS-KEY ((working AND conditions) OR injury OR safety OR union)	1930
Equal opportunities	TITLE-ABS-KEY (wom?n OR female OR gender OR discrimination OR equal)	2472
Community impacts	TITLE-ABS-KEY (stakeholder OR acceptance OR community)	2679

Table 6.4 Methods for ex-ante quantification of socio-economic impacts on the various spatial levels. The numbers relate to the number of studies that have been found to ex-ante quantify the indicators at a specific spatial level. The relevant indicators that have not been found to be ex-ante quantified are not included in this table.

			Disaggregation level						
Impact category	Indicator	Methods	project	household	local	regional	national	continental	global
Employment & income	Household income	bottom-up/process modelling	1			1			
		cfa		2			1		
		CGE		1			5		
		CGE; microsimulations		1					
		IO		1		1			
		IO; PE		1					
		optimisation		1					
		PE		1			4		
	Job creation	bottom-up/process modelling	8		2	3	2		
		CGE				1	5		
		CGE; PE					1		
		IO	6		2	10	8	1	
		IO; sLCA				1	3		
		IO; system dynamics					1		
		optimisation	1				2		
		PE					2		
		PE; IO						1	
		sLCA	1				1		
		system dynamics			1				
	Job loss	IO				1			
	Ratio skilled /unskilled jobs	bottom-up/process modelling	1						
		CGE					1		
		IO; sLCA					1		
	Total wages in the sector	bottom-up/process modelling	1				1		
		cfa	1						
		CGE				1	4		
		IO			1	2	2		
		IO; sLCA					2		
		IO; system dynamics					1		
		LCA; cfa	1						
		optimisation	2						
		sLCA	1						
Food security	Change in area for food crops	CGE					1		
		biophysical							1
		bottom-up/process modelling	1			1	2		
		PE					1	1	
		system dynamics			2				
	Change in calorie nutrient score	IAM						1	
	Food price	PE					5	3	1
		CGE				1	4	1	
		IAM						1	1
	Food supply	PE						2	

		PE; IO					1		
		CGE			1		4	1	
		CGE; microsimulations					1		
		IAM						1	
		biophysical							1
Macroeconomic development	Change in GDP	bottom-up/process modelling					3		
		cfa					1		
		CGE				1	14		
		CGE; PE					1		
		IAM						2	
		IO			1	5	9		
		IO; LCA				1			
		IO; system dynamics					1		
		PE					2		
		PE; IO						1	
	Sector contribution to GDP	CGE					4		
		IO					2		
	Trade volume	bottom-up/process modelling					3	1	
		CGE					3	1	
		equilibrium					1	1	
		game theory						1	1
		IAM						1	
		IO				1	2		
		PE					8	1	
		system dynamics					1		
Regional development	Poverty rate	CGE					3		
		CGE; microsimulations		1			2		
	value added	bottom-up/process modelling			1				
		CGE				1			
		IO	3		2	5			
		PE				1			
Energy independence	Change in fossil fuel imports	bottom-up/process modelling			1				
		CGE					2		
		IAM							1
		PE				1	2		
		PE; IO						1	
	Change in traditional biomass and fossil fuel use	bottom-up/process modelling	4	2			5		
		CGE				1	2		
		IAM						1	
		IO				1			
		LCA	2		1	1	1		
		optimisation			1		1		
		PE				1	1		
	Energy diversity	IAM							1
		IO						1	
		optimisation			1				
		PE				2	1		
		system dynamics					2		
Land rights	Expansion of biofuel feedstock over other crops	optimisation				1	1		
		PE			1		2		
		bottom-up/process modelling	1				2		
	Loss of grazing lands	bottom-up/process modelling					1		

		PE					1		
Economic feasibility	Profitability	agent based modelling	1						
		bottom-up/process modelling	17				1		
		bottom-up/process modelling; cfa	17			1			
		cfa	31	1		1			
		cfa; montecarlo	2						
		IO				1	1		
		LCA; cfa	1						
		optimisation	2		1	1	1		
		system dynamics					1		
	Resource efficiency	bottom-up/process modelling	2						
		LCA	1				1		
	Total investment	bottom-up/process modelling	6						
		bottom-up/process modelling; cfa	4						
		cfa	2						
		CGE					1		
Energy access	Access to energy	bottom-up/process modelling	1						
		optimisation		1					
	Access to modern energy	bottom-up/process modelling	1				1		
		optimisation		1					
Equal opportunities	Time spent collecting biomass	bottom-up/process modelling	2						
	Female participation in the workforce	IO; sLCA					1		
		optimisation		1					
Health & safety	Exposure to indoor smoke	bottom-up/process modelling		1					
		optimisation		1					
	Traffic safety	agent based modelling			1				
		bottom-up/process modelling	1		2				
		IO				1			
	Use of wood for cooking	bottom-up/process modelling	1						
Working condition	Occupational accidents	IO; sLCA					2		
			1						

CGE = computable general equilibrium; IO = input-output; PE = partial equilibrium; LCA = life cycle assessment; sLCA = social LCA; cfa = cash flow analysis; IAM = integrated assessment modelling;

Table 6.5 Overview of all found indicators of socio-economic impacts of bioenergy. An x in the column stakeholder means the indicator has been found to be important in an stakeholder consultation. The x in the column certification means the indicator has been used in a certification scheme.

Issue	Indicator	Unit	Stake-holder	Certifi-cation	Ql/ qn	Source
Employment & Income	Adequate standard of living	-			ql	[73]
	Average wage at company / income	€			qn	[44,460,461]
	Change in employment rate	%			qn	[73,459,473,475]
	Change in income	Δ € mth^{-1}			qn	[44,459]
	Comparison wages in the biofuel company to comparable sector/national average	€ mth^{-1}			qn	[44]
	Contribution of feedstock sales to household income	% or € yr^{-1}	x		qn	[32,44,73,470]
	Employment in the bioenergy sector as% of unemployment	%			qn	[44]
	Household income	€ dy^{-1}	x	x	qn	[33,64,84,434,439,471]
	Job creation (in the bioenergy sector or company)	# or # MJ^{-1} or fte or # ha^{-1}	x	x	qn	[32,33,469,470,472,473, 44,46,64,434,441,459, 464,468]
	Job growth rate	%			qn	[44]
	Job loss of other activities	#		x	qn	[33,439]
	Jobs created in industry	#			qn	[46]
	Jobs created in rural areas	#			qn	[46,474]
	Net jobs creation per hectare	# ha^{-1}			qn	[44]
	Purchasing power	€			qn	[44]
	Rate of recruitment	% new employees per year			qn	[461]
	Ratio between local/migrant workers	%		x	qn	[44,460–462,464,472]
	Ratio permanent/temporary (casual/daily) jobs	%	x		qn	[32,44,460,461]
	Ratio skilled/unskilled jobs and availability thereof	%	x		qn	[32,44,459,461,473]
	Salary variation compared to crop price development	-			qn	[44]
	Total wages in the sector	€	x		qn	[44,468,473]
	Wage levels at bioenergy company, compared to minimum or median wage	% or €	x	x	qn	[32,44,467,469,472,67, 441,442,446,461,462, 464,466]
	Wages at farm compared to traditional activities (like charcoal making, food production)	%			qn	[44]
	Wages for fixed jobs	€			qn	[73]
	Wages for temporal workers	€			qn	[73]
Food security	Amount of edible raw material diverted into bioenergy production	T yr^{-1}			qn	[33,44,64,460]
	Availability of main staple crops	t yr^{-1}			qn	[44,64]
	Change in access to food due to bioenergy	?			qn	[33,44,64,73,474]
	Change in area of foodcrops	ha or %		x	qn	[44,440]
	Change in calorie/nutrient deficit score	gr or kcal cap-1 day^{-1}		x	qn	[440,459,474]
	Change in food price volatility	%			qn	[33,64,434]
	Change in perception by people affected by bioenergy production regarding food security / Food security negatively impacted and discussed with stakeholders	-		x	ql	[44,460,465]
	Change in prices of 5 main staple crops	€ t^{-1}			qn	[44,459]

	Change in share of households income spend on food	%			qn	[44]
	Change in time spend on food production	Δhrs			qn	[44,73]
	Change in undernourishment	%			qn	[44,466]
	Change in yields of main staple crops	T ha^{-1}		x	qn	[44,440]
	Competition for labour	y/n			ql	[44]
	Income spent on basic needs	%			qn	[44,460]
	Land converted from (staple) food crops for bioenergy feedstock production	ha			qn	[44,460]
	Lowest monthly calorie deficit	kcal cap^{-1} day^{-1}		x	qn	[440]
	Malnutrition	%			qn	[459]
	Number of people that became food insecure	# or %			qn	[44]
	Price of national food basket	€ t^{-1} or % or \$ cap^{-1} day^{-1} or Δ%	x	x	qn	[32,44,73,74,440,459, 473,474]
	Supply of national food basket	€ t-1 or %	x		qn	[32,44,74,459,474]
	Risk of hunger	y/n			ql	[459]
	Time spend on biofuel activities by family labour (compared to time spend on own food production)	hour			qn	[44,439,460]
	Wage level sufficient to buy food and other household needs	y/n		x	ql	[44,73,439,446]
Macro economic development	Bio products exported as percentage of total worldwide production of the same bioenergy feedstock or product or of total exports	%			qn	[44]
	Change in animal-based net trade	€ yr^{-1} or t yr^{-1}			qn	[473]
	Change in cropland-based biomass net trade	€ yr^{-1} or t yr^{-1}			qn	[473]
	Change in cropland-based biomass product net trade	€ yr^{-1} or t yr^{-1}			qn	[473]
	Change in fish and fish product net trade	€ yr^{-1} or t yr^{-1}			qn	[473]
	Change in forest products	€ yr^{-1} or t yr^{-1}			qn	[473]
	Change in GDP	€	x		Qn	[44,73,468,473]
	Change in wood net trade	€ yr^{-1} OR t yr^{-1}			qn	[473]
	Contribution to technology development	y/n			ql	[73,472]
	Development of trade balance / terms of trade (price of exports/ price imports)	Ratio			qn	[84,434]
	GDP per capita	€ cap^{-1}			qn	[44,475]
	Sector contribution to GDP or GRDP	€	x		qn	[44,74,472,474]
	Taxes/royalties paid to the government / Amount of government revenue collected from the bioenergy sector	€			qn	[44,460,470]
	Technology development	-			ql	[33,64]
	Trade volume	€ yr-1	x		qn	[84,434,468]
	Value of industrial inputs in the bioenergy sector	€			qn	[44,84,460]
	Value of the sector (revenue or turnover)	€			qn	[44,473]
Rural economic development	(Change in) smallholder income/ paid to smallholders and suppliers	Δ € yr^{-1} or € ha^{-1} or € t^{-1} or €			qn	[44,46,460]
	(Share of total regional) investments by biofuel project	€ or %			qn	[44]
	Change in forest products	%			qn	[473]
	Change in real wood prices	%			qn	[473]
	Change in share of people below the poverty line	Δ%			qn	[33,44,64,73,474]
	GDP per capita compared to national average	%			qn	[44]
	Gini coefficient (or compared to national average) / L-Theil index / distribution of income	Index (or %)			qn	[33,42,44,73,459,474,475]
	Gross value added	€ MJ^{-1} or %	x	x	Qn	[32,44,442,460]

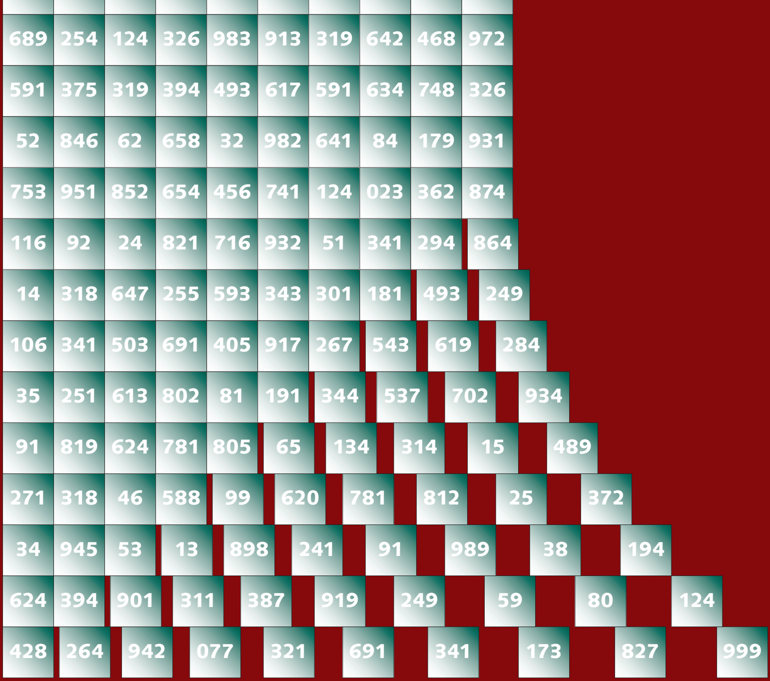
	Investment in the sector	€			qn	[44]
	Regional unemployment rate compared to national average	%			qn	[44]
	Sector contribution to agricultural GDP	%			qn	[44]
	Share of feedstock that originates from smallholders and outgrowers	%			qn	[33,44,46,73,460,462]
	Share of income by smallholder/large companies	%			qn	[44,466]
	Total investment in bioenergy infrastructure over the past decade	€			qn	[44]
	Volume of bioenergy production by business model (large plantation vs smallholders)	t			qn	[44]
Energy access	Bioenergy to expand access to modern energy services	L yr^{-1} or MJ yr^{-1} or %	x	x	qn	[32,44,73,464]
	Households with access to electricity grid	%			qn	[42]
	Share of population that has increased access to energy	%	x		qn	[32,44,46]
Energy Independence	Change in consumption of fossil fuel and traditional biomass	MJ yr^{-1} or € yr^{-1}	x		qn	[32,64]
	Change in fossil fuel imports	MJ yr^{-1} or € yr^{-1} or ktoe yr^{-1} or t yr^{-1}	x		qn	[33,46,74]
	Change in petroleum production	ΔMT			qn	[434]
	Change in ratio of fossil fuel inputs to amount of useful energy output	MJ/MJ			qn	[434]
	Energy diversity/diversification of the energy mix	(Herfindahl) index or MJ bioenergy in TPES		x	qn	[32,44,46,84]
	Energy security premium	\$ l^{-1} biofuel			qn	[434]
	Fuel price volatility	SD of monthly percent price changes over one year			qn	[434]
Economic feasibility	Actual growth rate	%			qn	[462]
	Availability of long-term management plan	y/n		x	ql	[446]
	Capacity of infrastructure and logistics for distribution of bioenergy	#, MJ yr^{-1}	x		qn	[32,33,64,439]
	Company turnover	€			qn	[44]
	Competitiveness of biofuel compared with alternatives such as fossil diesel	Δ €l^{-1}	x		qn	[44,470]
	Cost of feedstock conversion compared to other alternatives	€ GJ^{-1}			qn	[44]
	Cost of feedstock production compared to other alternatives	€ GJ^{-1}			Qn	[44]
	Feedstock price	€ t^{-1}			qn	[33,44]
	Labour costs	€ t^{-1}			qn	[44]
	Net energy balance	ratio	x		qn	[32]
	Product selling price	€ or Δ €l^{-1}			qn	[44]
	Production costs	€ MJ^{-1}	x		qn	[44,460,470,474]
	Productivity / resource efficiency	t ha^{-1} or MJ ha^{-1} or t ha^{-1} yr^{-1} or € MJ^{-1}	x	x	qn	[32,44,84,434,442, 462,471]
	Profitability (yearly, net present value, return on investment, payback period, internal rate of return)	€ yr-1 or € or % or year %	x		qn	[44,434,468,471,474]
	Revenue per ha from bioenergy crop compared to revenues of other crops	€ ha^{-1}			qn	[44]
	Total project investment	€			qn	[44]
	Used capacity for using bioenergy	ratio	x		qn	[32]
Health & safety	Change in mortality and burden of disease attributable to indoor smoke	%	x		qn	[32,44]
	Crime	?		x	qn	[73,439]
	Death due to indoor and outdoor air and water pollution	# per million people			qn	[466]
	Exposure to agrochemicals	?			?	[459]
	Health impacts	y/n			ql	[73]
	Indoor wood cooking	% of households		x	qn	[33,64,440]
	Level of compliance with a given standard for waste treatment and disposal	-			ql	[44]

	Number of multi-resistant organisms	#			qn	[459]
	Prevention and mitigation of armed conflicts	y/n armed conflict or measures taken			ql	[472]
	Risk of gas emissions	-			ql	[44]
	Risk of HIV/aids and other diseases	?		x	qn	[73,439]
	Toxicity of ‘green’ vs ‘grey’ industrial products	?			qn	[459]
	Traffic safety	?		x	qn	[439]
	Use of agrochemicals (incl fertilisers) and GMO crops	y/n			ql	[459]
	Use of agrochemicals (incl fertilisers) and GMO crops	y/n			ql	[459]
	Use of minimal and only selective use of pesticides	y/n			ql	[446]
Land rights	Amount of land under new ownership	ha			qn	[44,73,439,472]
	Area suitable for bioenergy production	ha			qn	[44]
	Area under public land in total or as part of total land cultivated by bioenergy	ha			qn	[44,460]
	Availability of documentation for local communities	-			ql	[44]
	Availability of treaties on land use issues with local stakeholders	-		x	ql	[44,441,442,467]
	Change in access to land	Positive/negative		x	ql	[33,44,73,439,459,473]
	Change in land prices	%			qn	[44,73,459,473]
	Coherent land ownership structure	-			ql	[44]
	Expansion of biofuel feedstock over grazing land	?			qn	[44]
	Expansion of biofuel feedstock over other crops	ha or %	x	x	qn	[32,44,439,472]
	Extent to which principles of FPIC (free, prior and informed consent) are followed in dealing with local communities and indigenous peoples, including when handling disputes	y/n		x	ql	[44,441,446,465]
	Hectares of land suitable for bioenergy production	ha			qn	[44]
	Land compensation	y/n		x	ql	[44,73,439,446]
	Language of the contract	-			ql	[44]
	Local / Indigenous people’s and tribe’s rights are respected	y/n	x		ql	[33,64,67,73,439,469]
	Loss of natural resources and grazing land	ha		x	qn	[73,439]
	Number of land conflicts	# or ha		x	qn	[44,73,446,460,472,475]
	Share of land acquisitions that have complied with formal or socially accepted procedure regarding absolute numbers and area	%	x	x	qn	[44,73,441,446,459,469]
	Share of land used for bioenergy production	%	x		qn	[32]
	Share of total planted area used for bioenergy feedstock production	%			qn	[44]
	The extent to which community land rights are determined and mapped	-			ql	[44,446]
	Water rights affected	y/n		x	ql	[465,474]
Working conditions	(Rate of) discrimination	y/n or availability of policies	x	x	ql	[44,67,73,441,442,446, 464,465,469]
	Access to flexible working time	y/n			ql	[461]
	Adhere to (inter)national principles / regulations such as those of ILO	y/n	x	x	ql	[33,44,46,64,74,441,464, 466,467,474]
	Amount of forced labour	y/n or availability of policies to prevent this or % of employees that can terminate their own working contract	x	x	ql	[44,67,469,472,73, 441, 442,446,464–467]

Amount of workers reporting health concerns related to agrochemical use	# or %			qn	[44]
Average age of employees	year			qn	[44]
Benefits for disability or fatalities	-			ql	[44]
Capital participation	y/n			ql	[461]
Corporal punishment	y/n		x	ql	[441,464]
Deaths due to occupational-related cancer	#			qn	[466]
Disability adjusted life years	DALY			qn	[466,474]
Duration of breaks	hours			qn	[44]
Education level of the employees	-			ql	[44]
Extent to which child labour laws / minimum age are complied with / Amount of child labour	y/n or availability of policies to prevent this or number of children working	x	x	Ql / qn	[44,67,472,475,73, 74, 442,446,464–467]
Extent to which legal requirement for social security and accident insurance are complied with				ql	[44,472]
Free to leave employment	y/n		x	qn	[441,442]
Incidence of occupational injury, illness and fatalities	# or % or ha^{-1} or MJ^{-1}	x		qn	[32,44,472]
Job quality				ql	[459]
Legal protection of employees	Share of employees with contract		x	qn	[441,442,465,467,621]
Level of provision of Operational safety and Health systems, training and protective equipment	y/n	x	x	ql	[44,67,468,469,471,621, 73,441,442,446,460, 464,465,467]
Mode of transport to the field	-			qn	[44]
Monthly payments of salary	y/n		x	ql	[441,464,467]
No wage deductions as punishment	y/n		x	ql	[464]
Noise above legal threshold / 85-90 dB	y/n			ql	[44,466]
Number of fatal accidents	# yr^{-1} per 1000 employees			qn	[461,466]
Number of staff with medical insurance	# or %			qn	[44]
Number of unjustified dismissals / end of contracts / resignations	#			qn	[44]
Number of work related accidents and health issues	# yr^{-1} per 1000 employees or time lost to accidents		x	qn	[44,442,460,461,466]
Other benefits provided	-			ql	[44,73]
Possible of retirement pension	y/n		x	ql	[44,73,621]
Preventive health measures	y/n (sick leave analayis, health activities)			ql	[461]
Profit-sharing and bonusses	y/n		x	ql	[461,464]
Rate of marginally employed employees	%			qn	[461]
Rate of part time employees	%			qn	[461]
Right to collective bargaining/respecting trade union (freedom of association) / Formation of unions / workers council /right to strike	Positive/negative		x	ql	[44,67,466,467,472,621, 73,441,442,446,460,461, 464,465]
Right to understand the employment contract	-			ql	[44]
Rights of casual workers (social security, medical assistance) compared to fully employed workers	-			ql	[44,73]
Risk of fire outbreak	-			ql	[44,67]
Secondary benefits provided	-			ql	[44,460]
Share of informal jobs	%			qn	[44]

	Training and/or education provided to employees	y/n or %/yr^{-1}	x	x	ql/qn	[32,44,73,460,461,464,465,468,471]
	Work days lost to sickness or injury	Days (employee^{-1}) yr^{-1}			qn	[434,461,473]
	Working hours	Max hrs (>48) or overtime payment	x	x	qn	[44,73,469,472,441,442,460,461,464–467]
Social acceptability	Access to information and knowledge	y/n			ql	[462]
	Availability of documented production procedures	y/n		x	ql	[446]
	Commitment to ethical conduct	y/n		x	ql	[446]
	Compliance with local laws	y/n		x	ql	[73,446,464]
	Effective stakeholder participation (share of documented responses addressing stakeholder concerns and suggestions, reported on annual basis)	%	x		qn	[73,434,471]
	Evidence of transparency	y/n		x	ql	[446]
	Public opinion (share of people with favourable opinion)	%			qn	[434,462]
	Risk of catastrophe	probability			qn	[434]
	Transparency (share of indicators that are reported in time)	%	x		qn	[434,470,471]
Equal opportunities	Change in unpaid time spent by woman and children in collecting biomass	Hrs household $^{-1}$ week $^{-1}$	x	x	qn	[32,44,440]
	Extent to which equal opportunities are extended to women and men in the workplace or other measures to improve gender equality	-		x	ql	[44,73,461,464]
	Extent to which women's reproductive rights are respected (including breastfeeding)	-		x	ql	[44,67,73,446]
	Female participation (in a type of work, sector, company, management)	%		x	qn	[44,441,461]
	Measures to support older employees	y/n			ql	[461]
	Participation of different races	%			qn	[44]
	Participation policies or benefits for women	y/n			ql	[44,460]
	rate of disabled employees	%			qn	[461]
	Share of women wages comparted to men's	%	x	x	qn	[44,67,441,464,468,472]
	Women should be able to search work outside the entity where the husband works	y/n		x	ql	[67,441,464]
Community Impacts	Access to water supply	%		x	qn	[73,439,440,446,462,466,472,474]
	Change in access to health care/insurance	-			ql	[44,73,462]
	Change in quality of life	-			ql	[473]
	Child mortality	# per 1000 births			qn	[42,466,475]
	Community investment	€		x	qn	[44,464]
	Community involvement in decision making	-			ql	[462]
	Contribution to education, health care and infrastructure investments	€			qn	[44,73,446]
	Densification and concentration of settlement	-		x	ql	[73,439]
	Disruption of social networks and relationships	-		x	ql	[73,439]
	Disturbance of graves	-		x	ql	[73,439]
	Households connected to sewer system	%			qn	[42,462,466,472]
	Human Development Index	index			qn	[42]
	Human rights are respected	Human rights policy available	x	x	ql	[74,446,465,474]
	Less compliance with local norms and regulations	-		x	ql	[439]
	Life expectancy	year			Qn	[42,44]
	Literacy rate/ Share of illiterates above 15	%			qn	[42,44]
	Number of poor people	% earning less than half minimum wage			qn	[42]

Quality of life	-		ql	[459]
Social conflicts	-		ql	[33,73]
Social conflicts for employment	-	x	ql	[439]
Social conflicts from increased crime	-	x	ql	[439]
Social conflicts from increased pressure on land	-	x	ql	[73,439]
Social conflicts with migrants	-	x	ql	[84,439]
Social tensions related to competition and differences between locals and migrants	-	x	ql	[439]
Human Poverty Index	Index		qn	[475]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91 819 624 781 805 65 134 314 15 489
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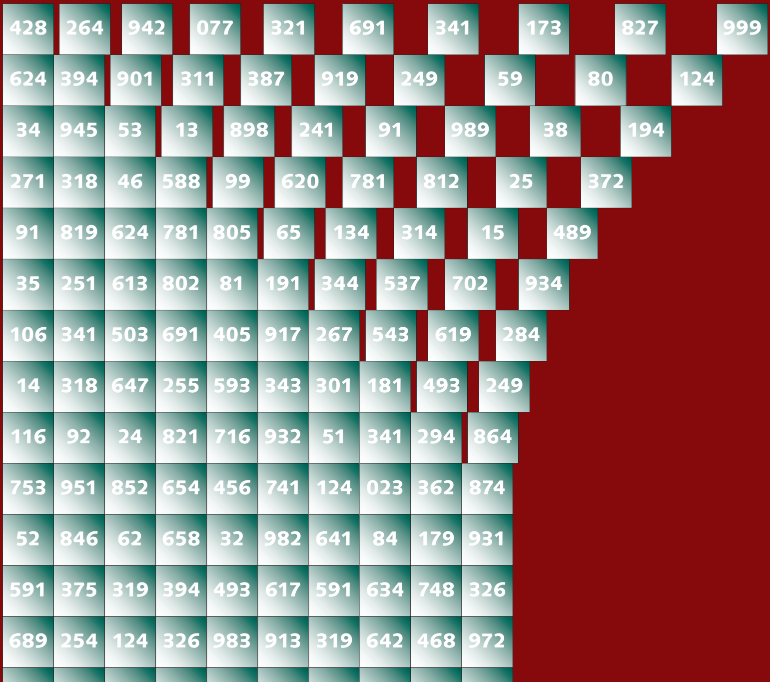
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7 Summary and Conclusions

7.1 Research background

Fossil fuels such as oil, coal and natural gas provide a large majority of the energy that is used to power modern society [622]. This dependence on fossil fuels is unsustainable and has far-reaching impacts on the environment and quality of life. Emissions from fossil fuel use negatively affect air quality and human health [623], and the emitted greenhouse gasses (GHG) are a main cause of climate change [4]. Rising temperatures, changing hydrological cycles and more extreme weather events can affect human society for example through reduced food security and increased poverty [9,15]. In addition, fossil fuel resources are inherently finite and their uneven geographic distribution makes countries dependent on imports [20]. For these reasons, alternatives for fossil fuels are needed.

Bioenergy, i.e. liquid, gaseous or solid fuel from organic matter is globally the most used alternative to fossil fuel [31,622]. Currently, a large part of the biomass used for energy is used in traditional ways, such as the use of wood and charcoal for cooking and heating. The use of modern bioenergy, i.e. biomass converted to modern energy services such as electricity and transport fuel, is promoted as it can provide energy with a lower GHG emission balance than fossil fuels. This potential reduction is the result of the plants' CO_2 uptake from the atmosphere during their growing period [33]. In addition, bioenergy is promoted as it can bring additional benefits such as rural economic growth, job creation, and reduced dependency on the import of fossil fuels [44,46]. This combination of potential environmental and socio-economic benefits makes it likely that bioenergy use will expand the coming decades [34,40].

However, bioenergy can also have negative sustainability impacts. The GHG emissions in the supply chain of bioenergy and the land use change (LUC) related GHG emissions resulting from biomass feedstock production can offset the GHG emission savings from replacing fossil fuels [59]. In addition, also other negative impacts, such as on food security [54,55], land rights [50,51], biodiversity [53] and working conditions [443] have been reported. The magnitude and direction of the positive and negative sustainability impacts can vary based on diverse aspects such as the local conditions, feedstock choice, technology used and management applied [62,63]

In order to ensure bioenergy is a sustainable alternative to fossil fuel use, the sustainability impacts of bioenergy need to be studied. This is preferably done ex-ante to be able to avoid negative impacts before they occur. In addition, quantification of impacts helps to present the environmental and socio-economic impacts in a transparent and objective manner, providing insight into the trade-offs between the positive and negative impacts [65,66]. This insight could contribute to informed decision-making regarding bioenergy projects and policies [68,69].

A complicating factor in assessing the impacts of bioenergy is that not all impacts are direct, but can also be indirect. A key example of a negative indirect impact is indirect land use change (ILUC). If bioenergy feedstock displaces other agricultural production, land use may change elsewhere in order to accommodate the displaced production. This can lead to high land use change GHG emissions [58]. Indirect impacts can be positive or negative. An example of a positive indirect impact of bioenergy expansion is an increase in demand for supplying industries (e.g. demand for transport vehicles) and the resulting employment in these industries. These indirect impacts are hard to track as these often occur outside the scope of influence for a specific producer or even in general bioenergy [78].

The distribution of the impacts of bioenergy is geographically and socially unequal, which can be problematic if negative impacts are concentrated with specific groups. Therefore, it is important to assess who wins and who loses from the implementation of bioenergy [88,89]. The distribution of the sustainability impacts of bioenergy needs to be assessed to avoid placing a burden on the most vulnerable. In order to include this distribution, the sustainability impacts can not only be assessed on a highly aggregated level such as national or global level, as this smooths out the differences in impacts between different groups or regions. Determining the geographical distribution requires the availability of methods to ex-ante quantify these impacts on low spatial aggregation level. For socio-economic impacts more research is necessary in this respect.

An option to limit the risk of indirect land use change is to improve the agricultural productivity in a region and thereby decreasing the land demand for non-bioenergy crops. The surplus land that is made available this way, can be used for bioenergy crop production. In this way, the region can accommodate the additional bioenergy and reduce the risk of displacement [115]. The various measures to improve agricultural productivity can however also have indirect impacts, such as GHG emissions from fertiliser use, or job losses from mechanisation [118]. Therefore, the options to reduce ILUC and their GHG and socio-economic impacts need to be further explored.

7.1.1 Aim and research questions

Although it is important to ensure bioenergy production leads to positive sustainability impacts and avoids negative impacts, there are still gaps in knowledge how to quantify the impacts of bioenergy. Therefore, the aim of this thesis was twofold. The first aim was to quantify impacts of bioenergy in different settings and on different spatial scales, and identify and develop methods for quantifying these impacts. The second aim was to determine the impacts of strategies to improve the sustainability performance of bioenergy. In order to meet these aims, the following three research questions were answered in this thesis:

1. What are available and suitable methods to ex-ante quantify socio-economic impacts of bioenergy and how can different methods for various spatial scales complement each other?
2. What is the geographic and social distribution of bioenergy impacts, and what explains the variations?
3. What strategies are available for reducing competition for land and what are their socio-economic and GHG emission impacts?

Chapters 2 to 6 addressed these three research questions, as shown in Table 1.2. **Chapter 2** presented a method to reduce the risk of indirect land use change. The chapter analysed the potential of four measures that can be applied in the complete agricultural sector to reduce the demand for agricultural land: above-baseline yield improvement, reduced losses in the agricultural chain, improved chain integration and taking under-utilised land into production. The reduction in land demand provided surplus land that can be used to produce low-ILUC-risk biofuel. In this chapter this method was demonstrated for ethanol from maize in Hungary. **Chapter 3** built on the method from the previous chapter and applied it to Eastern Romania in order to assess the potential to provide low-ILUC-risk biodiesel from rapeseed. In addition, the chapter also included an assessment of the GHG emissions from applying these four mitigation measures to verify these measures do not reduce ILUC-risk by increasing GHG emissions elsewhere. In **chapter 4** the impacts on gross domestic product, employment and trade of increased sugarcane ethanol production in Brazil in 2030 were assessed. These impacts were quantified on micro-regional level and included the spill-over impact between the various regions. This chapter also included an assessment of the impact of high yield improvement in the complete agricultural sector and the implementation of second generation ethanol production technology on the three socio-economic indicators. **Chapter 5** used a computable general equilibrium model to analyse the impacts of a biofuel mandate in Ghana on all four pillars of food security. In order to account for the variation in the distribution of the impacts over the country, the results were assessed for rural and urban households. **Chapter 6** reviewed the state-of-the-art in ex-ante quantification of socio-economic impacts of bioenergy. This chapter analysed the relevant indicators for ex-ante socio-economic assessment and the ability and suitability of methods to quantify these indicators on various spatial scales.

Table 7.1 Overview of the research questions, spatial scale and geographical focus that are addressed in each chapter of this thesis.

Chapter	Research questions addressed			Geographical focus	Spatial scale
	1	2	3		
2			•	Hungary	National
3			•	Eastern Romania	Regional
4	•	•	•	Brazil	Microregional to national
5	•	•	•	Ghana	Household and national
6	•			n/a [a]	Project to global

[a] The focus of this chapter is on general applicable indicators and methods, not limited to a specific area.

7.2 Main findings and conclusions

From the research presented in chapters 2-6, the following answers to the three research questions can be given.

Research Question 1

What are available and suitable methods to ex-ante quantify socio-economic impacts of bioenergy and how can different methods for various spatial scales complement each other?

Socio-economic impacts are an integral aspect of the sustainability footprint of bioenergy. They preferably require ex-ante quantification to enable informed decision-making [65,447]. In addition, it is important to quantify these impacts for different spatial aggregation levels to gain insight in the distribution of the impacts over a country or region. But only zooming in on the region neglects the effects that spill-over from other regions and cumulative effects of multiple projects within a country. The selection of a method for a study on the socio-economic impacts of bioenergy is important, as all methods have their specific strengths and weaknesses, which affect their ability and suitability to quantify the socio-economic indicators. Methods vary on aspects such as in the indicators that can be quantified, the input data that are required, the indirect impacts that can be included, and the spatial scales it can be applied to. The identification of methods for ex-ante quantification of socio-economic impacts of bioenergy on various spatial scales is based on work in three chapters of this thesis. It includes a review of existing methods (chapter 6), and the development and application of new approaches to quantify the socio-economic impacts of an increase in bioenergy production (chapters 4 and 5).

- Chapter 6 presented an overview of the available methods for the ex-ante quantitative assessment of the socio-economic impacts of bioenergy. It evaluated the availability and suitability of methods and their use on various spatial scales. This also included a discussion on how combinations of various models can extend the scope of the quantification of socio-economic impact in terms of the number of indicators that can be covered and the spatial and social distribution of effects that can be assessed.
- In chapter 4 an approach was developed that combined a computable general equilibrium model, a land use allocation model, and a multi-regional input-output model to assess the socio-economic impacts of bioenergy at microregional level. The approach was applied to assess the distribution impacts of an expansion of sugarcane ethanol production in Brazil in 2030 on gross domestic product, employment and trade. The combination of methods made it possible to assess the impacts of a nationwide increase in sugarcane expansion on various spatial scales between microregional and national scale, and to show the geographical and social distribution of these impacts. Thereby it illustrated how multiple methods can complement each other for the analysis of socio-economic impacts of bioenergy, including indirect effects, on various spatial scales and for the distribution of these socio-economic effects.
- The food security impacts of a biofuels mandate in Ghana in 2030 were quantified in chapter 5. In the chapter, a method was applied to ex-ante assess the impacts of a biofuel mandate on all four pillars of food security (availability, access, utilisation and stability) for rural and urban households. This served as an illustration of the potential to ex-ante quantify various indicators of the food security impacts of bioenergy and to assess the variation in impacts across various groups in society.

A review of certification schemes and guides of good practice of sustainable bioenergy production and previous review studies on socio-economic impacts of bioenergy in chapter 6, identified the relevant indicators for the ex-ante assessment of the socio-economic impacts of bioenergy, together with the quantification methods that are used to assess these indicators. This shows the methods that were most often used in previous studies for the ex-ante assessment of the socio-economic impacts of bioenergy, as well as the spatial aggregation level at which the impacts were quantified.

From the results of **chapter 6** it becomes clear that the range of methods, applied spatial aggregation levels and impact categories is large (see also Figure 7.1). The most commonly used quantification method for socio-economic impacts of bioenergy is bottom-up/process modelling and cash flow analysis to assess the economic feasibility at project-level. This is a collection of various approaches that have in common that these start with a detailed representation of the relevant process interactions between inputs and outputs and that they do not contain explicit modelling of interactions outside the production chain. In addition to determining the economic feasibility, these methods are also sometimes applied to quantify other indicators in case these can be directly related to the production process (e.g. direct employment of feedstock production).

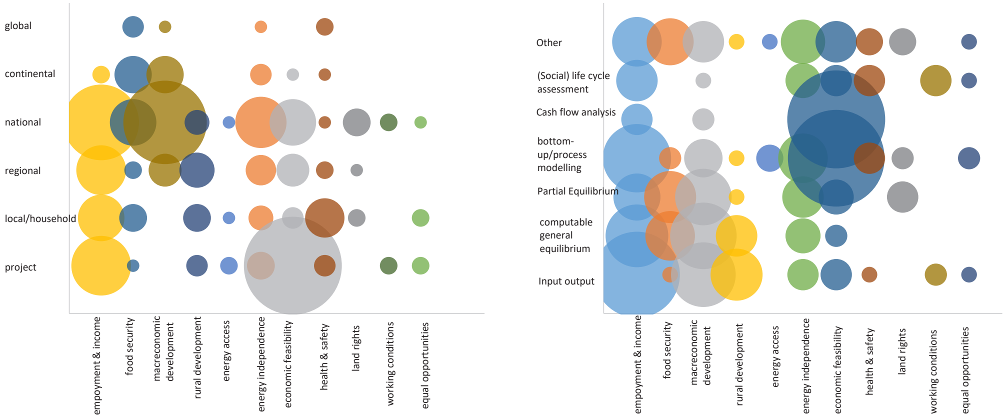

Figure 7.1 The quantitative methods to assess socio-economic impacts of bioenergy per impact category found in literature after 2014. The size of a bubble reflects the number of studies with a specific combination of impacts, method and spatial scale. (left) Spatial scale the impacts are mostly quantified at. (right) Most used methods for quantification of the socio-economic impacts of bioenergy. Data based on research in chapter 6

The overview of the coverage of impact categories addressed (Figure 7.1) also shows that for the community impacts and social acceptability, no ex-ante quantification methods were found. In addition, the focus of most studies is found to be on national level, which creates blind spots at lower aggregation levels. This means for example that few studies are available that determined the household level food security impacts of bioenergy production, although household level is the level where these impacts are most strongly felt [378,379]. The national focus can be explained as a result of the frequent application of macro-economic models that are often used for national or higher aggregation level analysis.

For the quantification of the socio-economic impacts of bioenergy, the most applied group of models is macro-economic models. Macro-economic models are a type of models that include an overview of economic sectors and the monetary interactions of supply and between them. Types that are used for the assessment of socio-economic impacts of bioenergy are input-output analysis (IO), computable general equilibrium (CGE) models and partial equilibrium (PE) models. Of these three model types, CGE models have the broadest scope, as they include all economic sector and offer a global coverage. In contrast, IO models focus mainly on one country or region and PE models are often applied for one or two sectors.

CGE models are applied for the quantification of socio-economic impacts of bioenergy as their high aggregation level can include indirect impacts and impacts from outside the specific region of the actual bioenergy projects. There are however also some downsides that limit their suitability for the assessment of impacts of bioenergy. The interactions between the sectors in a CGE model (the social accounting matrix and the elasticities) are based on historic data. This means that new developments, such as emerging sectors and improved technologies cannot be represented in the standard CGE model. This is especially relevant for the quantification of the sustainability impacts of bioenergy. New technologies may reduce the input of land or increase mechanisation and demand for skilled labourers at the expense of unskilled labour. Improving CGE models in this respect is a clear challenge for the future.

The aggregation level of the CGE also presents a drawback for the assessment of the sustainability impacts. CGE models include for each region only one household type for which all socio-economic impacts are assessed. This disregards the variation and unequal distribution of the impacts within a country or region. This blind spot was addressed in chapter 5 on the food security effects of a bioenergy mandate in Ghana (see below) in which distribution of effects between rural and urban households are assessed.

In order to extend the number of socio-economic impacts that can be ex-ante quantified, multiple methods can be combined. For example sLCA is often used to extend the possibilities of IO models to quantify other socio-economic impacts than only those that can be expressed in monetary terms [304,478,573]. Combining different models can also help to move the analysis beyond one spatial aggregation level. In chapter 4 a computable general equilibrium model, a land use allocation model and a input output model were used to quantify the socio-economic impacts of sugarcane ethanol expansion in Brazil.

Another option to analyse the socio-economic impacts at various spatial levels to use a disaggregated model. Such a disaggregation can be included within a model, such as disaggregating a CGE model to include multiple households rather than one representative household for a whole country (as was done in the case of Ghana) or a multi-region IO model. These approaches include not only the interaction between various sectors within one region, but also include the interaction between households or sectors in different regions. This enables the quantification of impacts at lower aggregation level.

Chapter 5 Illustrated the disaggregation of a macroeconomic model in order to quantify socio-economic impacts on various spatial scales. This chapter showed a method to assess the food security impacts of bioenergy for urban and rural households in Ghana. These impacts were analysed using the CGE model MAGNET, which instead of a single representative household for the whole country, as is typical in CGE models, used a rural and an urban household to show the differences in the food security impacts of the expansion of bioenergy [406]. The household level information on income and expenditure was taken from a national household survey [409]. This made it possible to distinguish the responses of rural and urban households based on their typical income and consumption patterns. The model results at the national level shows the general direction of the food security impacts of bioenergy, but the rural and urban households respond differently to the introduction of the bioenergy mandate. The impacts do not only vary in magnitude, but can go in opposite directs. Although further disaggregation, for example to various income classes or regions, would increase the insight provided in the distribution of the impacts (see research question 2), this analysis demonstrated this is a viable approach to include the food security impacts of bioenergy on a lower aggregation level.

The approach to assess socio-economic impacts of bioenergy using multiple models to be able to include multiple spatial scales in one study was explored in **chapter 4**. In this chapter, a combination of different models was used to analyse the impacts of sugarcane expansion in Brazil in 2030 at different spatial levels. The CGE model MAGNET [268] was used to assess the impacts of the increased demand in sugarcane ethanol on supply and prices of all sectors in the Brazilian economy. Given the total supply for each agricultural commodity, the land use per land use category (sugarcane, other crops, pasture, etc.) for each of the six macro regions in Brazil was used as an input for the land allocation model PLUC [269,270]. This model translated the land use requirements for each land use function, to spatially explicit land use maps. The changes in sugarcane production and other agricultural production (i.e. crops and livestock) in each microregion were used as input to a multi-region IO model [271]. This IO model was used to assess the socio-economic impacts in the micro-regions Piracicaba, Presidente Prudente (in the state of Sao Paulo) and South West Goiás (in Goías), the states in which these microregions are located, the macroregions, and the country Brazil. The range in spatial levels made it possible to analyse the differences in socio-economic impacts between the three microregions, the states and the macroregions (see next section) and the spill-over effects between them. The added value of the combination of these models was that it made it possible to analyse the different spatial scales in more detail. The macro level results from the CGE model account for the dynamic price and supply impacts, indirect impacts, and impacts from developments outside Brazil. The land use allocation model made it possible to consider the specific geographic distribution of the sugarcane production and the displacement of other agricultural activities. The inter-regional IO model then allowed for the comparison of the impacts in the microregions, thereby considering the distribution of the socio-economic impacts.

The results of both cases illustrate the importance of quantifying the impacts on various spatial levels and analysing the differences between the regions. As in Brazil only considering the national level results would show few negative impacts of bioenergy on the socio-economic indicators, as employment and GDP both increase significantly. However, when zooming in on the microregions, also negative socio-economic impacts of bioenergy become visible. For example, at the microregional level, it is clear the additional ethanol scenario is unfavourable for South West Goiás. The reduction in GDP in the rest of the agricultural sector as a result is not compensated by other by growth in other sectors and the net impact compared to the baseline with no increase in ethanol production is negative. The disaggregation to urban and rural households in Ghana shows the same principle. Only considering national level results would mask the differences between the two household types in their food security response to the introduction of a bioenergy mandate. The negative impact on household income the scenario with bioenergy is much larger in the urban region than in the rural region, which means the national average does would mask large part of the negative impacts. Further disaggregation to e.g. regions or to income groups is likely to show larger range in responses between households that benefits and households that mainly feel negative impacts of bioenergy.

Research Question 2

What is the geographic and social distribution of bioenergy impacts, and what explains the variations?

The social and geographical distribution of the impacts of bioenergy needs to be considered, as different groups and regions are likely to be affected in different ways, and the resilience of groups and regions to negative impacts is expected to vary [85]. In order to avoid negative impacts for specific groups or regions, it is important to understand the variation in impacts that occur between regions and groups in society and what causes these variations [88,89]. In this thesis chapters 4 and 5 addressed this research question.

- The analysis in chapter 4 of the socio-economic impact of the expansion in sugarcane ethanol production in Brazil from 24 billion litres in 2012 to 54 billion litres in 2030 showed the employment, trade and GDP impacts for three microregions. Disaggregation to the level of the microregion (i.e. a cluster of multiple municipalities) made it possible to analyse the geographic distribution of the impacts, assess the differences between the microregions, and quantify the size of the spill-over effect between the regions. The microregions Piracicaba, Presidente Prudente, and South West Goiás varied in the structure of the economy, present sugarcane production and ability to further expand their production. In order to assess the social distribution of the impacts of sugarcane, the employment impacts were disaggregated to twelve income classes.
- Chapter 5 showed the variation in food security impacts between rural and urban households in Ghana in 2030 as a result of expanding biofuel production. Changes in the agricultural sector affect urban and rural households differently as these differ for example in income, dependence on agriculture, and energy security [380]. This leads to differences in the size and direction of the socio-economic impacts of biofuel production

In **chapter 4**, the socio-economic impacts of sugarcane ethanol expansion in Brazil were assessed using a combination of a computable general equilibrium model, a land use allocation model and an interregional IO model. The effects of an expansion in sugarcane ethanol were assessed by comparing two scenarios for 2030 i) a reference scenario with a no increase in global ethanol demand compared to 2012 (total production: 28 billion litres) and ii) a scenario with a large expansion in ethanol demand (54 billion litres production in Brazil). The impact of the expansion in ethanol production on the economy of the three microregions is significantly different, as is illustrated in Figure 7.2.

A key explanation of the differences in socio-economic impacts between the regions is the current and projected distribution of sugarcane cultivation in Brazil. The traditional sugarcane region Piracicaba offers little opportunity for sugarcane expansion, whereas in South West Goiás and Presidente Prudente there is ample room for sugarcane to expand. In the results of the IO model this corresponded to larger direct impacts of the sugarcane ethanol production expansion on economic activity and employment in these two regions. However, the expansion of sugar cane for ethanol in South West Goiás was projected to be at the expense of other agricultural activities. This resulted in lower economic activity and employment in the region compared to the scenario with no additional ethanol demand. The net impact of expanding sugarcane ethanol, including this indirect impact, was therefore negative. The sugarcane expansion in Presidente Prudente, was less at the expense of other agricultural activities. As a result, the net impacts of the sugarcane ethanol expansion were much more positive in this microregion.

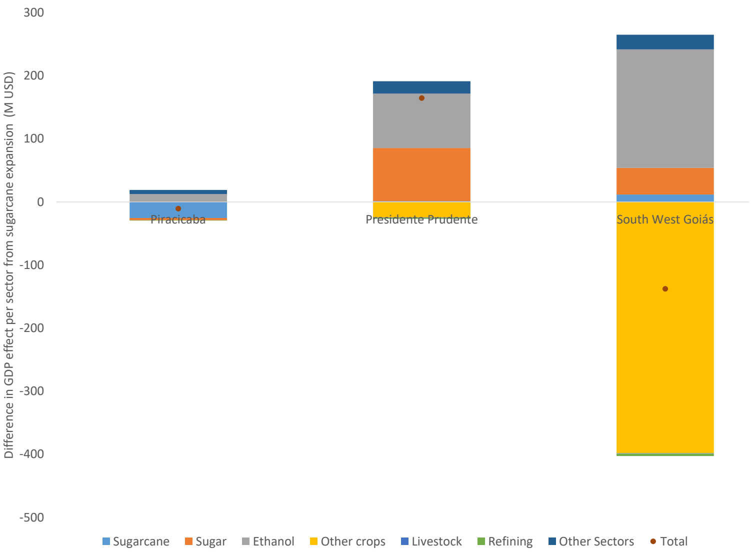

Figure 7.2 Difference in GDP per microregion between the scenario with an additional sugarcane ethanol demand (54 billion litres) and the reference scenario (a small increase in sugarcane ethanol production from 2012 at 28 billion litres).

Another key aspect that determined the geographical distribution of the socio-economic impacts of sugarcane expansion is related to the structure of the local economy. Piracicaba for example is a region with a long history of sugarcane production. The region is therefore home to industries that supply the biofuel industry. Therefore, the region benefits most from the indirect effects of ethanol production and retains the largest share of positive socioeconomic impacts of sugarcane production within its own border. The differences between the microregions in the structure of their economy, means that the ability to absorb the spill-over impact from other regions also differs. In the increased sugarcane ethanol scenario, there is almost no additional sugarcane ethanol production in Piracicaba. Still, the microregion is projected to benefit from the additional ethanol production elsewhere, as more than a quarter of the GDP and employment impacts in Piracicaba come are spilled over from outside the region.

Analysis of the social distribution of the socio-economic impacts showed that most employment impacts were in agriculture and transport. Two sectors that are relatively low paying. This is also reflected in the distribution of the employment over twelve income classes (see Figure 7.3). This shows that most employment in the bioenergy producing regions is in the lowest income classes. When considering the country as a whole, the distribution is more equal as the indirect impacts determine a larger share of the total impacts and these are also in higher paying sectors.

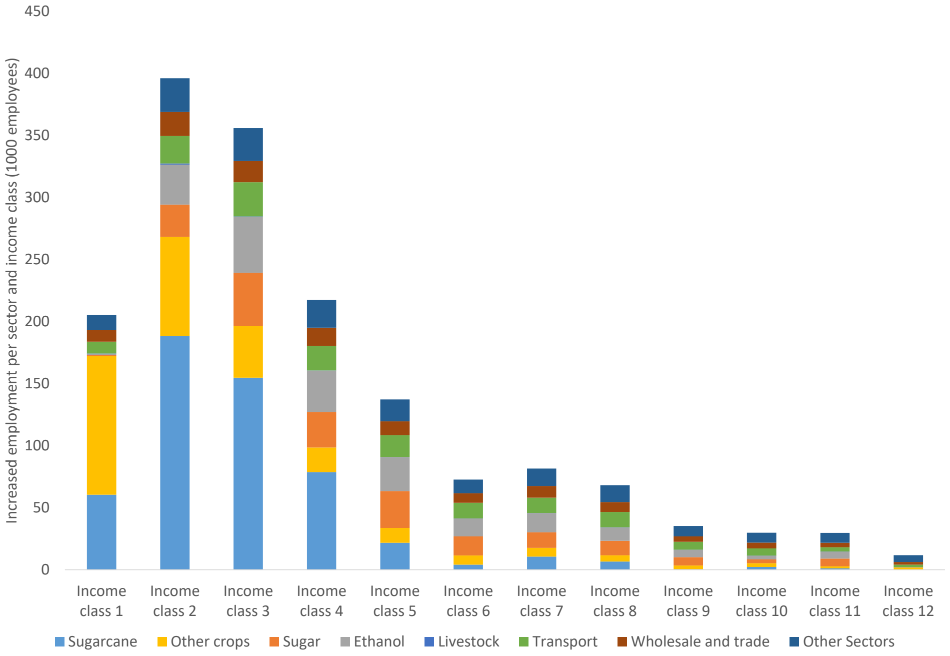

Figure 7.3 Distribution of the additional employment as a result of sugarcane ethanol expansion in Brazil. The distribution is presented per sector and income class (see Table 4.7)

Chapter 5 analysed the food security impacts of a biofuel mandate of 15% ethanol in the gasoline and 10% biodiesel in the diesel supply (E15/B10) in Ghana in 2030. The impacts were assessed for the four pillars of food security: availability, access, utilisation and stability [322] and were differentiated for urban and rural households in order to compare the distribution of the food security impacts. The food security impacts were assessed by comparing the food security situation in a baseline scenario without a biofuel mandate to a scenario with the implemented biofuel mandate in Ghana in 2030.

The food security situation in the Ghana was projected to improve significantly towards 2030 in the baseline scenario. The impacts on food security were dominated by general economic progress in the country. As productivity and GDP were shown to increase in the period 2010-2030, the food security indicators demonstrated strong improvement. Household income and food consumption increased in both household types, and food prices and import dependency decreased. There were however differences between the rural and urban areas. The improvement in food security was much larger in urban households compared to rural households as household income and consumption increased faster. Also, urban households benefited from a relatively faster expansion of non-agricultural production in the country. Furthermore, the share of household income spent on food increased in rural areas, mainly due to a switch to the more expensive processed foods.

To cover the E15/B10 mandate in Ghana in 2030 most biodiesel is projected to be produced from oil seeds (mostly palm oil) and ethanol from grains (mostly maize). The increased demand for oil seeds was covered by decreased exports and partly by increased production. Direct consumption impacts are limited. For grains the additional demand is fulfilled by reduced food consumption as well as lower supplies to other sectors.

The effects of the biofuel mandate vary between the rural and urban households (see Table 7.2). The dependence of rural households on agriculture is beneficial for their income as demand for land and agricultural labour increases to satisfy the demand more agricultural products. Income from labour, land and capital increases (+3.2%), whereas this declines in urban areas (-0.9%) compared to the baseline without biofuel production. The small decrease in rural income is caused by a reduction in other income, mainly from governmental transfers. As food prices increase (2.3%), access to food decreases and households increase the share of food in their total expenditures. However, the effects of the biofuel mandate are small and availability of food is barely affected for both urban and rural households, as consumption of food shows only a very small decrease. The largest effect of the biofuel mandate is on stability as the dependency on imported food increases.

Table 7.2 Impact of a E15/B10 biofuel mandate in Ghana in 2030 on the four pillars of food security, for urban and rural households.

		Urban	Rural
Availability	Food energy consumption per capita	-0.03%	-0.01%
	Protein consumption per capita	-0.03%	0.00%
	Fat consumption per capita	-0.02%	0.00%
	Carbohydrates consumption per capita	-0.03%	-0.01%
	Supply of protein from animal sources (excluding fish)	-0.03%	-0.01%
	Average value of food production per capita [a]	2.3%	
Access	Household income	-1.6%	-0.1%
	Food price index a	2.1%	
	Share of food in total household expenditure	3.1%	2.6%
Utilisation	Share of calories from fruit and vegetables	0.0%	0.0%
	Share of energy supply from cereals roots and tubers	0.0%	0.0%
Stability	Cereal import dependency ratio	2.5%	4.1%
	Ratio of food imports over total merchandise exports a	2.0%	

[a] These are analysed on national level.

As was seen in Brazil, the socio-economic impacts are more positive for those directly involved with the bioenergy production, in this case the rural households. However, the differences in impacts between the rural and urban households are small and the initial food security situation of urban households is better. In addition, the impacts of the biofuel mandate on overall food security is very small compared to the progress achieved between 2010 and 2030.

The results from chapters 4 and 5 showed the geographic and social distribution of the impacts of bioenergy and what explains the differences between regions and households. The distribution of the impacts between rural and urban regions shows that the socio-economic benefits of the bioenergy expansion are concentrated in the rural areas. Additional demand for agricultural products means that unskilled agricultural labourers and landowners benefits from this expansion as demand and thereby prices increase. The geographic distribution shows a similar trend, direct impacts are mainly located in regions that produce bioenergy and is dependent on their ability to expand production.

There are a number of factors that further impact these general trends. The chapter on Brazil showed that competition for land may mean that other agricultural land use decreases to such an extent that the decreased economic activities and employment cannot be compensated by the increase in bioenergy production. This leads to a negative outcome for that region. The regions tend to vary in their ability to retain the positive effects, for some regions a large share of the economic activity and employment spills-over to other regions reducing the benefit of the bioenergy expansion in the region significantly.

Urban areas and regions where no bioenergy production takes place, can still be affected trough indirect impacts. These regions can still profit economically from bioenergy production as impacts spill-over from bioenergy producing regions. This can for example be in the form of additional demand for goods and services from regions producing bioenergy. The regions without bioenergy expansion, such as urban areas, are also confronted with higher food prices. However, as the socio-economic food security situation of urban areas is likely to be better, it means income distribution becomes more equal. In addition, chapter 5 shows the impacts of bioenergy on food security to be very small compared to projected growth. The study however underlines the importance of further disaggregation of the socio-economic impacts as the impacts are likely to differ between various income groups within a city. The resilience of landless urban populations to negative impacts on urban employment and rising food prices is likely to be lower than of skilled employees or business owners, that can easily afford slightly higher food prices. This further disaggregation to other would be a subject for further research.

Research Question 3

What strategies are available for reducing competition for land and what are their socio-economic and GHG emission impacts?

The additional demand for agricultural land that is associated with the expansion of bioenergy is one of the largest sustainability risks of bioenergy. It can be a source of direct or indirect land use change which can cause GHG emissions that may even exceed the benefits of bioenergy use [58,59] or lead to land tenure conflict and food security issues. It is therefore important to minimise the competition for land between bioenergy and the rest of the agricultural sector. Chapter 2, 3 and 4 included specific measures to limit the land demand for bioenergy production.

- Chapter 2 demonstrated an approach to limit the risk of bioenergy production leading to indirect land use change. This approach was demonstrated for a case study in Hungary. It showed the potential of four measures to limit land demand in the agricultural sector in order to make land available for bioenergy production, with a low risk of displacing other agricultural production. These measures relate to increased productivity and efficiency in the agricultural sector, and using currently under-utilised land for expansion.
- Chapter 3 applied the same approach to another case study, in order to test it for different settings and to account for the differences between various regions in terms of agricultural development and potential to implement these measures. The

focus in this chapter was on Eastern Romania and demonstrated the use of the four ILUC mitigation measures to make land available for low-ILUC-risk rapeseed biodiesel production. The chapter extended the work of chapter 2 by also assessing the GHG emissions of the ILUC mitigation measures. The GHG emissions of ILUC were assessed to verify the effectiveness of the ILUC mitigation measures to limit ILUC without causing additional GHG emissions.

- The scenarios in chapter 4 for future land use in Brazil for sugarcane ethanol production also included options that limit the demand for land. One scenario assumed higher yields in the entire agricultural sector to limit the land demand of all uses. Another scenario assumed implementation of second generation sugarcane ethanol production that also utilises the sugarcane bagasse, which effectively increases the useful production of the land. For both scenarios, the socio-economic impacts were analysed to account for the impacts of these measures on employment and GDP.

The underlying idea of the ILUC mitigation measures as applied in **chapters 2 and 3** is that the risk of land use expansion can be reduced. This can be done by improving the efficiency and productivity of the entire agricultural sector in a region. As a result, land use for other activities can be decreased and surplus land becomes available for bioenergy production. In addition, if under-utilised land is available in the region, this may also serve as a resource for additional production with a low risk of causing ILUC. The ILUC mitigation measures that were applied here were i) above-baseline yield development; ii) increased chain efficiency; iii) chain integration; and iv) use of currently under-utilised lands. The application of these measures reduces the land demand compared to the baseline or made more land available. The surplus land that is made available as a result of the mitigation measures can be used to produce low-ILUC-risk bioenergy. This approach was applied to Hungary in chapter 2, where the surplus land was used to estimate the production potential of maize for low-ILUC-risk ethanol, and in chapter 3 to Eastern Romania where the surplus land was assumed to be allocated to rapeseed for low-ILUC-risk biodiesel production.

The application of the measures in both cases illustrated the potential of this strategy to reduce the competition for land. In both settings the amount of biofuel that could be produced on the surplus land was higher than the amount that was projected in the countries' National Renewable Energy Action Plans [176,198]. Both cases relied strongly on above-baseline yield increases. This is illustrated in Figure 7.4 that shows the relative contribution of the four different mitigation measures in both cases. Yield increases in crop and livestock production were responsible for around 75% of the potential. The yield increases that were assumed to make this land available were in both cases based on what is already achieved in other regions in the country or in a neighbouring country with similar agro-ecological conditions. The yield gaps in both countries are fairly large, which makes it easier to increase the yields [140].

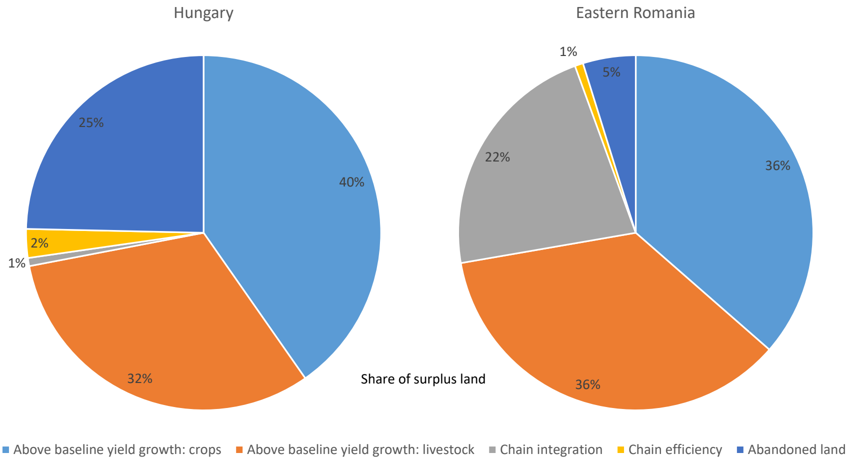

Figure 7.4 Relative contribution of the ILUC mitigation measures in the medium scenario in Eastern Romania and Hungary.

The ILUC mitigation measures were designed to reduce the risk of indirect land use change and to avoid the associated emissions. Therefore, the emissions of the ILUC mitigation measures also need to be assessed in order to avoid reducing the ILUC risk at the cost of higher overall GHG emissions. This was done in chapter 3, where the GHG emissions of the ILUC mitigations were assessed. For each measure, the GHG emissions were determined and compared to the life cycle emissions of rapeseed biodiesel. This allowed checking whether these measures can be used to meet a 60% GHG emission reduction compared to fossil fuels, as required in the European Union as minimum reduction target. The comparison of the ILUC mitigation GHG emissions to the 60% reduction target showed it is possible to provide low-ILUC-risk biofuel within this limit. However, sustainable intensification of the entire agricultural sector is required in order to provide low-ILUC-risk biodiesel with low ILUC-risk-mitigation-emissions. Sustainable intensification in these cases is intensification through better management practices (e.g. no tillage, precision farming, etc.) rather than increased inputs [118]. Without sustainable intensification, the GHG emissions were still lower than the projected ILUC emissions, but it was then not possible to meet the 60% reduction target compared to fossil fuels. In addition, the productivity on abandoned lands may be too low to compensate for a reduction in carbon stocks (e.g. shrubs or bushes) present on that land. Increased chain efficiency that targeted the reduction of crop losses and increased chain efficiency that reduced the demand for feed crops by using coproducts from biodiesel production are always favourable in terms of the GHG emissions as these reduce the demand for other production. These measures have a positive ILUC mitigation potential. Even if this potential is much lower than the above baseline yield measure (Figure 7.4), they also reduce GHG emissions compared to the baseline and can therefore be considered as no-regret options.

The potential of high yield and second generation sugarcane ethanol was explored in **chapter 4**. In the high yield scenario [9], the agricultural yield growth rate was assumed to double compared to the business as usual scenario. The assumed yields are still modest, when compared to historic yield growth and other regions [270]. This yield growth led to a reduction in the amount of land allocated to sugarcane (-13% nationwide, compared to the ethanol scenario) and land for livestock and other crops decreased as well. The land was instead allocated to planted forest, grass and shrubs or was abandoned. An implementation of second generation sugarcane ethanol reduces the demand for land for sugarcane as the process also utilises the bagasse and trash from the sugarcane plant and therefore requires a smaller amount of sugarcane to produce ethanol. This scenario also assumed a higher yield increase than the baseline ethanol scenario, but only for sugarcane production. Nationwide land use for sugarcane decreased by 36% compared to the situation without this measure, but the impacts on the other agricultural sectors was limited to small increases in land for livestock production and other crops (see Table 7.3).

Table 7.3 Land use changes per category in Brazil in different scenarios.

	Ethanol - compared to business as usual	*High yield* - compared to ethanol scenario	*2G* - compared to *ethanol* scenario
Natural forest	0%	1%	0%
Rangeland	-5%	-2%	5%
Planted forest	-2%	7%	2%
Crops	0%	-5%	2%
Grass and shrubs	-1%	2%	1%
Sugar cane	38%	-13%	-36%
Pasture (planted)	-1%	-3%	0%
Bare soil	0%	0%	0%
abandoned	3%	12%	-2%

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[9] In addition to the reference scenario with low ethanol demand growth in Brazil until 2030 (total production 28 billion litres) and the scenario with a large sugarcane ethanol expansion (total production: 54 billion litres), also a high yield and second generation scenario were analysed. These two also assumed large growth in the sugarcane ethanol production (total production 58 billion litres) in addition to measures to limit the total land use.

Higher yields in sugarcane production and increased conversion efficiencies in ethanol production reduce the competition for land. This creates space to accommodate both an expansion in sugarcane and other agricultural products. This allows for increased economic activities, which has positive impacts on employment and economic growth in Brazil. The development of second generation ethanol and accompanying increased conversion efficiencies mean less sugarcane needs to be produced for the same amount of ethanol and fewer employees are needed to produce the sugarcane. The reduction in employment in the sugarcane sector is, however, compensated by an expansion of other agricultural sectors.

The results from chapters 2, 3 and 4 showed that there is a significant potential to reduce the competition for land between bioenergy and other agricultural products. In general, the measures to reduce the land demand do not only focus on bioenergy crops alone, but on the agricultural sector as a whole. The existence and potential impact of ILUC show the interconnectedness of agriculture, land use and bioenergy as the impacts of bioenergy production can ripple through the agricultural sector and affect land use far beyond the location of the biofuel production. This illustrates why reducing competition for land and mitigating the ILUC risk require an approach for the agricultural sector as a whole. This approach is possible even with low emissions, but this requires high yield growth, sustainable intensification of the entire agricultural sector and strict limitations on the carbon stocks of the surplus land. In addition, the increasing productivity in the agricultural sector has positive socio-economic impacts. Because the competition for land decreases, production in other sectors can increase, which has positive effects on GDP and employment.

7.3 Key conclusions

This thesis analysed the availability and suitability of methods for ex-ante quantification of sustainability impacts of bioenergy. In addition, new ex-ante quantification methods were developed and applied to assess the impacts of bioenergy production on land use, employment, food security and economic development. This was done for case studies in Hungary, Eastern Romania, Brazil, and Ghana. The case studies varied in their approach and the topics that were considered. From this variety of assessments, general conclusions for the quantification of sustainability impacts of bioenergy can be drawn as follows.

The risk of land use change can be mitigated using a combination of measures that target the entire agricultural sector in a region or country. These measures, i.e. above-baseline yield development, chain efficiency, chain integration and taking under-utilised lands into production, were applied in Hungary and Eastern Romania. In these two case studies, the measures were able to provide sufficient space to accommodate bioenergy production without the risk of displacing other production. A key factor for making this land available, is the ability to increase yields in the entire agricultural sector, including both crops and livestock production. In both studies, yield increases account for around 75% of the potential. As this approach is not focused on bioenergy crops alone, also the rest of the agricultural sector benefits from this. Increased yields of other crops and livestock lead to higher production and result in higher economic activity and more employment. However, the yield increases come with a risk of increasing GHG emissions through higher agrochemical use or increased mechanisation. Analysis in this thesis confirmed previous findings by Gerssen-Gondelach [118] that it is possible to increase the productivity in the entire agricultural sector, with a low impact on GHG emissions under a strict policy of sustainable intensification, rather than increasing yield through higher fertiliser application.

The socio-economic impacts of bioenergy expansion vary between the regions and households that have been analysed in this thesis. Regions where bioenergy expands, demand for land and agricultural labour increases, which stimulates the local economy and is directly beneficial for those involved in terms of employment income and economic activity. However, competition with other agricultural sectors may decrease the benefits as other activities are displaced and reduce employment and income.

Although effects are strongest in the regions where expansion takes place, additional economic activity can spill-over from regions with bioenergy expansion to regions without expansion, for example when these supply goods or services to production process. Also, negative effects can occur in the form of higher food prices that are not completely compensated by higher income. This is especially problematic in areas that do not benefit from bioenergy, but are confronted with the indirect effects.

The socio-economic impacts can be stimulated by increasing yields in the entire agricultural sector and reduced competition for land, as this enables higher agricultural production in an area. This is favourable for total economic activity and employment. Additionally, as reduced competition for land makes it possible to achieve higher production without risk of competing with food production the risks in that respect are also reduced.

A large share of the analyses of sustainability impacts of bioenergy use macro-economic models in their assessment. The broad scope of these models makes them suitable to quantify the impacts of bioenergy throughout the agricultural sector and the rest of the economy. In addition, these models can account for the indirect impacts that occur outside the direct bioenergy production chain. However, the current application of these models also has disadvantages.

A drawback of the macroeconomic models that is that these are in general aggregated on national or higher level. This means the distribution of the sustainability impacts over various regions and groups in society cannot be shown. However, by disaggregating the macroeconomic models or using a combination of different models, it becomes possible to extend the analysis and present the impacts on the level of regions or different household groups (e.g. rural/urban). Here it was demonstrated for three microregions in Brazil (chapter 4), and urban and rural households in Ghana (chapter 5). The first case combined a CGE, land use allocation, and IO model where the land use allocation model made it possible to translate the macro effects to low aggregation level spatial data that was used to analyse the microregions. In the second case a CGE model was used with two households to be able to distinguish between different households in the country.

The application of these methods showed there are significant differences between the regions and households that were not visible at national aggregation level. Thereby it was possible to discern winners and losers from the development of bioenergy. This underlines the value of presenting impacts at lower aggregation level.

This thesis mainly refers to biofuels for transport. However, the measures to reduce land competition help make land available for other uses, and this is not exclusively for biomass for biofuel production. Instead, the findings can apply to all other energy and material applications of biomass. The findings in this thesis underline importance of analysing the sustainability impacts of bioenergy and contributed to this by proposing novel approaches for analysing socio-economic impacts of bioenergy on sub-national aggregation levels. These approaches can help to improve the ex-ante assessment of the socio-economic impacts of bioenergy and thereby minimise negative impacts and stimulate positive impacts during implementation. This contributes to the overall sustainability of bioenergy.

7.4 Recommendations

From the results of this thesis a number of recommendations for policy-makers and future research can be identified.

7.4.1 For policy-makers

The production and use of bioenergy has been identified as a driver or risk to nearly all the Sustainable Development Goals (SDGs) of the United Nations [436]. As the world recognises the SDGs as the agenda for transforming the world, this underlines the importance of ensuring bioenergy production is sustainable. From this thesis, a number of recommendations for policy-makers can be made that can help bioenergy production to maximise benefits and minimize burdens on the environment as well as socio-economic conditions:

- To limit the risk of indirect land use change as a consequence of the expansion of bioenergy, policies have to consider bioenergy as an integral part of the agricultural sector. This means incentives for biofuel producers are needed to improve the agricultural practices in the sourcing region in order to reduce the risk of displacing other production or expanding land through market-mediated impacts. Current policies do not contain these incentives, but this may be part of new certification schemes were entire regions can be certified for the ILUC mitigation measures that are taken there.
- In a holistic approach, all land use would be governed by the same sustainability criteria. The indirect land use change as a result of bioenergy expansion is the direct land use change of other activities. Thus, ensuring no expansion of agriculture takes place on high carbon stock lands would mean not only the impacts of ILUC on GHG emissions will diminish but also the impacts of land use at large would be reduced.
- The ILUC-mitigation measures that are shown in this thesis, i.e. above-baseline yield development, chain efficiency, chain integration and taking under-utilised lands into production, can help to ex-ante assess the potential of a region to produce bioenergy with a low risk of indirect land use change. This method can be used by decision-makers when considering expanding bioenergy production in a specific region.
- Part of the implementation of the ILUC-mitigation measures is extensive monitoring of the progress in the agricultural sector to verify their effectiveness. Slower progress in the development of the agricultural sector means the potential to reduce ILUC-risk reduces as well and the bioenergy target for the region needs to be adapted or effort to improve the sector strengthened.
- Socio-economic indicators are currently under-represented in certification schemes, despite the importance of socio-economic development for sustainable development. Inclusion of socio-economic criteria should focus on quantifiable indicators in order to enable transparent measuring, and presenting the trade-offs between the various impacts.

- Ex-ante quantitative assessment of the impacts of bioenergy projects and policies is advised, preferably on a low spatial level, in order to be able to consider the distribution of the impacts. This information allows for better decision-making processes as the various advantages and disadvantages in terms of environmental and socio-economic impacts can be transparently weighed.

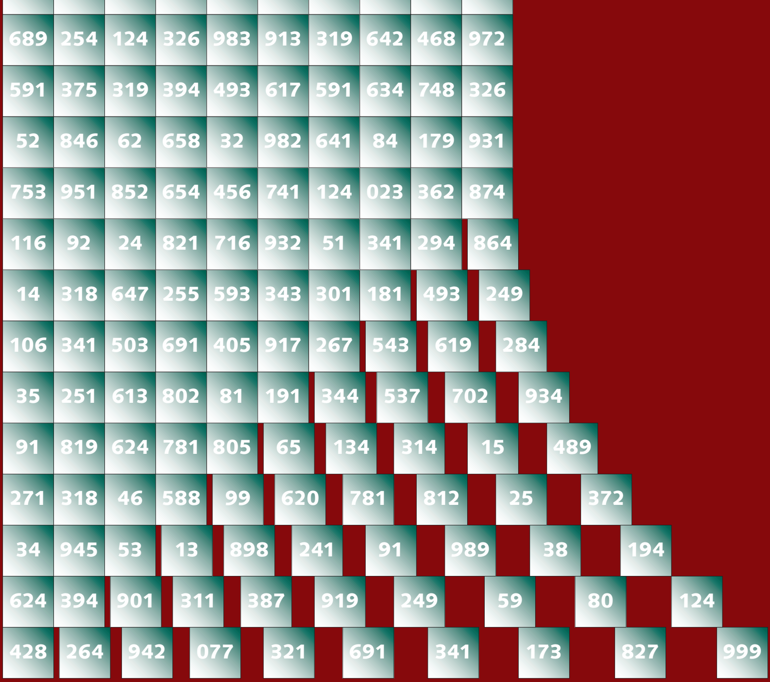
7.4.2 Future research

From the findings in this thesis the following recommendations for further research can be made:

- The ILUC mitigation measures in chapters 2 and 3 were shown to reduce the competition for land in a specific region and provide low-ILUC-risk biofuel. This was done in a post-model test that did not include the feedback mechanisms of a macro-economic model that allows for the inclusion of indirect impacts. Analysing the ILUC mitigation measures using a macro-economic model, potentially coupled to a land allocation model, would be a first step for future research. Inclusion of the ILUC mitigation measures in macroeconomic models would also enable a more extensive analysis of the socio-economic impacts of the measures to reduce the competition for land.
- The next step would be to test these measures in practice to explore to what extent the potential that was determined in the studies can also be achieved in practice. As the measures apply to the entire agricultural sector, this requires work with many stakeholders. Certification schemes apply in general to one operator, but when the entire agricultural sector needs to improve many farmers are involved, providing an additional challenge.
- The work in chapters 4 and 5 analysed socio-economic impacts of bioenergy on a sub-national aggregation level. The differences between the microregions in chapter 4 and the rural and urban household in chapter 5 illustrated the value of such an approach. Future assessments of bioenergy impacts needs to focus on including these lower aggregation level impacts in order to better understand the distribution of these impacts. This disaggregation can go further than the urban/rural disaggregation that has been shown in chapter 5. Impacts are likely to differ also for various income groups and different regions. In addition, gender inequality may be an important source of inequality within a household. Some studies (e.g. [553,561,624]) already refer to the benefits for women in reduced time spent on bioenergy collection when expanding modern energy access, but further analysis is needed on the role that modern bioenergy could play.

- The research in this thesis showed differences in impacts of bioenergy in different regions and how to quantify this. Future research should consider what conditions make that some regions benefit more than others and how this can be influenced.
- In order to provide a comprehensive quantitative ex-ante assessment on the socio-economic impacts of bioenergy, the blind spots that were identified in chapter 6 need to be addressed. These blind spots relate to poor coverage of the community impacts and social acceptability of bioenergy in the quantification methods, and, more general, to the lack assessments at sub-national aggregation levels. This hampers the analysis of the social and geographic distribution of bioenergy impacts.

Improving the quality of the available data that are used to construct the social accounting matrices and CGE models can help to improve the quality of the sustainability assessments. Especially in developing countries where impacts can be high and people are less resilient to negative impacts, high quality assessment is crucial. In addition, increased availability of data on options for improved agriculture (e.g. sustainable intensification) can help to integrate these options in the macro-economic models.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52 846 62 658 32 982 641 84 179 931
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116 92 24 821 716 932 51 341 294 864
14 318 647 255 593 343 301 181 493 249
106 341 503 691 405 917 267 543 619 284
35 251 613 802 81 191 344 537 702 934
91 819 624 781 805 65 134 314 15 489
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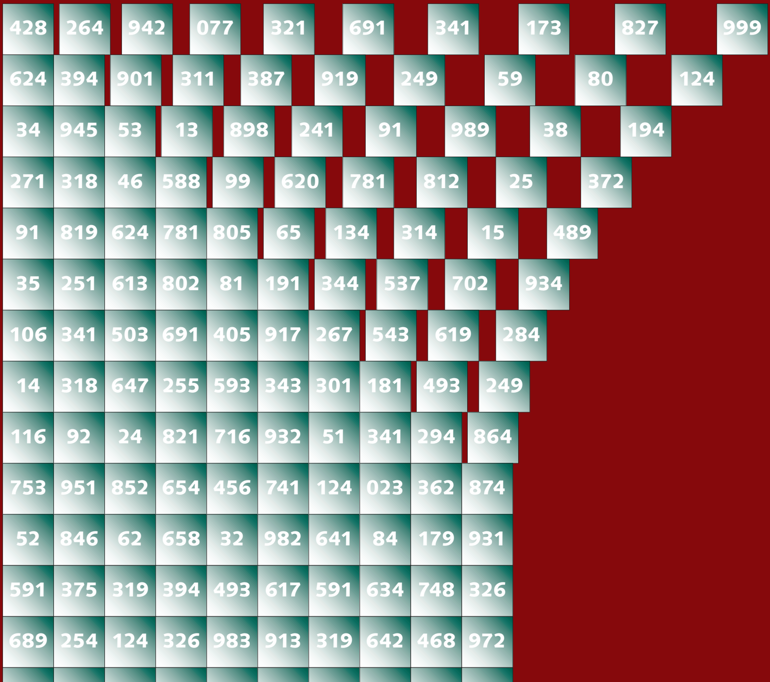
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8 Samenvatting en conclusie

8.1 Achtergrond

De energie die nodig is om de huidige economie en samenleving draaiende te houden is voornamelijk afkomstig van fossiele brandstoffen zoals olie, kolen en aardgas [622]. De huidige afhankelijkheid van fossiele brandstoffen is niet duurzaam en heeft een grote impact op het milieu en de kwaliteit van leven. De emissies van fossiele brandstoffen hebben een negatieve invloed op de luchtkwaliteit en gezondheid [623] en de uitgestoten broeikasgassen zijn een van de voornaamste oorzaken van klimaatverandering [4]. Stijgende temperaturen, veranderingen in hydrologische cycli en extremer weer kunnen verstrekkende gevolgen hebben voor de samenleving, bijvoorbeeld door problemen met voedselzekerheid en een toename in armoede [9,15]. Bovendien zijn fossiele brandstoffen inherent eindig en de ongelijke geografische verdeling van de voorraden maakt landen afhankelijk van import [20]. Daarom zijn er alternatieven nodig voor fossiele brandstoffen.

Bio-energie dat wil zeggen, vloeibare, gasvormige of vaste brandstof gemaakt van organisch materiaal, is wereldwijd het meest gebruikte alternatief voor fossiele brandstof [31,622]. Een groot deel van de bio-energie betreft vandaag de dag nog traditioneel gebruik, bijvoorbeeld het gebruik van hout en houtskool voor koken en verwarming. Het gebruik van moderne bio-energie, dat wil zeggen biomassa die is omgezet naar moderne energiedragers zoals elektriciteit en transportbrandstof, wordt gestimuleerd omdat het in potentie een lagere broeikasgasbalans heeft dan fossiele brandstoffen. Deze potentieel lagere broeikasgasemissies zijn het gevolg van de opname van CO_2 uit de atmosfeer tijdens de plantengroei [33]. Daarnaast wordt bio-energie gestimuleerd omdat het ook andere voordelen zou kunnen opleveren, zoals economische groei in rurale gebieden, werkgelegenheid en verminderde afhankelijkheid van geïmporteerde fossiele brandstoffen [44,46]. Door deze combinatie van milieu- en sociaaleconomische voordelen is het waarschijnlijk dat het gebruik van bio-energie de komende jaren zal groeien [34,40].

Het gebruik van bio-energie kan echter ook negatieve duurzaamheidseffecten hebben. De broeikasgasemissies in de productieketen van bio-energie en als gevolg van landgebruiksveranderingen kunnen de broeikasgasemissiereductie ten opzichte van fossiele brandstoffen tenietdoen [59]. Daarbij komt dat er ook negatieve gevolgen gerapporteerd zijn voor onder andere voedselzekerheid [54,55], landrechten [50,51], biodiversiteit [53] en arbeidsomstandigheden [443]. De omvang en de richting van de effecten (positief of negatief) zijn afhankelijk van verschillende aspecten, zoals de lokale omstandigheden, de gewas- en technologiekeuze en management [62,63].

Om ervoor te zorgen dat bio-energie een duurzaam alternatief is voor het gebruik van fossiele brandstoffen, moeten de duurzaamheidseffecten in kaart gebracht worden. Bij voorkeur moet dit vooraf (ex-ante) gedaan worden, zodat negatieve gevolgen voorkomen kunnen worden. Daarnaast helpt het kwantificeren van de effecten bij het transparant en objectief presenteren van de milieu- en sociaaleconomische effecten en de trade-off tussen de positieve en negatieve effecten [65,66]. Het inzicht dat verkregen wordt uit een dergelijke ex-ante kwantificering kan bijdragen aan een afgewogen besluitvorming met betrekking tot nieuwe bio-energieprojecten en -beleid [68,69].

Een complicerende factor bij de analyse van de effecten van bio-energie is dat een deel van de effecten niet direct, maar alleen indirect gekoppeld is aan bio-energie. Een belangrijk voorbeeld van een dergelijk indirect effect is indirecte landgebruiksverandering. Als de biomassateelt andere gewassen verdringt, kan dit elders leiden tot landgebruiksveranderingen om de verdrongen productie op te vangen. Deze indirecte landgebruiksverandering kan leiden tot hoge broeikasgasemissies [58]. Indirecte effecten kunnen echter ook positief zijn. Een stijgende productie van bio-energie kan bijvoorbeeld leiden tot een toenemende vraag bij toeleverende industrieën, wat daar kan leiden tot een toenemende werkgelegenheid. Aangezien de indirecte effecten vaak buiten de invloedsfeer van de bio-energiesector liggen, is het lastig om de indirecte effecten te meten [78].

De effecten van bio-energie zijn geografisch en sociaal ongelijk verdeeld. Dit kan een probleem zijn als negatieve effecten geconcentreerd zijn bij een specifieke groep. Het is daarom van belang om te onderzoeken wie de winnaars en verliezers zijn van bio-energie, zodat de lasten van bio-energie niet worden afgeschoven op de meest kwetsbare in de samenleving [88,89]. Om deze verdeling van effecten mee te nemen in de analyse is het van belang de duurzaamheidseffecten niet alleen op een hoog aggregatieniveau, zoals wereldwijd of landelijk te bekijken, omdat dit de verschillen tussen verschillende regio's en groepen kan verbloemen. Om de geografische verdeling van de effecten te kunnen bepalen zijn methodes nodig die de effecten op een laag aggregatieniveau kunnen kwantificeren. Vooral voor sociaaleconomische effecten is hiervoor meer onderzoek noodzakelijk.

Een mogelijkheid om het risico op indirecte landgebruiksverandering te verkleinen is de landbouwproductiviteit in een regio te verhogen en daardoor de vraag naar land voor niet-bio-energie gewassen te verminderen. Het extra land dat hierdoor beschikbaar komt, kan dan gebruikt worden voor de productie van biomassa voor bio-energie. Op deze wijze kan een regio biomassa voor bio-energie produceren met een laag risico op verdringing van andere gewassen [115]. De verschillende maatregelen om de landbouwproductiviteit te verhogen kunnen ook leiden tot indirecte effecten, zoals broeikasemissies als gevolg van kunstmest gebruik of vermindering van werkgelegenheid door mechanisering [118]. Het is daarom van belang de opties voor het verminderen van indirecte landgebruiksverandering, hun broeikasgasemissies en sociaaleconomische effecten verder te onderzoeken.

8.1.1 Doel en onderzoeksvragen

Het is van belang dat bio-energie positieve duurzaamheidseffecten teweegbrengt en negatieve effecten worden vermeden. Er zijn echter nog gaten in de huidige kennis over het kwantificeren van de effecten van bio-energie. Het doel van dit proefschrift was daarom tweeledig. Het eerste doel was het kwantificeren van de impacts van bio-energie in verschillende situaties en op verschillende ruimtelijke aggregatieniveaus en het identificeren en ontwikkelen van methodes hiervoor. Het tweede doel was het bepalen van de effecten van verschillende strategieën voor het verbeteren van de duurzaamheid van bio-energie. Om deze doelen te bereiken, zijn de volgende drie vragen beantwoord in dit proefschrift:

1. Welke methodes zijn beschikbaar en geschikt voor het ex-ante kwantificeren van sociaaleconomische effecten van bio-energie, en hoe kunnen methodes voor verschillende ruimtelijke aggregatieniveaus elkaar aanvullen?
2. Wat is de geografische en sociaaleconomische verdeling van de impacts van bio-energie en wat is de oorzaak van de verschillen?
3. Welke strategieën zijn er beschikbaar om de concurrentie tussen verschillende vormen van landgebruik te verminderen en wat zijn de sociaaleconomische en broeikasgasemissie effecten daarvan?

Deze drie onderzoeksvragen zijn behandeld in hoofdstuk 2 tot en met 6 van dit proefschrift, zoals getoond in het overzicht in Tabel 8.1. In **hoofdstuk 2** werd een methode gepresenteerd om het risico op indirecte landgebruiksverandering te verminderen. In het hoofdstuk werden vier maatregelen voor het verlagen van de vraag naar landbouwgrond geanalyseerd: i) productiviteitsverhoging bovenop de standaard ontwikkeling; ii) vermindering van verliezen in de agrarische productieketen; iii) verbeterde integratie van productieketens en iv) het beter gebruik van onderbenut agrarisch land. Door de vermindering in vraag naar landbouwgrond, komt er extra land beschikbaar voor de productie van bio-energie met een laag risico op indirecte landgebruiksverandering. Dit hoofdstuk demonstreerde het potentieel van deze aanpak en berekende de mogelijkheid van het gebruik van dit land voor de productie van ethanol uit mais uit Hongarije. **Hoofdstuk 3** bouwde voort op de methode uit het vorige hoofdstuk, maar werd toegepast op Oost-Roemenië om het potentieel van biodiesel uit koolzaad te bepalen. Daarbij werd ook onderzocht of de vier maatregelen om landgebruiksverandering te verminderen niet leiden tot hogere broeikasgasemissies. Deze analyse werd toegepast om te zorgen dat het verminderen van indirecte landgebruiksverandering niet leidt tot hogere emissies dan de indirecte landgebruiksverandering zelf zou kunnen veroorzaken. In **hoofdstuk 4** zijn de effecten op het bruto binnenlandsproduct (BBP), de buitenlandse handel en de werkgelegenheid van een uitbreiding in ethanol uit suikerriet in Brazilië in 2030 bepaald. Deze effecten werden gekwantificeerd op microregionaalniveau en bevatten ook de spill-overeffecten tussen de verschillende regio's. Bovendien is ook het effect van hogere productiviteit in de landbouwsector en het gebruik van tweede generatie brandstoffen op de sociaaleconomische indicatoren meegenomen in de analyse. **Hoofdstuk 5** bekeek de effecten van biobrandstofproductie in Ghana in 2030 op alle vier de pilaren van voedselzekerheid: i) beschikbaarheid; ii) toegankelijkheid; iii) gebruik, en iv) stabiliteit in de andere drie pilaren. In de analyse werd een onderscheid gemaakt tussen effecten in stedelijke en landelijke gebieden. **Hoofdstuk 6** analyseerde de huidige stand van zaken wat betreft methodes voor ex-ante kwantificering van sociaaleconomische effecten van bio-energie. Hierbij zijn de relevante indicatoren voor de analyse van de sociaaleconomische effecten en de beschikbaarheid en geschiktheid van methodes voor het kwantificeren hiervan op verschillende ruimtelijke aggregatieniveaus geanalyseerd.

Tabel 8.1 Overzicht van de onderzoeksvragen, ruimtelijk aggregatieniveau en geografische focus in elk van de hoofdstukken van dit proefschrift.

Hoofdstuk	**Onderzoeksvragen**			**Geografische focus**	**Aggregratieniveau**
	1	2	3		
2			•	Hongarije	Nationaal
3			•	Oost-Roemenië	Regionaal
4	•	•	•	Brazilië	Microregionaal tot nationaal
5	•	•	•	Ghana	Huishouden en nationaal
6	•			nvt [a]	Project tot wereldwijd

[a] Dit hoofdstuk richt zich op algemeen toepasbare indicatoren en methodes, zonder beperking van specifiek gebied.

8.2 Bevindingen en conclusies

8.2.1 Onderzoeksvraag 1

Welke methodes zijn beschikbaar en geschikt voor het ex-ante kwantificeren van sociaaleconomische effecten van bio-energie, en hoe kunnen methodes voor verschillende ruimtelijke aggregatieniveaus elkaar aanvullen?

De sociaaleconomische effecten zijn een belangrijk onderdeel van de duurzaamheidseffecten van bio-energie en zouden bij voorkeur ex-ante gekwantificeerd moeten worden om kwaliteit van de besluitvorming te verhogen [65,447]. Om de geografische en sociaaleconomische verdeling van de effecten binnen een land of regio inzichtelijk te maken is het van belang de analyse op laag aggregatieniveau uit te voeren. Inzoomen op één regio heeft echter als gevolg dat interregionale effecten wegvallen. Dit betekent dat het van belang is meerdere aggregatieniveaus mee te nemen in de analyse. Dit speelt ook een rol in de keuze voor een methode, aangezien methodes verschillen in hun mogelijkheden en geschiktheid voor het kwantificeren van sociaaleconomische effecten en het aggregatieniveau waarop ze opereren. Drie hoofdstukken van dit proefschrift behandelden deze vraag.

- In hoofdstuk 6 is een overzicht gegeven van de beschikbaarheid en geschiktheid van methodes voor de analyse van sociaaleconomische effecten van bio-energie op verschillende aggregatieniveaus. Het hoofdstuk bevatte daarnaast ook nog een discussie hoe de combinatie van verschillende modellen het bereik (in termen van aantal indicatoren en de geografische en sociaaleconomische verdeling) van de modellen kan vergroten.
- Hoofdstuk 4 en 5 presenteerden nieuwe methodes voor het kwantificeren van de sociaaleconomische effecten van bio-energie op verschillende aggregatieniveaus. Hoofdstuk 4 deed dit voor een de toename van suikerrietethanol in Brazilië in 2030. Hierbij werd het effect van de groei op het bruto binnenlands product (BBP), werkgelegenheid en buitenlandse handel geanalyseerd door middel van een combinatie van een algemeen evenwichtsmodel (EN: computable general equilibrium, CGE), een landgebruiksmodel en een input-output model. De combinatie van deze modellen zorgde er voor dat de effecten op landelijk-, macroregionaal-, staat- en microregionaalniveau bepaald konden worden en voor verschillende inkomensgroepen. Hiermee kon ook de geografische en sociaaleconomische verdeling van de effecten worden berekend. Dit illustreerde hoe een combinatie van verschillende modellen kan zorgen dat deze modellen elkaar kunnen aanvullen bij de analyse van sociaaleconomische effecten en hun verdeling.

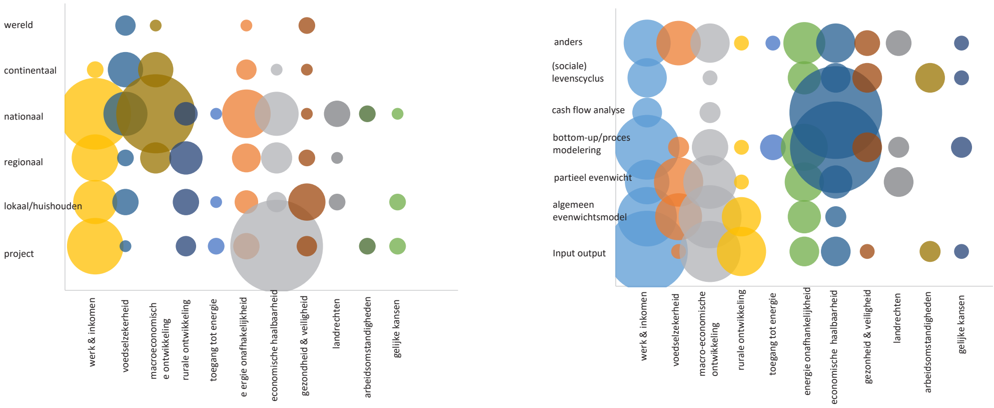
- Hoofdstuk 5 verkende de effecten van bio-energie in Ghana in 2030 op de voedselzekerheidssituatie in het land. Hierbij werden de effecten bepaald voor alle vier de pilaren van voedselzekerheid (beschikbaarheid, toegankelijkheid, gebruik en stabiliteit) voor zowel een stedelijk als landelijk huishouden. Dit illustreerde de mogelijkheden voor het analyseren van de voedselzekerheidseffecten en de variatie in impact voor de verschillende huishoudens.

Uit de analyse van eerdere studies in **hoofdstuk 6** blijkt dat er een grote spreiding zit in de methodes, indicatoren en ruimtelijke aggregatieniveau (zie ook Figuur 8.1). Uit het overzicht van beschikbare methodes blijkt dat niet alle impacts ex-ante gekwantificeerd worden. Voor de effecten op de gemeenschap en sociale acceptatie zijn geen methodes beschikbaar. Bovendien zijn er een aantal blinde vlekken in de analyses waar de tot nu toe gebruikte methodes niet op alle relevante niveaus voor bepaalde impacts toegepast worden of kunnen worden. De meeste indicatoren zijn op nationaal niveau gekwantificeerd. Dit komt doordat macro-economische modellen die gebruikt worden vaak op dit niveau opereren. Deze economische modellen hebben als gemene deler dat ze opgebouwd zijn uit een overzicht van de economische sectoren en de financiële interacties hiertussen. Voor de analyse van sociaaleconomische effecten worden vooral input-output analyse (IO), algemene evenwichtsmodellen en partiële evenwichtsmodellen gebruikt. Hierbij hebben de algemene evenwichtsmodellen de breedste reikwijdte doordat ze op mondiaal niveau opereren, terwijl input-output modellen vooral nationaal of regionaal niveau zijn en partiele evenwichtsmodellen zich op één of enkele sectoren richten. Een aantal studies toonde ook de potentie van een combinatie van verschillende methodes om zo de kwantificering van verschillende indicatoren op verscheidene aggregatieniveaus uit te breiden. Een andere methode is het desaggregeren van de macro-economische modellen zelf, waarbij niet alleen de relaties tussen de verschillende sectoren in één regio worden bekeken, maar ook de interacties tussen sectoren in verschillende regio's. In hoofdstuk 4 en 5 zijn deze methodes ook aan bod gekomen.

In **hoofdstuk 4** werden drie verschillende modellen aan elkaar verbonden om zo verschillende aggregatieniveaus te kunnen analyseren. Het algemeen evenwichtsmodel MAGNET [268] werd gebruikt om de effecten van een toename in vraag naar suikerrietethanol in 2030 op alle sectoren van de Braziliaanse economie te bepalen. Gegeven de totale vraag naar elk landbouwproduct, werd het landgebruik per gebruikscategorie (suikerriet, andere gewassen, weides) voor elk van de zes macroregio's in Brazilië gebruikt als input voor het landgebruiksmodel PLUC [269,270]. Dit model vertaalde de vraag naar land voor elke functie naar landgebruikskaarten. De lokale veranderingen in productie van suikerriet en andere landbouwproducten (gewassen, vee) voor elke microregio werd gebruikt als input voor multi-regio input-output model. Dit maakte het mogelijk effecten te analyseren op verschillende aggregatieniveaus variërend van laag (microregio) tot aan hoog (nationaal). De toegevoegde waarde van de combinatie van de verschillende modellen is dat er gebruik gemaakt kan worden van de kracht van elk model. Zo kon het algemeen evenwichtsmodel de dynamiek van vraag, aanbod en prijzen en de indirecte effecten meenemen. Het landgebruiksmodel kon de specifieke ruimtelijke verdeling en verdringing van andere landbouwgewassen bepalen. Het IO model zorgde er uiteindelijk voor dat de resultaten vergeleken konden worden tussen de verschillende microregio's en daarmee de verdeling van de sociaaleconomische effecten bepalen.

Hoofdstuk 5 illustreerde de desaggregatie van een macro-economisch model, de toepassing in dit hoofdstuk toonde de voedselzekerheidseffecten van bio-energie in Ghana op verschillende ruimtelijke aggregatieniveaus. Het hoofdstuk gebruikt een algemeen evenwichtsmodel, dat, in tegenstelling tot gebruikelijk, nu meerdere representatieve huishoudens bevatte om zo de effecten te bepalen voor stedelijke en landelijke huishoudens in Ghana in 2030. De verschillen tussen de huishoudens in het model werden hierbij bepaald op basis van een nationale huishoudenquête [406] [409]. Op landelijk niveau toonden de resultaten van het economisch model de algemene richting van de effecten van bio-energie op de voedselzekerheidssituatie, maar ook werden deze op lager aggregatieniveau bepaald, omdat in landelijke en stedelijke gebieden de effecten van een bio-energiemandaat anders zijn en anders beleefd worden. De effecten verschillen namelijk niet alleen in grootte, maar ook de richting (positief of negatief) tussen de gebieden. Hoewel verdere desaggregatie meer inzicht in de verdeling van de sociaaleconomische effecten van bio-energie zou kunnen tonen, illustreert de hier toegepaste methode dat het mogelijk is extra inzicht op verschillende ruimtelijke aggregatieniveaus te bepalen.

De resultaten uit hoofdstuk 4 en 5 onderstreepten het belang van de analyse op verschillende schaalniveaus en het bestuderen van de verschillen tussen de regio's. Zo toonde een analyse in Brazilië op enkel nationaalniveau weinig negatieve sociaaleconomische effecten van uitbreiding van suikerrietproductie in het land. Echter, inzoomen op specifieke regio's toonde ook negatieve effecten. Zo leidde uitbreiding van suikerrietethanolproductie in Zuidwest Goiás tot een vermindering van zowel economische activiteit als werkgelegenheid, omdat de verdringing van andere landbouw activiteiten onvoldoende gecompenseerd werd door de uitbreiding van de suikerriet- en ethanolproductie in de regio. De studie in Ghana toonde hetzelfde principe. Hier werden ook de verschillen tussen de huishoudtypes gemaskeerd door enkel op nationaal niveau te analyseren. De negatieve effecten zijn namelijk vele malen groter in stedelijke gebieden, dan in landelijke gebieden. Door alleen op nationaal niveau te analyseren, zou dit niet aan het licht komen.



Figuur 8.1 Overzicht van belang van verschillende kwantificeringsmethodes voor de sociaaleconomische effecten van bio-energie gevonden in literatuur na 2014. De omvang van elke bol geeft het aantal studies met die specifieke combinatie van impacts, methode en ruimtelijk aggregatieniveau weer. (links) Ruimtelijk aggregatieniveau waarop de impacts het meest gekwantificeerd zijn. (rechts) Meest gebruikte methode voor het kwantificeren van sociaaleconomische impacts van bio-energie. Data komt uit hoofdstuk 6.

8.2.2 Onderzoeksvraag 2

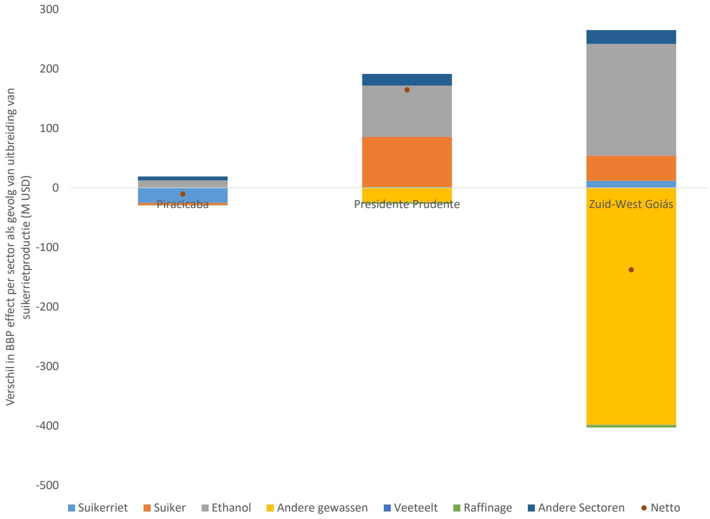
Wat is de geografische en sociaaleconomische verdeling van de impacts van bio-energie en wat is de oorzaak van de verschillen?

De sociaaleconomische en geografische verdeling van de effecten van bio-energie moeten worden beschouwd, omdat verschillende groepen en regio's anders beïnvloed worden door expansie van bio-energie. Daarnaast zijn niet alle groepen even weerbaar tegen de negatieve effecten [85]. Het is daarom van belang deze verschillen te bestuderen en te bekijken wat deze veroorzaakt [88,89]. In dit proefschrift is dit gedaan in hoofdstuk 4 en 5.

- De analyse in hoofdstuk 4 toonde de effecten van een uitbreiding in de productie van suikerrietethanol in Brazilië van 24 miljard liter in 2012 tot 54 miljard liter in 2030 op werkgelegenheid, buitenlandse handel en bruto binnenlands product (BBP) van drie microregio's. Doordat de effecten bepaald werden per microregio (cluster van meerdere gemeentes) was het mogelijk de microregio's met elkaar te vergelijken en de weglekeffecten tussen de regio's te beschouwen. De microregio's Piracicaba, Presidente Prudente, en Zuidwest Goiás verschillen in structuur van de lokale economie, huidige suikerrietproductie en de mogelijkheden om suikerrietproductie verder uit te breiden. Bovendien werden de inkomenseffecten in dit hoofdstuk verdeeld over 12 inkomensklassen om zo de sociaaleconomische verdeling van de effecten inzichtelijk te maken.

- In hoofdstuk vijf werden de voedselzekerheidseffecten van een bio-energiemandaat in Ghana in 2030 vergeleken tussen stedelijke en landelijke gebieden. De gevolgen van veranderingen in de landbouwsector zijn anders voor deze twee type huishoudens aangezien ze bijvoorbeeld verschillen in inkomen, gebondenheid aan landbouw en energiezekerheid. Dit leidde tot verschillen in de grootte en richting van de sociaaleconomische effecten van bio-energie.

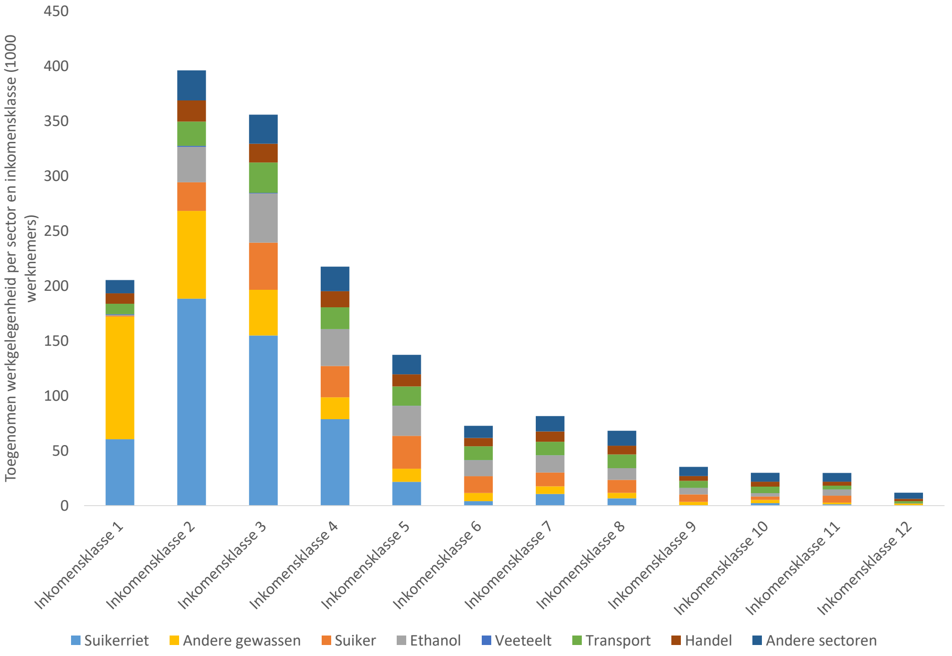
Er zaten grote verschillen tussen de microregio's in de omvang en richting van de effecten die gevonden zijn in hoofdstuk 4. Deze verschillen worden geïllustreerd in Figuur 8.2. Een belangrijk aspect voor de omvang van de sociaaleconomische effecten van de suikerrietexpansie was de huidige en voorspelde verdeling van suikerrietproductie in Brazilië. Piracicaba, een traditioneel suikerrietgebied, heeft weinig ruimte om productie verder uit te breiden, terwijl groeigebieden als Zuidwest Goiás en Presidente Prudente dat wel hebben. De mogelijkheid om uit te breiden was gekoppeld aan grotere directe effecten van suikerrietproductie in deze regio's. De uitbreiding in Zuidwest Goiás verdringt echter andere landbouwproductie wat leidde tot netto lagere economische activiteit en werkgelegenheid in vergelijking met een situatie zonder extra suikerrietproductie. In Presidente Prudente was dit niet het geval en was het resultaat positiever.



Figuur 8.2 Verandering in BBP per microregio en sector in 2030 als gevolg van een uitbreiding van suikerrietethanolproductie van 28 miljard tot 54 miljard liter.

Een andere factor die meespeelde voor de omvang van de sociaaleconomische effecten in de microregio's was de structuur van de lokale economie. Als meer traditioneel suikerrietgebied heeft Piracicaba ook meer gerelateerde industrie binnen de grenzen en kan daardoor ook profiteren van expansie buiten de eigen grenzen. Doordat het benodigdheden voor suikerriet en ethanol productie kan leveren, houdt het een groter deel van de economische activiteit binnen de eigen grenzen en kan het profiteren van activiteit in andere regio's. Dit betekent dat deze regio, ondanks minieme uitbreidingsmogelijkheden voor suikerriet, wel kan profiteren van landelijk toegenomen productie, doordat ruim een kwart van het effect van suikerrietexpansie van buiten de eigen microregio komt.

Analyse van de sectoren waar de extra arbeidsplaatsen gecreëerd worden, toonde dat de toegenomen economische activiteit veel neerslaat bij de transport- en landbouwsector (zie Figuur 8.3). Deze twee sectoren zijn relatief laagbetaald en kennen zwaardere arbeidsomstandigheden. Wanneer naar het gehele land gekeken wordt, is de verdeling gelijker, aangezien de indirecte effecten dan een grotere rol spelen binnen de totale effecten en die ook in hoger betalende sectoren vallen.



Figuur 8.3 Verdeling van de extra werkgelegenheid ten gevolge van suikerrietethanolproductie uitbreiding in Brazilië in 2030. De verdeling is per sector en inkomensklasse (zie ook Table 4.7).

In **hoofdstuk 5** werden de voedselzekerheidseffecten van een mandaat van 15% ethanol in de benzine en 10% biodiesel in de dieselmix (E15/B10) in Ghana in 2030 geanalyseerd. Deze effecten werden bepaald voor de vier pilaren van voedselzekerheid: beschikbaarheid, toegang, gebruik en stabiliteit in de andere drie pilaren [322] en gedifferentieerd voor landelijke en stedelijke gebieden. De analyse werd gemaakt doormiddel van een vergelijking tussen een scenario met een scenario zonder bio-energie.

De resultaten in hoofdstuk 5 toonden dat hoe de voedselzekerheidssituatie in Ghana sterk lijkte te verbeteren tussen 2010 en 2030, als gevolg van algemene economische ontwikkeling in het land. Productie en productiviteit namen toe en als gevolg hiervan verbeterde de voedselzekerheidssituatie in het land. Inkomens en voedselconsumptie stegen in zowel de stedelijke als landelijke huishoudens, terwijl prijzen en afhankelijkheid van import daalden. De verbetering van de voedselzekerheid in stedelijke gebieden was relatief groter, als gevolg van relatief sterkere groei in niet-landbouw sectoren. De resultaten van het algemeen evenwichtsmodel toonden dat de om E15/B10 te produceren in 2030 de meeste biodiesel geproduceerd zou worden uit oliezaden (voornamelijk palmolie), terwijl ethanol voornamelijk van granen (voornamelijk mais) zou komen. De toegenomen vraag naar oliezaden werd in het model voornamelijk gedekt door het verminderen van de export en toegenomen productie, waarbij de binnenlandse consumptie weinig veranderde. Voor granen gold het omgekeerde: de extra vraag werd voornamelijk gedekt door het verminderen van productie voor andere sectoren en directe consumptie. Deze twee processen hadden gevolgen voor de voedselzekerheidssituatie in het land (zie Tabel 8.2). Doordat landelijke huishoudens meer leunen om landbouwsector profiteerden ze meer van de toegenomen vraag naar producten uit deze sector via toegenomen vraag naar land en arbeid. De inkomsten uit de productiefactoren arbeid, land en kapitaal namen toe in landelijke gebieden (3.2% in vergelijking met het basispad zonder bio-energie), terwijl in stedelijke gebieden een daling toonden (-0.9%). De netto krimp in het inkomen in landelijke gebieden werd voornamelijk veroorzaakt door de vermindering van overheidsbetalingen. Omdat voedselprijzen in heel het land stegen (2.3%) was het netto effect op de toegankelijkheid van voedsel negatief en werd een groter deel van inkomens gespendeerd aan voedsel. De beschikbaarheid van voedsel veranderde amper en netto effecten van bio-energie op voedselzekerheid zijn miniem in vergelijking met de voorspelde groei tussen 2010 en 2030. De grootste verschuiving is in de afhankelijkheid van geïmporteerd voedsel.

Tabel 8.2 Impact van E10/B15 biobrandstofproductie in Ghana in 2030 op de vier pilaren van voedselzekerheid, voor stedelijke en rurale huishoudens.

		Stedelijk	Ruraal
Beschikbaarheid	Energie geleverd door voedsel per capita	-0.03%	-0.01%
	Proteïneconsumptie per capita	-0.03%	0.00%
	Vetconsumptie per capita	-0.02%	0.00%
	Koolhydratenconsumptie per capita	-0.03%	-0.01%
	Toevoer van dierlijke proteïne (zonder vis)	-0.03%	-0.01%
	Per capita gemiddelde waarde voedselproductie [a]	2.3%	
Toegankelijkheid	Huishoudinkomen	-1.6%	-0.1%
	Voedselprijs index [a]	2.1%	
	Aandeel van voedsel in totale huishoud uitgaven	3.1%	2.6%
Gebruik	Aandeel van groente en fruit in totale calorieconsumptie	0.0%	0.0%
	Aandeel van graan, knolgewassen en peulvruchten in totale calorieconsumptie	0.0%	0.0%
Stabiliteit	Graan import afhankelijkheid	2.5%	4.1%
	Voedselimport als deel van totale export [a]	2.0%	

[a] Deze zijn berekend op nationaal niveau.

De resultaten uit hoofdstuk 4 en 5 toonden de sociaaleconomische en geografische verdeling van de impacts en oorzaken van verschillen tussen regio's en groepen. De verdeling toonde dat de positieve sociaaleconomische effecten van bio-energie vooral geconcentreerd zijn in de landelijke gebieden. Extra vraag naar landbouwproducten betekent dat vooral ongeschoolde arbeiders en landeigenaren profiteren van de extra vraag en de bijbehorende stijgende prijzen. De geografische verdeling toont een vergelijkbare situatie, waarbij de directe effecten vooral in regio's die bio-energie produceren zijn geconcentreerd, en afhankelijk zijn van de mogelijkheden om de productie in een regio uit te breiden.

Een aantal factoren draagt bij aan afwijkingen van deze algemene trends. Het hoofdstuk over Brazilië toonde bijvoorbeeld een situatie waarbij de krimp in niet bio-energie gerelateerde landbouwproducten zo groot was, dat de toename in suikerriet en ethanol productie hier niet tegenop woog. Dit leidde tot een netto negatieve uitkomst voor deze regio. Bovendien verschillen regio's in de capaciteit om te profiteren van de productie in andere regio's. Zo is voor sommige regio's een aanzienlijk deel van de economische- en werkgelegenheidsgroei het resultaat van uitbreiding buiten de eigen grenzen.

Stedelijke en landelijke gebieden waar geen bio-energie productie plaatsvindt, kunnen wel indirect beïnvloed worden door een uitbreiding van bio-energieproductie. Deze regio's kunnen bijvoorbeeld profiteren als effecten weglekken naar deze regio's. Dit kan bijvoorbeeld zijn in de vorm van extra vraag naar producten en diensten die geleverd worden uit deze regio's. Aan de andere kant kunnen deze regio's ook geconfronteerd worden met hogere voedselprijzen. De uitgangssituatie van stedelijke gebieden is echter meestal beter wat betekent dat bio-energie kan zorgen voor een gelijkere verdeling. Deze studie onderstreept wel het belang van het verder desaggregeren van de sociaaleconomische effecten, omdat de effecten waarschijnlijk zullen verschillen tussen verscheidene inkomensgroepen binnen de stedelijke gebieden van een land. Geschoold personeel of mensen met een eigen bedrijf zullen beter weerbaar zijn tegen negatieve effecten dan de bezitloze onderlaag in de in de stad en makkelijker hogere voedselprijzen kunnen veroorloven. Toekomstig onderzoek zou hier op moeten ingaan.

8.2.3 Onderzoeksvraag 3

Welke strategieën zijn er beschikbaar om de concurrentie tussen verschillende vormen van landgebruik te verminderen en wat zijn de sociaaleconomische en broeikasgasemissie effecten daarvan?

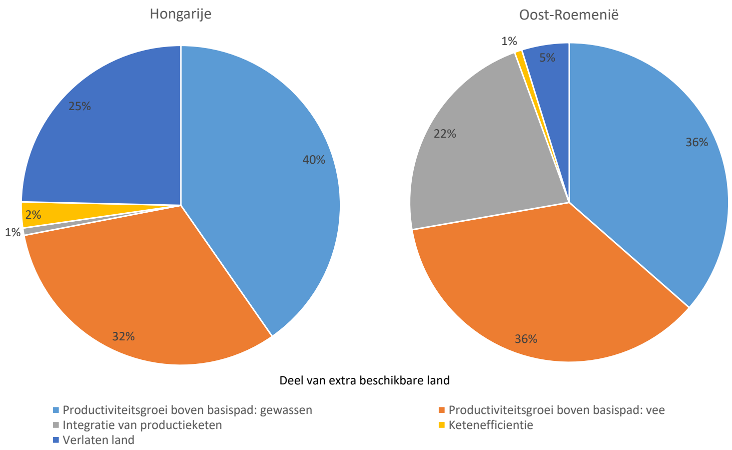
De toegenomen vraag naar landbouwgrond als gevolg van de uitbreiding van bio-energieproductie is een van de grootste duurzaamheidsproblemen van bio-energie. Bio-energie productie kan een bron zijn van directe of indirecte landgebruiksverandering die de broeikasgasemissiereductie van bio-energie teniet kunnen doen [58,59]. Ook kan het leiden tot conflicten rondom eigendom van land of voedselzekerheidsproblemen. Het is daarom van belang de concurrentie tussen bio-energieproductie en de rest van de landbouwsector te verminderen. In hoofdstuk 2, 3 en 4 zijn specifieke maatregelen behandeld die de vraag naar land en daarmee de concurrentie tussen verschillende vormen van landgebruik kunnen verminderen.

- Hoofdstuk 2 toonde een methode om het landgebruik in de gehele landbouwsector te verminderen, waardoor er meer ruimte vrijkomt voor de productie van bio-energie zonder de concurrentie te vergroten. Deze methode bestond uit drie maatregelen die efficiënt gebruik van land bevorderen en samen met het weer in gebruik nemen van recent verlaten landbouwgrond zorgen voor de beschikbaarheid van extra land voor bio-energieproductie. In dit hoofdstuk werd de methode toegepast in Hongarije.
- Hoofdstuk 3 bouwde verder op de methode van hoofdstuk 2 en paste deze toe in Oost-Roemenië om zo de methode te testen voor verschillende situaties. Bovendien werd in dit hoofdstuk de broeikasgasbalans van de maatregelen bepaald. De broeikasgasbalans van de maatregelen hielp bij het bepalen of de vier maatregelen effectief zijn om land beschikbaar te maken voor extra bio-energieproductie, zonder dat ze leiden tot extra broeikasgasemissies.

- In hoofdstuk 4, waar de sociaaleconomische effecten van suikerrietethanolproductie in Brazilië bepaald werden, zijn ook twee scenario's doorgerekend die maatregelen bevatten om concurrentie tussen verschillende landgebruikstypen te verminderen. Het eerste scenario ging hierbij uit van een sneller stijgende productiviteit in de gehele landbouwsector, terwijl de ander uitging van de introductie van tweede generatie ethanol, waardoor minder suikerriet, en dus minder landbouwgrond, nodig is voor de productie van dezelfde hoeveelheid ethanol. Van deze twee scenario's werden de sociaaleconomische effecten geanalyseerd.

Het achterliggende idee van de maatregelen die in **hoofdstuk 2 en 3** voorgesteld worden tegen indirecte landgebruiksverandering, is dat het mogelijk is het risico hierop te verkleinen. In deze hoofdstukken wordt dat gedaan door het verhogen van de efficiëntie en productiviteit van de gehele landbouwsector. Het gevolg van deze verbetering is dat niet bio-energieproductie met minder land toe kan en er land beschikbaar komt voor de productie van bio-energie. Dit land, plus het land dat recent in onbruik is geraakt, maken samen extra beschikbaar land dat gebruikt kan worden voor de productie van bio-energie met laag risico op verdringing. De maatregelen die hier toegepast werden zijn: i) productiviteitsverhoging bovenop de standaard ontwikkeling ii) vermindering van verliezen in de landbouwketen iii) verbeterde integratie van productieketens en iv) het gebruik van onderbenut agrarisch land. Deze maatregelen verminderden de vraag naar land in vergelijking met het basispad of verhoogden de hoeveelheid beschikbaar land. Het extra land kan worden ingezet voor de productie van bio-energie met laag risico op verdringing. Deze maatregelen zijn toegepast in studies voor Hongarije (hoofdstuk 2) en Oost-Roemenië (hoofdstuk 3). In het eerste geval werd berekend hoeveel ethanol geproduceerd zou kunnen worden indien het land ingezet zou worden voor maisproductie, en in het tweede geval werd uitgegaan van koolzaad voor biodiesel.

Beide studies tonen de potentie aan van de vier maatregelen, in zowel Hongarije als Oost-Roemenië kon in theorie meer biobrandstof geproduceerd worden met laag risico op verdringing dan verwacht op basis van het nationaal hernieuwbare energie actieplan [176,198]. In beide gevallen is een groot deel van de potentie wel afhankelijk van de productiviteitsverhoging. Figuur 8.4 toont het aandeel van elke maatregel in beide studies; hieruit kan worden opgemaakt dat het aandeel van productiviteitsverhoging in beide gevallen rond de 75% lag. Deze productiviteitsverhogingen zijn gebaseerd op wat er in het verleden gehaald is, of nu gehaald wordt in vergelijkbare regio's. Omdat het gat tussen de huidige opbrengst en de mogelijke opbrengst erg hoog is in beide regio's, is het naar verwachting relatief makkelijk de opbrengst te verhogen [140].



Figuur 8.4 Relatieve bijdrage van de verschillende maatregelen aan de totale beschikbaarheid van land voor biobrandstofproductie met laag risico op verdringing.

Het doel van de maatregelen om de concurrentie tussen verschillende landgebruiken te verminderen is het tegengaan van indirecte landgebruiksverandering en daarmee het voorkomen van extra broeikasgasemissies. Het is daarom ook van belang de broeikasgasemissies van de maatregelen te bepalen, om te voorkomen dat het verlagen van het risico op indirecte landgebruiksverandering leidt tot hogere emissies. In hoofdstuk 3 zijn de emissies van elk van de maatregelen bepaald en het totaal werd vergeleken met de broeikasgasbalans van de koolzaadbiodiesel om te bepalen of de in de Europese Unie verplichte 60% reductie ten opzichte van fossiele brandstoffen behaald kon worden bij de inzet van de maatregelen. De resultaten van hoofdstuk 3 toonden aan dat dit mogelijk is, maar alleen onder voorwaarden van duurzame intensivering. Bij duurzame intensivering wordt de productiviteit verhoogd, door middel van verbeterde productiemethodes, in plaats van toegenomen kunstmestgebruik [118]. Zonder duurzame intensivering was het mogelijk biodiesel te produceren met lagere emissies dan die voor indirecte landgebruiksverandering berekend zijn, maar dit voldeed niet aan de 60% reductienorm. Een ander probleem in de broeikasgasbalans, was de mogelijkheid dat de opbrengst op verlaten land zo laag kan zijn, dat de koolzaadbiodieselproductie niet opweegt tegen de verlaging van de koolstofopslag in de grond en aanwezige planten. Het verminderen van verliezen in de landbouwketen en verbeterde integratie van productieketens zijn maatregelen die altijd gunstig zijn, omdat deze andere productie verminderen en daardoor negatieve broeikasgasemissies met zich meebrengen.

De maatregelen die in **hoofdstuk 4** aan de orde kwamen zijn toegenomen productiviteit en de implementatie van tweede generatie ethanolproductie. In het Hoge opbrengst (High yield) scenario[10] werd de productiviteitsstijging verdubbeld ten opzichte van de standaard ontwikkeling in het basispad. Deze groei is nog bescheiden wanneer deze vergeleken wordt met andere regio's en historische groeipercentages [270]. Deze productiviteitsgroei leidde tot een vermindering van het land dat nodig is voor suikerrietproductie en het landgebruik voor andere landbouwactiviteiten (veehouderij, akkerbouw) verminderde ook, daarmee leidde het tot een toename in grasland en aangeplante bossen of werd verlaten. Implementatie van tweede generatie technologie vermindert het land dat nodig is voor suikerrietproductie, aangezien een groter deel van het suikerriet omgezet kan worden in ethanol. Omdat dit scenario ook een verhoging van de suikerriet productiviteit aannam, verminderde het landgebruik voor suikerriet met 36%, maar effecten in de rest van de landbouwsector waren beperkt (zie Tabel 8.3).

Tabel 8.3 landgebruiksverandering per categorie in Brazilië in verschillende scenarios.

	Ethanol scenario – vergelijking met *reference*	*High yield* scenario – vergelijking met *ethanol* scenario	*2G* scenario – vergelijking met *ethanol* scenario.
Bos	0%	1%	0%
Open graasland	-5%	-2%	5%
Aangeplant bos	-2%	7%	2%
Gewassen	0%	-5%	2%
Grasland	-1%	2%	1%
Suikerriet	38%	-13%	-36%
Graasland (aangeplant)	-1%	-3%	0%
Onbedekte bodem	0%	0%	0%
Verlaten	3%	12%	-2%

Verhoogde productiviteit in suikerrietproductie en verbeterde omzettingsefficiëntie naar ethanol verminderen de concurrentie tussen verschillende landgebruiken. In hoofdstuk 4 zorgde dit voor ruimte voor suikerriet en andere landbouwgewassen om productie uit te breiden. Dit leidde tot een toename in economische activiteit, met positieve gevolgen voor werkgelegenheid en economische groei in Brazilië. De ontwikkeling van tweede generatie ethanolproductie betekende dat minder suikerriet nodig zou zijn voor dezelfde hoeveelheid ethanol en verkleint daardoor de werkgelegenheid. Deze teruggang werd echter gecompenseerd door een groeiende werkgelegenheid in de rest van de landbouw.

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[10] Naast een referentie scenario (reference) met een lage groei in ethanolvraag tot aan 2030 in Brazilië (in totaal 28 miljard liter) waren er drie andere scenario's. Er was een scenario met hoge groei in ethanolproductie (ethanol, totale productie: 54 miljard liter), één met hoge productiviteitsgroei (ethanol: high yield) en een met implementatie van tweede generatie suikerrietethanol (ethanol: 2G). Deze laatste twee namen ook een grote groei in ethanolproductie aan (totale productie 58 miljard liter) naast de specifieke maatregelen om landgebruik te verminderen.

De resultaten in hoofdstukken 2, 3 en 4 toonden aan dat er een grote mogelijkheid is om de concurrentie met betrekking tot landbouwgrond tussen bio-energie en andere landbouwactiviteiten te beperken. In het algemeen richten deze maatregelen zich niet alleen op de bio-energiesector, maar op de landbouwsector als geheel. Indirecte landgebruiksverandering en de potentiele impacts ervan tonen de onderlinge verbondenheid van landbouw, landgebruik en bio-energie, aangezien de effecten van bio-energie doorwerken ver buiten de fysieke locatie van de bio-energieproductie. Dit onderstreept waarom het belangrijk is de concurrentie tussen verschillende landgebruiken te verminderen en waarom dit maatregelen in de gehele landbouwsector behoeft. Deze maatregelen kunnen genomen worden zonder dat het leidt tot hogere emissies, maar hoge productiviteitsstijgingen op basis van duurzame intensivering zijn daarvoor noodzakelijk. Daarnaast heeft de stijging van de landbouwproductiviteit positieve sociaaleconomische effecten; omdat de concurrentie vermindert kunnen andere sectoren relatief meer produceren wat gunstig is voor het BBP en de werkgelegenheid.

8.3 Kernconclusies

In dit proefschrift zijn de beschikbaarheid en geschiktheid van methodes voor ex-ante kwantificering van impacts van bio-energie geanalyseerd. Daarnaast zijn ook nieuwe methodes ontwikkeld en toegepast voor het bepalen van de impacts van bio-energie op landgebruik, werkgelegenheid, voedselzekerheid en economische ontwikkeling. Hierbij zijn studies uitgevoerd over Hongarije, Oost-Roemenië, Brazilië en Ghana. De studies varieerden in de onderwerpen en toegepaste methodes. Uit deze studies kunnen een aantal algemene conclusies worden getrokken over het kwantificeren van de effecten van bio-energie.

Het risico op landgebruiksverandering kan worden beperkt door een combinatie van maatregelen, gericht op de gehele landbouwsector in een land of regio. Deze maatregelen: productiviteitsverhoging bovenop de standaard ontwikkeling; vermindering van verliezen in de landbouwketen; verbeterde integratie van productieketens; en het gebruik van onderbenut agrarisch land, zijn toegepast in studies over Hongarije en Oost-Roemenië. In beide studies waren de maatregelen afdoende om land beschikbaar te maken voor de productie van bio-energie, zonder het risico op verdringing te vergroten. Verreweg de belangrijkste maatregel hiervoor is het verhogen van de productiviteit in de gehele landbouwsector, dus zowel akkerbouw als veeteelt. Aangezien dit niet alleen gericht is op bio-energie, maar op de landbouwsector als geheel, profiteert de gehele sector hiervan. Toegenomen productiviteit van andere gewassen en veeteelt, leidt tot hogere productie en verhoogt daarmee de economische activiteit en werkgelegenheid. Het verhogen van de productiviteit heeft wel als risico dat broeikasgasemissies meestijgen met de productiviteit als gevolg van toegenomen mechanisering of stijgend kunstmestgebruik. Doormiddel van duurzame intensivering is het mogelijk om productiviteit te laten stijgen, zonder dat broeikasgasemissies meestijgen.

De sociaaleconomische effecten van bio-energie verschillen tussen de regio's en huishoudtypes die geanalyseerd zijn in dit proefschrift. In de regio's waar bio-energieproductie zich uitbreidt, neemt de vraag naar land en arbeid toe, dit stimuleert de lokale economie en heeft directe positieve invloed. De concurrentie van andere bronnen van landgebruik kan de positieve effecten verkleinen als andere activiteiten worden verdrongen en werkgelegenheid en economische activiteit krimpt.

Hoewel de effecten het sterkst zijn in de regio's waar de bio-energieproductie zich uitbreidt, kunnen de effecten ook overslaan op andere regio's, bijvoorbeeld als deze goederen of diensten leveren aan de bio-energieproductieketen. Deze effecten zouden ook negatief kunnen zijn, bijvoorbeeld als hogere voedselprijzen niet volledig worden gecompenseerd door hogere inkomsten. Deze negatieve impacts zijn vooral problematisch in gebieden die niet profiteren van bio-energieproductie, maar wel met negatieve indirecte effecten worden geconfronteerd.

De sociaaleconomische effecten kunnen worden gestimuleerd door het verhogen van de productiviteit in de gehele landbouwsector, aangezien dit leidt tot hogere productie. Dit heeft een gunstig effect op de totale economische activiteit en werkgelegenheid. Bovendien zorgt verminderde concurrentie om land er voor dat ook de kans dat voedselzekerheid in het gedrang komt afneemt.

De meeste studies naar de sociaaleconomische effecten van bio-energie maken gebruik van macro-economische modellen. De brede reikwijdte van deze modellen maakt ze uitermate geschikt voor het kwantificeren van de impacts van bio-energie in de gehele landbouwsector en de rest van de economie. Daarnaast kunnen deze modellen ook de indirecte effecten meennemen.

Een nadeel van de macro-economische modellen die gebruikt worden, is dat deze in het algemene geaggregeerd zijn op nationaal of hoger niveau. Dit betekent dat de meeste studies de verdeling van de effecten tussen regio's of andere groepen niet inzichtelijk kunnen maken. Door macro-economische modellen te desaggregeren of verschillende modellen met elkaar te combineren wordt het mogelijk de analyse uit te breiden en inzicht te krijgen op lager aggregatieniveau. Dit werd hier bijvoorbeeld getoond voor microregio's in Brazilië (hoofdstuk 4) en stedelijke en landelijke huishoudens in Ghana (hoofdstuk 5). In het eerste geval werd een algemeen evenwichtsmodel gecombineerd met een landgebruiksmodel en een input-output model. In het tweede geval werd er een algemeen evenwichtsmodel gebruikt met meerdere huishoudens in één land.

De toepassing van deze methodes toonde dat er belangrijke verschillen zijn tussen de regio's en huishoudens, die niet zichtbaar zijn wanneer alleen op nationaal niveau beschouwd wordt. Dit onderstreept het belang van het analyseren van deze effecten op verschillende aggregatieniveaus.

In dit proefschrift wordt vooral de term biobrandstof gebruikt dat vooral gerelateerd is aan transportbrandstof. De maatregelen die land beschikbaar maken, kunnen echter ook toegepast worden om land voor andere gebruiken in te zetten. De bevindingen in dit proefschrift kunnen daarom toegepast worden op verschillende vormen van bio-energie en biomaterialen. De bevindingen tonen ook het belang van het analyseren van de duurzaamheidseffecten op sub-nationale aggregatieniveaus. Deze methodes kunnen helpen om de ex-ante kwantificering van de impacts van bio-energie te verbeteren. Dit kan bijdragen aan het voorkomen van negatieve effecten van bio-energie en het promoten van positieve effecten. Dit versterkt de duurzame inzet van bio-energie.

8.4 Aanbevelingen

Op basis van de resultaten in de hoofdstukken 2-6 kunnen een aantal aanbevelingen voor beleidsmakers en toekomstig onderzoek worden geformuleerd.

8.4.1 Voor beleidsmakers

Het gebruik van bio-energie en de productie van de grondstoffen kan zowel een risico als een stuwende kracht zijn voor bijna alle Sustainable Development Goals (duurzame ontwikkelingsdoelstelling, SDGs) van de Verenigde Naties [436]. De SDGs worden gezien als de ontwikkelingsagenda om de wereld te veranderen en dit onderstreept het belang van duurzame productie van bio-energie. Uit dit proefschrift kunnen een aantal aanbevelingen voor beleidsmakers worden gehaald die kunnen bijdragen aan het vergroten van de positieve effecten en het minimaliseren van de negatieve gevolgen voor milieu en sociaaleconomische omstandigheden.

- Om het risico van indirecte landgebruiksverandering als gevolg van bio-energieproductie te beperken, zal bio-energieproductie in het beleid moeten worden beschouwd als integraal onderdeel van de landbouwsector. Dit betekent dat producenten gestimuleerd moeten worden om hun methodes te verbeteren in de gehele landbouwsector. Zo wordt het risico op verdringing van andere productie, door toegenomen vraag naar land of andere markteffecten, verminderd. Huidig beleid houdt hier nog geen rekening mee, maar dit zou bijvoorbeeld onderdeel kunnen worden van certificeringsprogramma's waarbij regio's gecertificeerd kunnen worden voor de maatregelen die ze nemen tegen indirecte landgebruiksverandering.
- Bij een allesomvattend beleid gelden voor elke vorm van landgebruik dezelfde duurzaamheidscriteria. De indirecte landgebruiksverandering van bio-energie is de directe landgebruiksverandering van een andere vorm van landgebruik. Indien het lukt om elke vorm van uitbreiding op land met hoge biodiversiteitswaarde of met veel koolstof in de bodem te voorkomen, dan zijn de effecten van indirecte landgebruiksverandering als gevolg van bio-energieproductie ook aanzienlijk lager.
- De maatregelen die in dit proefschrift gepresenteerd zijn om indirecte landgebruiksverandering te beperken: productiviteitsverhoging bovenop de standaard ontwikkeling in het basispad, vermindering van verliezen in de landbouwketen, verbeterde integratie van productieketens en het in gebruik nemen van recent verlaten landbouwgrond kunnen bijdragen aan de productie van bio-energie met laag risico op indirecte landgebruiksverandering. Deze methode kan door beleidsmakers worden toegepast om voor hun eigen regio te bepalen hoeveel bio-energie geproduceerd zou kunnen worden.
- Om de maatregelen voor de verlaging van het risico op indirecte landgebruiksverandering goed te implementeren is het observeren en bijhouden van de uitwerking van belang. Dit kan helpen vroegtijdig problemen te identificeren, waar de ontwikkeling van de landbouwsector te traag gaat en de potentie om bio-energie daardoor afneemt. Tijdige signalering van problemen kan er voor zorgen dat er extra maatregelen genomen kunnen worden om de vooruitgang te stimuleren.
- Ondanks het feit dat veel beleidsmakers positieve sociaaleconomische ontwikkeling expliciet noemen als reden om te kiezen voor bio-energie, zijn sociaaleconomische indicatoren ondervertegenwoordigd in certificeringsprogramma's. Het opnemen goed kwantificeerbare sociaaleconomische indicatoren in certificeringsprogramma's kan bijdragen aan een transparante afweging tussen de verschillende positieve en negatieve effecten.

Het is van belang om de effecten van bio-energiebeleid en –projecten vooraf te kwantificeren, bij voorkeur op een laag aggregatieniveau om zo inzicht te krijgen in de verdeling van de effecten. Deze informatie kan bijdragen aan het maken van beslissingen op het gebied van bio-energie omdat op deze wijze de voor- en nadelen zowel in op het gebied van milieu als sociaaleconomische effecten goed en transparant gewogen kunnen worden.

8.4.2 Voor onderzoek

Op basis van de bevindingen in de dit proefschrift kunnen de volgende aanbevelingen voor toekomstig onderzoek gedaan worden:

- De maatregelen om het risico op indirecte landgebruiksverandering te verminderen die gepresenteerd zijn in hoofdstuk 2 en 3, zijn toegepast in een post-model analyse. In deze analyse zijn de terugkoppelingsmechanismen die aanwezig zijn in een macro-economisch model niet meegenomen, waardoor de indirecte effecten van de maatregelen niet berekend worden. Dit is het gevolg van de afwezigheid van de maatregelen in de macro-economische modellen. In toekomstig zou dit wel geïmplementeerd kunnen worden, bij voorkeur in combinatie met een landallocatiemodel. Wanneer deze maatregelen wél in het model geïmplementeerd worden zou ook een verdergaande sociaaleconomische analyse van de effecten gemaakt kunnen worden.
- De volgende stap in het onderzoek naar de maatregelen om het risico op indirecte landgebruiksverandering te verminderen, is het gebruik van praktijktesten. Hiermee kan worden bepaald in hoeverre de maatregelen daadwerkelijk gerealiseerd kunnen worden. Aangezien de maatregelen zich richten op de gehele landbouwsector behelst dit het werken met vele belanghebbenden, in tegenstelling tot reguliere certificeringsprogramma's die zich vaak richten op één producent.
- In hoofdstuk 4 en 5 zijn sociaaleconomische effecten van bio-energieproductie op sub-nationaal aggregatieniveau geanalyseerd. De verschillen die gevonden zijn tussen de verschillende microregio's en in inkomensgroepen in Brazilië in hoofdstuk 4 en de stedelijke en rurale gebieden in Ghana in hoofdstuk 5 toonden het belang aan van dergelijke analyse. Toekomstig onderzoek moet zich daarom richten op verdere analyse van deze sociaaleconomische effecten op lager aggregatieniveau, ook om de verdeling van de effecten mee te kunnen nemen. De desaggregatie van de effecten kan verder gaan dan wat is getoond in deze hoofdstukken, aangezien de verdeling van de effecten zal verschillen voor andere aspecten. Binnen een huishouden kan bijvoorbeeld sexe-ongelijkheid een rol spelen als vrouwen worden achtergesteld op mannelijke gezinsleden [553,561,624].
- Waar dit onderzoek zich vooral richtte op de verschillen tussen de regio's en hoe dit te kwantificeren is, zal toekomstig onderzoek zich verder moeten richten op wat de verschillen zou kunnen beïnvloeden.

- De blinde vlekken in de huidige ex-ante kwantitatieve sociaaleconomische analyse die in hoofdstuk 6 geïdentificeerd zijn, moeten geadresseerd worden in toekomstig onderzoek. Deze blinde vlekken gaan over analyse op laag aggregatieniveau en het gebrek aan methodes voor ex-ante beoordeling van impacts op de gemeenschap en sociale acceptatie. Deze blinde vlekken beperken de mogelijkheden voor het analyseren van de sociaaleconomische effecten en de verspreiding van de effecten.
- Het verbeteren van de kwaliteit van de beschikbare data die gebruikt wordt voor de social accounting matrices en evenwichtsmodellen kan helpen bij het verbeteren van de kwaliteit van de duurzaamheidsbeoordelingen. Vooral in ontwikkelingslanden waar de impacts hoog kunnen zijn en mensen minder weerbaar zijn ten opzichte van negatieve effecten is een goede analyse zeer belangrijk. Bovendien is een toename in beschikbare data voor verbeteringen in de landbouwsector (bijvoorbeeld duurzame intensivering) handig voor het opnemen van deze opties in macro-economische modellen.

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Curriculum Vitae

Marnix Brinkman was born on the 3rd of October 1988 in Utrecht. He stated his bachelor Science and Innovation Management at Utrecht University in 2006 and in 2009 he obtained his BSc and completed the honours programme of faculty of Geosciences. His bachelor thesis focused on the innovation system of torrefaction. He then continued at the same university to study Energy Science, and obtained his MSc in 2012. During his master programme he completed a five month internship at Rabobank on a study of shale gas and his MSc thesis on the life cycle assessment of the conversion of a waste stream of paper production to a bio-based plastic.

After a short teaching period at Albert Ludwigs University in Freiburg, Germany he started as junior researcher at the Copernicus Institute of Sustainable Development at Utrecht University in the spring of 2013. He worked on the ILUC prevention project and the BE-Basic project. For the latter he focused on the socio-economic impacts of bioenergy feedstock production. For this he worked with multiple macro-economic models and developed new methods for quantification of the socio-economic impacts. During his PhD he spent time at UNICAMP in Campinas, Brazil and at the headquarters of the UN Food and Agriculture Organisation in Rome. His research resulted in multiple peer reviewed articles in international journals and presentations at biomass conferences. During his PhD he taught in multiple bachelor and master courses at Utrecht University, mostly focused on life cycle assessment.

Colofon

Quantifying impacts of bioenergy: Model advancements to analyse indirect land use change mitigation and socio-economic impacts

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