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BIOFUELS FROM AGRICULTURAL BIOMASS - LAND USE CHANGE IN A SWEDISH PERSPECTIVE

Report from a project within the collaborative research program *Renewable transportation fuels and systems*

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Photo: Lovisa Björnsson.

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THE SWEDISH KNOWLEDGE CENTRE FOR RENEWABLE TRANSPORTATION FUELS

PREFACE

This project has been carried out within the collaborative research program *Renewable transportation fuels and systems* (Förnybara drivmedel och system), Project no. 40584-1. The project has been financed by the Swedish Energy Agency and f3 – Swedish Knowledge Centre for Renewable Transportation Fuels.

f3 Swedish Knowledge Centre for Renewable Transportation Fuels is a networking organization which focuses on development of environmentally, economically and socially sustainable renewable fuels, and

- Provides a broad, scientifically based and trustworthy source of knowledge for industry, governments and public authorities
- Carries through system oriented research related to the entire renewable fuels value chain
- Acts as national platform stimulating interaction nationally and internationally.

f3 partners include Sweden's most active universities and research institutes within the field, as well as a broad range of industry companies with high relevance. f3 has no political agenda and does not conduct lobbying activities for specific fuels or systems, nor for the f3 partners' respective areas of interest.

The f3 centre is financed jointly by the centre partners and the region of Västra Götaland. f3 also receives funding from Vinnova (Sweden's innovation agency) as a Swedish advocacy platform towards Horizon 2020. Chalmers Industriteknik (CIT) functions as the host of the f3 organization (see www.f3centre.se).

This project was carried out during 2015-2017. Besides the project group (authors of this report), a reference group was associated with the project. During two half-day workshops and email discussions, the reference group participated in determining the specific objectives of the papers that were written during this project, identifying relevant case studies, interpreting results and formulating relevant key messages for stakeholders such as policymakers. The reference group consisted of:

- Otto von Arnold, Jordberga Farm
- Pål Börjesson, Lund University
- Henrik Dahlsson, The Swedish Gas Association
- Håkan Eriksson, E.on
- Lisa Germundsson, Partnership Alnarp
- Ellenor Grundfelt, The Swedish Gas Association
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SUMMARY

The Swedish parliament has decided that by 2045, Sweden will not be a net emitter of greenhouse gases. There is also a goal to have a fossil fuel free transport sector by 2030. However, the transport sector is still dominated by fossil fuels and many efforts are needed to lower emissions. Sweden has a relatively high share of biofuels, around 20% of the energy use in domestic transportation. However, almost 90% of these fuels are imported or produced from imported feedstock.

In this study it was investigated whether and how the forecast biofuel demand for 2030 (20 TWh) can be met by biofuels produced from domestic feedstock. The scope was narrowed to biomass that does not cause land use change effects, since the European Commission has communicated that use of biofuels based on feedstock which could be used instead for food or feed will not be supported in the future. The reason for this policy decision is that increased biofuel production could stimulate direct land use change (dLUC) or indirect land use change (iLUC), leading to release of soil carbon and other greenhouse gases.

We found that about 4-10 TWh of biofuels can be produced from iLUC-free agricultural feedstock in Sweden; the range is dependent on the assumed biofuel conversion rate. The raw material studied was (1) agricultural residues, (2) ley produced on previously unused arable land, (3) crops from arable land such as intermediate crops and (4) intensification of ley cultivation.

Literature indicates that iLUC-free feedstock from other sectors (forest residues, industrial by-products and residues, and residues from other parts of society in Sweden, marine feedstock not included) could contribute 8-11 TWh biofuel. In other words, there is good potential to reach the required 20 TWh of biofuels by 2030 based on domestic iLUC-free feedstock. Lowering domestic consumption of meat and alcoholic beverages and lowering land use for recreational horse keeping could provide additional space for biofuel production.

However, steering towards iLUC-free feedstock would mean higher production costs compared to conventional biofuel production. It is therefore of particular interest to study the potential trade-offs between greenhouse gases and economics. The production of ethanol and biogas based on wheat grain and wheat straw was studied, where wheat grain represented the current production system and wheat straw represented an iLUC-free production system.

We conclude that wheat straw-based biofuels do not compete with food production and have lower greenhouse gas emissions than those based on wheat grain, but higher production costs. The reasons for higher production costs are mainly the lower biofuel yield and more expensive pre-treatment. In order to enable general conclusions on trade-offs when steering towards iLUC-free feedstock, more case studies are however needed with a larger set of studied feedstocks, biofuels and including other environmental impacts.

SAMMANFATTNING

Riksdagen har röstat igenom ett nytt klimatpolitiskt ramverk, vilket innebär att Sverige senast 2045 inte ska ha några nettoutsläpp av växthusgaser. Transportsektorn domineras fortfarande av fossila bränslen, och det behövs kraftiga insatser för att sänka utsläppen. Sverige har en relativt hög andel biodrivmedel, cirka 20% av energianvändningen inom transportsektorn. Närmare 90% av dessa biodrivmedel importeras dock, eller produceras från importerad biomassa.

I denna studie undersöktes om och hur det går att tillgodose transportsektorn år 2030 med den mängd biodrivmedel som behövs (20 TWh), baserad på inhemsk råvara. Omfånget på studien begränsas till biomassa som inte orsakar förändrad markanvändning. Detta eftersom EU har meddelat att biomassa som istället skulle kunna användas för mat eller foder inte kommer att stimuleras som råvara framöver. Anledningen till detta politiska beslut är en rädsla för att ökad produktion av biodrivmedel kan ge direkt eller indirekt förändrad markanvändning (förkortad iLUC, efter engelskans indirect land use change), vilket kan leda till utsläpp av kol och andra växthusgaser från mark.

I denna studie visar vi att cirka 4-10 TWh biodrivmedel kan produceras från iLUC-fri jordbruksråvara, det stora spannet beror på antagen omvandlingseffektivitet till biodrivmedel. De studerade råvarorna var (1) restprodukter från jordbruket, (2) vall odlad på nerlagd åkermark, (3) grödor från existerande odling så som mellangrödor (4) vall från intensifiering av pågående odling.

Genom litteraturstudier bedömdes den iLUC-fri råvara från andra sektorer (skogsrester, industriella biprodukter och avfall från andra delar av samhället, marina råvaror exkluderade) till 8-11 TWh biodrivmedel. Med andra ord har vi goda möjligheter att nå de 20 TWh biobränslen som krävs år 2030 baserat på inhemskt iLUC-fri råvara. Om vi minskar vår konsumtion av kött och alkohol, samt minskar markanvändning för hästar, kan vi producera ännu mer biodrivmedel.

Styrning mot biomassa med lägre iLUC skulle dock kunna innebära högre produktionskostnader jämfört med dagens biodrivmedelsproduktion. Det är därför intressant att studera potentiella trade-offs mellan växthusgaser och ekonomi. I det här projektet undersökte vi produktion av etanol och biogas baserat på vetekärna och vetehalm. Här representerar vetekärna det nuvarande produktionssystemet, och halm representerar ett iLUC-fritt produktionssystem.

Resultaten visar att halmbaserade biodrivmedel visserligen inte konkurrerar med livsmedelsproduktionen och har lägre utsläpp av växthusgaser jämfört med vetekärna, men högre produktionskostnader. De högre produktionskostnaderna beror framförallt på lägre utbyte av drivmedel och dyrare förbehandling av råvaran. För att kunna dra generella slutsatser om trade-offs av iLUC-fri råvara behövs dock fler fallstudier där fler råvaror, biodrivmedel studeras, och andra miljöpåverkanskategorier inkluderas.

CONTENTS

1 INTRODUCTION

1.1 THE PROJECT

This project has been carried out during 2015-2017 within the collaborative research program *Renewable transportation fuels and systems* (Förnybara drivmedel och system), Project no. 40584-1. The project has been financed by the Swedish Energy Agency and f3 – Swedish Knowledge Centre for Renewable Transportation Fuels. The main outcomes of this project have been published in two scientific papers (Prade et al, 2017; Lantz et al., 2017), and the present report summarises the published results, and adds aspects that were not included in the papers.

1.2 BACKGROUND

Many industrialised and developing countries have implemented policies for stimulating production of biofuels. The European Union (EU) has a target of 10% renewable fuels in the transport sector by 2020. Sweden stands out by having met the EU target already in 2011 and by having a share of above 20% in 2015 when including electricity and allowing for double accounting of some fuel categories (Eurostat, 2017).

However, Sweden has even higher ambitions. In June 2017, the Swedish parliament voted to accept a new bill for a climate policy framework. This bill states that by 2045, Sweden will not have any net emissions of greenhouse gases into the atmosphere and thereafter will achieve negative emissions. The transport sector is the only energy sector in Sweden that is still dominated by fossil fuels, and the bill sets a specific target for this sector whereby greenhouse gas emissions from domestic transport (excluding domestic aviation included in the EU Emissions Trading System) are to decrease by at least 70% by 2030 compared with 2010 (Swedish Government, 2017).

The total amounts, type of biofuels and the shares of imported biofuels in Sweden are variable over time and highly policy dependent (Sanches-Pereira & Gómez, 2015). In 2016, 15 TWh of biodiesel (HVO and FAME) were consumed, while ethanol and biogas consumption was 1.3 TWh each. A large share, 89%, of these fuels was imported or produced from imported feedstock (SEA, 2017).

In the political agreement on a fossil-free society by 2045, no specific goals are set for the development of domestic biofuel production based on nationally available biomass. However, good domestic availability of biomass suitable for biofuel production is important for many reasons, including security of supply, regional development, sustainability and traceability. In the present study it was investigated whether and how the predicted biofuel demand in 2030 can be met by biofuels produced from domestic feedstock.

The implications of introducing biofuel mandates have been under heavy debate. One concern is that increased biofuel production will stimulate land use change, leading to large amounts of soil carbon and other greenhouse gases being released to the atmosphere. In such discussions, a distinction between direct and indirect land use change is often made.

Converting land from one state to another (e.g. from forest to agriculture) to grow biofuel crops is referred to as direct land-use change (dLUC), since there is a direct link between the biofuel crop and the converted land. However, if biofuel crops are sourced from existing agricultural land, this might displace food or feed crop production, which may lead to land conversion elsewhere, referred to as indirect land use change (iLUC). ILUC effects are closely coupled with supply and demand for agricultural commodities, which can ultimately lead to a change in market behaviour causing changes in land use and related greenhouse gas emissions. In other words, iLUC are the changes in land use that take place as a consequence of a bioenergy project, but take place in another geographic location (Berndes et al., 2012).

For iLUC, it is common to use economic equilibrium models to quantify the effects. These tools are complex optimisation models and require in-depth understanding in order to be used (Ahlgren & Di Lucia, 2014). Several alternatives to the economic models have been developed using different approaches, often based on a causal descriptive or normative approach. These models can be based on a combination of biological and physical land models, assumptions on elasticities or elasticity values taken from literature, historical statistical data etc. These approaches tend to be simpler than economic models, reducing both the computational effort and the data requirement (De Rosa et al., 2016). However, while simplified models have lower parametric uncertainty, they lose accuracy and increase the model uncertainty. An overview of causal descriptive models for estimating iLUC can be found in Appendix 1.

Due to the much debated land use issue, the EU has amended its biofuel policy with the inclusion of so-called iLUC factors for reporting, which add a greenhouse gas emissions penalty to certain feedstock (cereals and other starch-rich crops, sugars and oilseed crops) for biofuel production. The European Commission (EC) has also communicated that use of biofuels based on feedstock which could be used instead for food or feed will not be supported in the future (EC, 2015). Considering this policy situation, it is of particular interest to investigate the potential for domestic biomass supply that can be expected to have a low land use change effect.

However, steering towards lower iLUC could cause higher greenhouse gas emissions elsewhere in the production chain and could also result in higher production costs. It is therefore of particular interest to study these potential trade-offs.

At the same time, biomass use for purposes other than energy production is increasing, e.g. in feed for horses, feed for meat production and production of alcoholic beverages from Swedish feedstock. An estimation of how much land is used for biofuel production is lacking, and it is unclear how large land use for biofuel is in proportion to other activities. This is important information in a land use policy perspective when different land uses have to be weighed against each other, considering that land is a restricted resource.

1.3 AIM

The overall aim of this study was to investigate how Swedish biofuel production will affect the use of arable land in Sweden. Specific objectives were to:

- map Swedish land use of biomass for biofuels in relation to other uses, feed for horses, feed for meat production and cereal grain for production of alcoholic beverages;
- discuss and suggest scenarios for Swedish biofuel production and estimate the potential for agricultural biomass feedstock that does not cause iLUC;
- study trade-offs between greenhouse gas emissions, land use change emissions and economic aspects in four case studies of Swedish biofuel production.

2 METHODS

Below we give a short summary of the methods used. A more detailed description can be found in the project outcomes published in scientific journals (Prade et al., 2017; Lantz et al., 2017).

2.1 MAPPING LAND USE IN SWEDEN

In mapping land use in Sweden, data from Statistics Sweden was used. The results are presented as the Swedish average land use per person and year. Yield and land use statistics are reported by type of crops grown, and not by end-use of the crops. We therefore made several assumptions on how crops are used, and the conversion rates that apply when they are used e.g. for biofuel production.

We also made assumptions about the proportion of total cereal grain production used for animal feed, horse feed, alcoholic drink production and biofuels. For animal production, we used data from a survey where consumers were asked what they consume, and then counted upwards what this means in terms of animal feed and land use, mainly using data taken from Röös et al. (2015). For estimating the horse feed demand, data on the annual feed requirements per horse (Jansson et al., 2012) and the average number of horses in Sweden was used.

Data for land use abroad and exports were mainly taken from Statistics Sweden, combined with data from Röös et al. (2015).

2.2 SCENARIOS FOR SWEDISH BIOFUEL PRODUCTION

The work on development of scenarios for Swedish biofuel production was divided into four sub-tasks (Prade et al, 2017).

First, we needed to establish how much biofuel will be required in the future. To estimate this, we carried out a review of political targets and scenarios for expected development until 2030. The resulting estimated demand for biofuels is mainly dependent on assumptions on expected transportation needs, developments in vehicle technology and fuel consumption, and the rate of electrification of the car and truck fleet.

The future production of biofuels based on agricultural feedstock was estimated as the expected future biofuel demand minus the ability of other sectors to produce biofuels. A review of how much biofuel can be produced by other sectors such as forestry (forest residues), industrial by-products and residues, and residues from other parts of society (excluding mine feedstock) was carried out. We developed two scenarios; one in which these sectors produce a high amount of biofuel and one in which they produce a low amount of biofuel. The remaining part was assumed to be met by agricultural feedstock, with different amounts for the two scenarios.

Third, we examined the potential for agricultural feedstock that does not cause land use change to meet the future biofuel demand by a detailed mapping of current cultivation of feedstock, land in fallow and abandoned land. For the assessment, data on crop cultivation area and standard yield calculated from 15-year averages and an 8-year regression analysis were available for major crops in official Swedish statistics. For other crops, such as grass leys, 10-year average yield data were available. Since most yield data refer only to harvested parts of the crop, amounts of crop residues had to be estimated. Yield and e.g. straw/rain ratio were used to calculate the biomass potential for all major agricultural crops and residues. Potential from additional crops including intermediate crops and crops grown on Ecological Focus Areas (EFA) was simulated. The assessment of the potential contribution of agricultural biomass to the supply of biofuels in 2030 was based on the current crop production situation in Sweden. This approach assumes that in the period until 2030, no major changes will occur in the cultivation area of the current crop portfolio, which is likely unless powerful measures (e.g. subsidies) are implemented in the next few years.

Lastly, the biomass potential was recalculated to potential biofuel production for two conversion scenarios of the feedstock, high and low, representing conversion of biomass to biogas and ethanol, respectively. Data for conversion efficiency was based on literature (see assumptions in Prade et al., 2017). Due to the short time until 2030 we did not account for technical development, e.g. of pre-treatment processes and fermentation processes, that will likely improve conversion efficiencies, especially for lignocellulosic feedstock.

2.3 TRADE-OFF GREENHOUSE GAS EMISSIONS AND ECONOMICS

We performed four case studies for Swedish biofuel production where potential trade-offs between greenhouse gases, land use and economic aspects were studied (Lantz et al., 2017):

- production of ethanol based on wheat
- production of ethanol based on straw
- production of biogas based on wheat
- production of biogas based on straw

where wheat grain represented the current production systems and wheat straw represented iLUC-free production systems.

For calculation of greenhouse gases related to the production chain, including land use emissions, life cycle assessment (LCA) methodology was used. LCA is a method in which the environmental impact of a product or service is calculated over the product’s entire life cycle, from cradle to grave.

For biofuel producers/sellers, there are sustainability criteria to be met in order to obtain tax reductions. The sustainability criteria for biofuels are regulated within the EU by the Renewable Energy Directive (RED) (EC, 2009), where a simplified LCA methodology is used to calculate greenhouse gas emissions. The RED uses e.g. allocation of emissions based on lower heating value between products and by-products. Furthermore, residues such as straw from cereal are counted as free of emissions up to point of collection.

However, in an LCA according to the ISO standard (ISO, 2006), system expansion is preferred over allocation. For straw, this means e.g. that soil carbon changes due to straw removal should be included and that if straw has an alternative use, the effects of redirecting straw to biofuel production must be accounted for in the LCA. For the calculations, both the RED and the ISO methodology was used.

The feedstock cost was calculated for different production regions in Sweden, reflecting the impact of local agricultural conditions and feedstock availability in different regions considering competing utilization. The transportation cost for feedstock and digestate from biogas production is based on the calculated transportation distance, assumptions on average velocity and time for loading and unloading as well as hourly rates for different transport carriage. Here, we only present the aggregate values. The more detailed regional data can be found in Lantz et al. (2017).

The biofuel production cost was calculated for different cases chosen to represent current biofuel production systems based on crops as well as a potential future production based on crop residues. Data on investments, operating costs and estimated yields of biofuels and co-products etc. was based on a literature review updated with current market data. Details on assumed interest rates and depreciation time can be found in Lantz et al. (2017).

3 RESULTS

3.1 LAND USE IN SWEDEN

Figure 1 shows our estimate of how the average Swede uses arable land, in Sweden and abroad. After reduction for export, the average Swede is estimated to use 0.39 hectares of arable land.

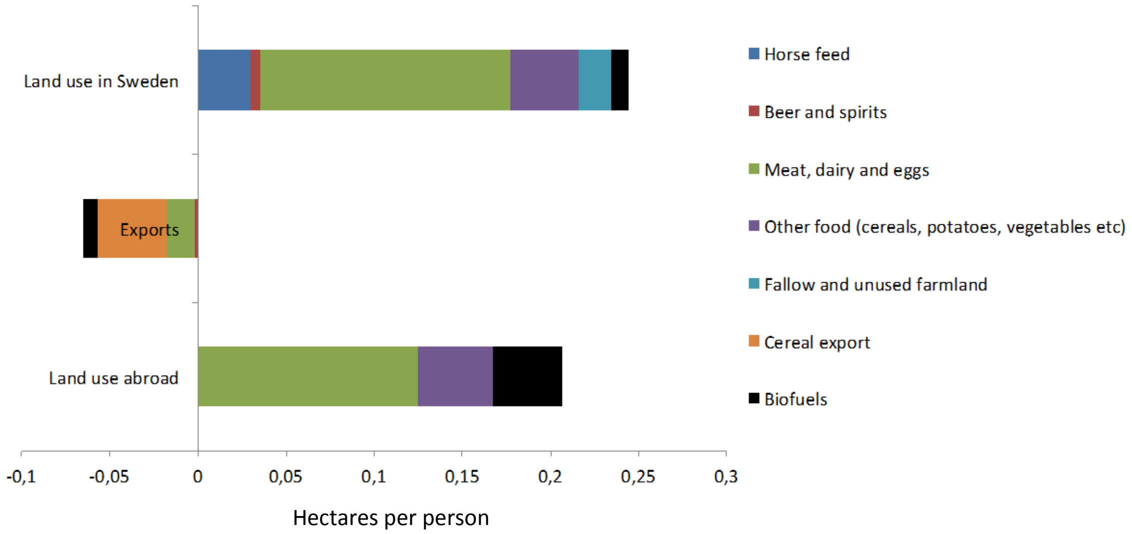

Figure 1. Use of arable land at home and abroad (pasture excluded) by the average Swede. Products that are exported are plotted as negative land use.

From this diagram, we can draw a number of interesting conclusions. First, average Swedish consumption requires a larger area of land than is available domestically and we import a lot of products. We included land use for all imports, including e.g. fruit, coffee, tea and chocolate.

As far as biofuels are concerned, about 4% of the Swedish arable area is used for this purpose, and that most of the domestic biofuel production is currently exported (Figure 1). The majority of Swedish biofuel production is grain-based ethanol and part of this biofuel area could be accounted for in meat and dairy production, as one metric tonne (ton) of grain for ethanol yields 0.3-0.4 tons of animal feed as a by-product.

Sweden imports a large amount of biofuels that occupy land abroad. By-products from the palm oil industry (palm fatty acid distillate, PFAD), which actually constitute a major part of Swedish biofuel imports, are not included, however. This is because PFAD is currently classified as a waste/residue, meaning that all land use is allocated to the main product, in this case palm oil.

Further, the production of meat, dairy and eggs occupies a large part of the average Swede’s land use, both abroad and in Sweden. Feed for horses and raw materials for beer and spirits also occupy large arable areas in Sweden, approximately 12% and 3% respectively. In total, land for meat production, horse feed and cereal grain for alcoholic beverages occupies 73% of total Swedish available land and any reductions in the consumption pattern of these items can free up land for biofuel feedstock production. In addition, there is quite a lot of land in fallow that could be used for biofuel production, land in fallow has been stable at a level of about 6% (150 000 ha) since 2008.

Figure 1 is a compilation of data from different sources and therefore has some uncertainties. For example, the sources have different perspectives. Some are national statistics recalculated to a per person basis, while other values are based on the "Riksmaten" survey (Röös et al., 2015), where consumers report what kind of food they eat. Moreover, the data sources have different years of origin, and generalisations were made about yield levels and yields of biofuels.

3.2 SCENARIOS FOR SWEDISH BIOFUEL PRODUCTION

3.2.1 Biofuel demand in 2030

Several inquiries and investigations in which different scenarios for the development of the transport sector have been performed. We have reviewed some of these approaches and present som of them (Figure 2), to reach an understanding of how much biofuels will be needed in 2030.

The changes required to reach the 2030 policy target will be a combination of reduced transport demand and technical solutions such as higher energy efficiency, electrification and use of biofuels. The assumptions regarding these developments differ between studies and the assumed total amount of energy in the transport sector in 2030 also varies (Figure 2). For comparison, 92 TWh was actually used in the Swedish domestic transport sector in 2015 (SEA, 2017). None of the scenarios reviewed is totally free from use of fossil fuels.

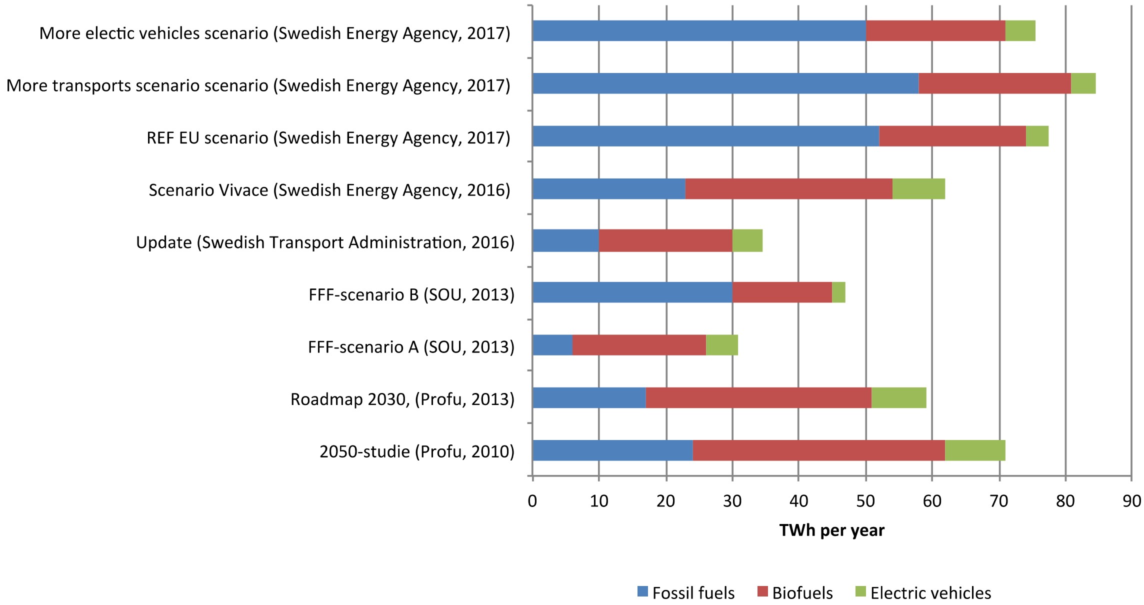

Figure 2. Review of inquiries and investigations of the use of fuels in the Swedish transport sector in 2030.

Based on the above review, we decided to set the expected biofuel demand in 2030 to 20 TWh/a. These are the same values as in the scenario described by the Swedish Transport Administration (2016), which has been important as a background to setting the 2030 target for the transport sector.

3.2.2 Biofuel production from different sectors

It was investigated how much domestically produced biomass from arable land may contribute to the national biofuel targets. With a total demand of 20 TWh in 2030, an estimation of the contribution of biofuels from other domestic sources of biomass in 2030 was first carried out, in order to determine the need for agricultural iLUC-free biofuel feedstock.

The potential contributions from by-products and residues from the forest sector and from industrial and societal waste fractions were estimated based on inventories and scenario descriptions from different sectors, or on own assumptions if such descriptions were lacking. The estimated contribution from each sector is described more in detail in Prade et al. (2017), and the outcome is summarized in Table 1. The total biofuel production from by-products and residues from Swedish forestry, industry and society by 2030 was estimated to 8-11 TWh/a, implying that biofuel production from agricultural biomass should provide between 9 and 12 TWh/a for a 100% domestic feedstock base.

Table 1. Range of biofuel contributions in 2030 from different sectors. A low and a high contribution are estimated. A more detailed description and list of references can be found in Prade et al. (2017).

Biomass/biofuel chain	Biofuel contribution (TWh/a)	Comment
Other sectors		
Forestry residues, biofuel type not defined	3.9-6.0	Average to good economic conditions and technical development
Forest industry residues to hydrotreated vegetable oil bio-diesel (HVO)	1.49-1.68	80-90% of available tall oil (based on current pulp and paper production) is refined to HVO
Forest industry residues to biogas	0.10-0.14	10% of the energy potential in the fibre sludge is extracted as biogas, whereof 50-70% is upgraded
Food industry waste to HVO	0.2-0.3	25-38% of the potential available for biogas production is assumed to be fats suitable for HVO production
Food industry waste to biogas	0.3-0.4	38-50% of the potential that has been described as available for biogas production is assumed to be realised
Food industry waste to ethanol	0.2-0.3	Rough estimate based on current production
Household waste to biogas	0.72-0.96	60-80% of the food waste in households is source-separated and used for biogas production
Sewage sludge to biogas	0.57-0.66	70-80% of the biogas produced is upgraded
Manure to biogas	0.38-0.77	25-50% of manure is used for biogas production, whereof two-thirds in co-digestion plants with upgrading of 90% of the gas
Total from the above sectors	**7.9-11.2 (8-11)**	
Total needed from agriculture	**8.8-12.1 (9-12)**	
Total biofuels in 2030	**20**	

3.2.3 iLUC-free feedstock

The iLUC concept is closely coupled with supply and demand for agricultural products. By this definition, if a feedstock has no demand, utilisation for biofuel production does not imply an iLUC effect and can be considered 'iLUC-free'.

However, if a feedstock is to be utilised in the future for biofuel production, it obviously has a potential demand on the market. However, in this case it can be argued that the demand is within the biofuel market and there is no other competition for the biomass. On the other hand, the possibility that the biomass feedstock will find other uses in the future, e.g. as feedstock for chemicals, bio-plastics, textiles, pharmaceuticals etc., cannot be ruled out.

As can be seen, the concept of iLUC-free feedstock is not easily defined. We treated iLUC-free feedstock as a highly theoretical concept and made the assumption that the biomass has no other uses and can be utilised for biofuel production. While this might not yield a true picture of the future potential of biofuel feedstock, it gives an order of magnitude that can be important when discussing future developments in biofuel production, especially since policy makers have sent clear signals that iLUC-free is the preferred feedstock (EC, 2015).

With this argumentation, we defined four different categories of iLUC-free biomass from agriculture (Prade et al., 2017):

1. Agricultural residues.
2. Crops produced on previously unused arable land.
3. Additional crops from arable land.
4. Additional biomass from arable land via intensification.

iLUC-free biomass (Categories 1-4) corresponded to an energy potential of 20 TWh in biomass (Figure 3), with the main contributor being grass ley from intensification where an average increase of 30% in grass ley yield compared with present was assumed. This can be compared with current total output from agricultural production in Sweden, which we estimated to an energy potential of 68 TWh annually, including crops and residues.

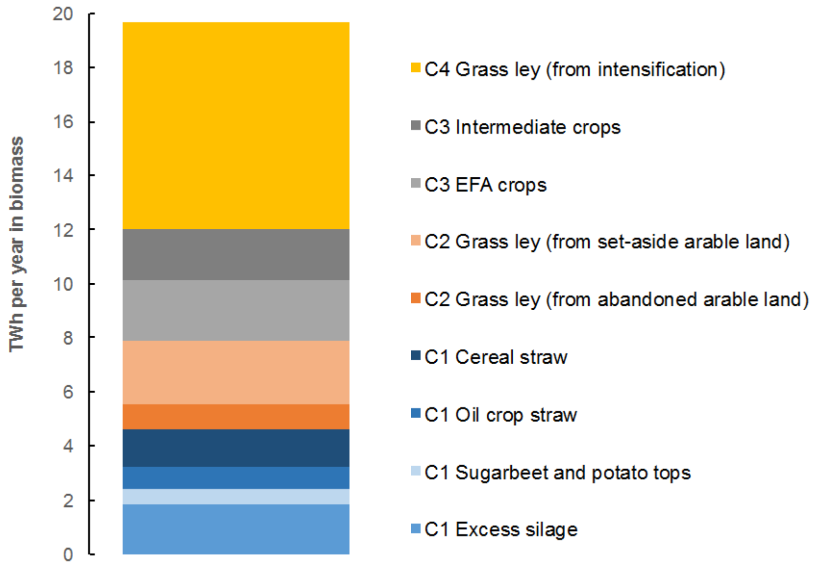

Figure 3. Potential for iLUC-free biomass production in Sweden in the different categories C1-C4 (given as higher heating value of the feedstock).

3.2.4 iLUC-free biofuel potential

To determine whether estimated iLUC-free biomass will be enough to cover the biomass demand in 2030, which we estimated to be 9-12 TWh/a, we calculated a conversion of the feedstock in a high and a low scenario, representing the conversion of biomass to biogas and ethanol, respectively, given as lower heating value of the biofuel.

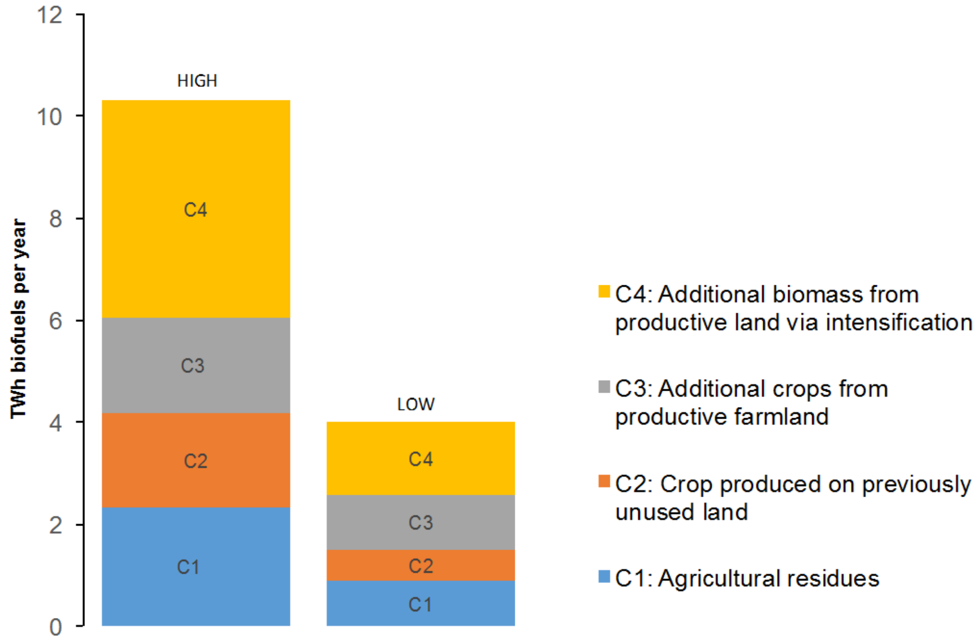

Figure 4. Potential for production of iLUC-free biofuels (category C1-C4) for a high and a low feed-stock conversion scenario.

As can be seen in Figure 4, about 4-10 TWh of biofuels can be produced from iLUC-free feed-stock, depending on the conversion rate. Together with the 8-11 TWh from other sectors, Sweden thus has good opportunities to meet the required 20 TWh of biofuels by 2030 based on domestic iLUC-free feedstock.

3.3 TRADE-OFF BETWEEN GREENHOUSE GAS EMISSIONS AND ECONOMICS – A CASE STUDY

Steering towards lower iLUC could cause higher dLUC and greenhouse gas emissions from the production chain and could result in higher production costs. Therefore, we examined these potential trade-offs. In case studies, we investigated the production of ethanol and biogas based on wheat and wheat straw, where wheat grain represented the current production system and wheat straw represented an iLUC-free production system. It was assumed that straw was removed at a rate that would not lower soil carbon content.

The greenhouse gas emissions from the four production systems studied, calculated with the two LCA methodologies RED and ISO (further explained in the Methodology section), are shown in Figure 5. The two methodologies yielded clearly different results; the straw-based systems gave lower emissions than the wheat grain-based systems, for both ethanol and biogas production, in both methodologies (Figure 5). Furthermore, all four systems gave lower greenhouse gas emissions in comparison with fossil fuels. The suggested EU fossil fuel reference is 94.1 g CO_2-eq per MJ, meaning that the systems studied provided a 69-108% reduction in emissions. The requirement set by the EU sustainability criteria is 60% reduction (EC, 2015).

The suggested EU iLUC factor for cereals is 12 g CO_2-eq per MJ biofuel (EC, 2015). Adding this to the figure obtained in the RED wheat grain ethanol scenario gives total emissions of 33 g CO_2-eq per MJ ethanol, or a 65% reduction, meaning that even with the iLUC factor for cereals, wheat-based ethanol is able to meet the current emissions reduction requirement.

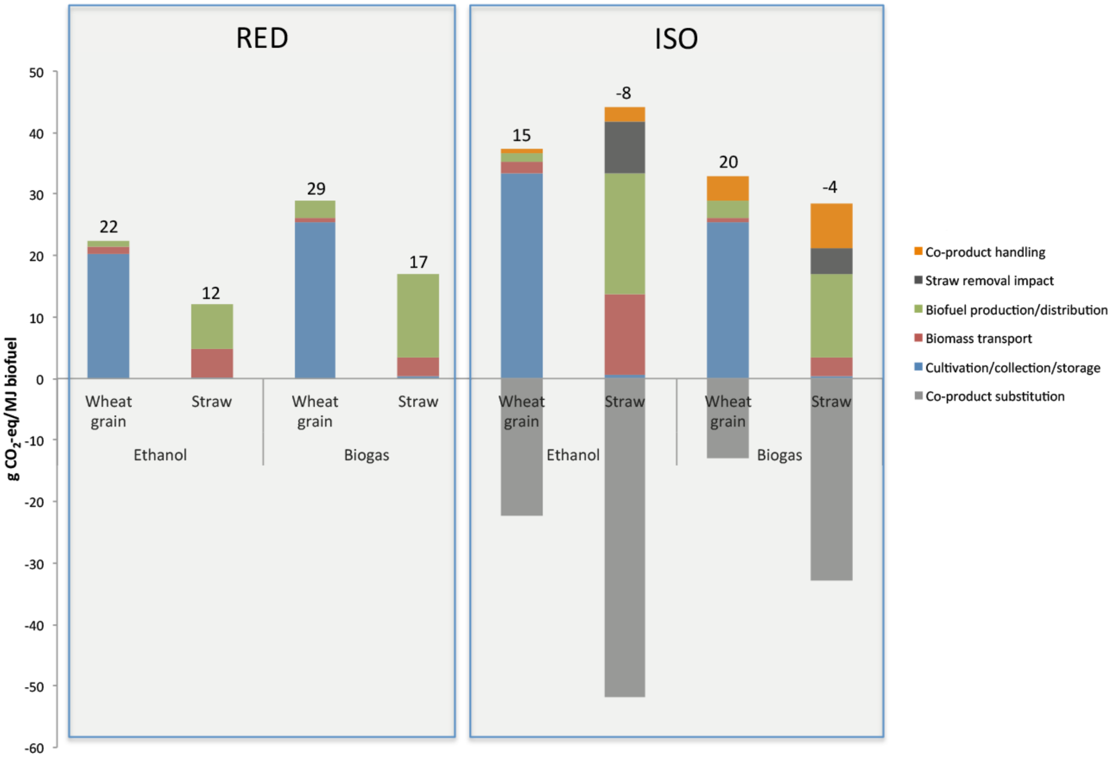

Figure 5. Calculated greenhouse gas emissions in ethanol and biogas production systems based on wheat grain and wheat straw, calculated using the RED and ISO methodologies. Numbers on top each bar represent the total value.

The calculated production cost for biogas and ethanol show that although straw is a much cheaper feedstock on a dry matter basis, the overall production cost increase as compared to biofuel production based on grain (Figure 6). The reason are e.g. a lower biofuel yield and a more expensive pre-treatment. Ethanol from wheat grain, which is commercially produced in Sweden today, has the lowest production cost.

All biofuel systems generate co-products such as DDGS, lignin pellets and digestate. These co-products diversify the production and generates an extra income for the producer. However, with current market prices, the impact is minor except for the ethanol from grain system. In fact, income from co-products are the reason that ethanol from grain has the lowest production cost.

For comparison, current market price of gasoline is approximately 40 Euro per GJ. Thus, the production cost even for straw-based biofuels is in the same range as today's market price for gasoline, including energy and CO_2 tax.

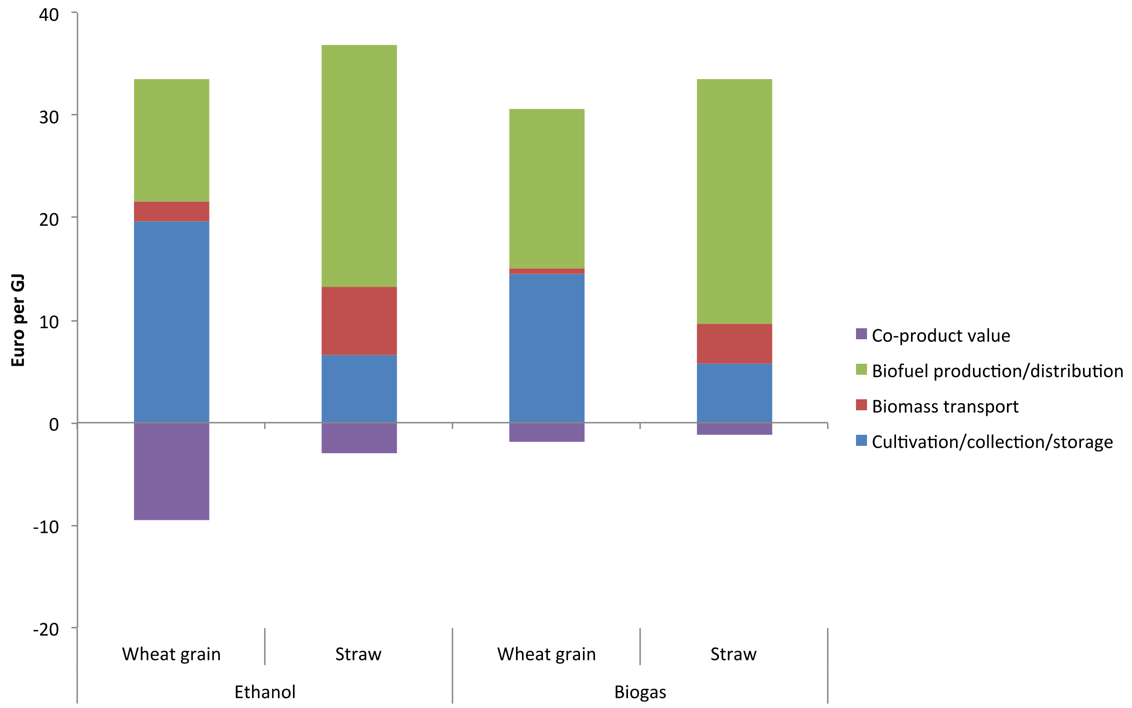

Figure 6. Production cost of the studied systems.

To conclude, straw-based biofuels based on sustainably recovered straw do not compete with food production and have lower greenhouse gas emissions compared to wheat grain, but higher production costs. However, in order to enable general conclusions on trade-offs when steering towards iLUC-free feedstock, more case studies are however needed with a larger set of studied feedstocks, biofuels and including other environmental impacts.

4 DISCUSSION AND CONCLUSIONS

We estimated the potential for iLUC-free feedstock that could be used for biofuels in the year 2030. We show that about 4-10 TWh of biofuels can be produced from iLUC-free agricultural feedstock, the range is dependent on the assumed conversion rate to biofuel. Based on the literature, we estimated that iLUC-free feedstock from other sectors (forest residues, industrial by-products and residues, and residues from other parts of society) can contribute 8-11 TWh biofuel. In other words, Sweden has good opportunities to meet the required 20 TWh of biofuels by 2030 based on domestic iLUC-free feedstock. We also show that straw-based biofuels, which under our definition are iLUC-free, do not compete with food production and have lower greenhouse gas emissions but higher production costs than wheat grain-based biofuels.

We made the assumption that feedstock which has no market demand is iLUC-free. However, it is possible that biomass feedstock will find other uses in the future, e.g. as feedstock for chemicals, bio-plastics, textiles, pharmaceuticals etc. Conversely, feedstock currently used for food or feed applications may become available for future biofuel production. We demonstrated that the use of land for meat production, horse feed and cereal grain for alcoholic beverages occupies 73% of total Swedish land available and any reductions in the consumption pattern of these items can free up land for biofuel feedstock production.

The critical limiting factor for feedstock production, i.e. availability of arable land area, will most likely lead to political prioritisation of uses, as suggested e.g. in the EU regulations on the promotion of use of energy from renewable sources after 2020 (EC, 2016). While constraints on EU level are currently restricted to transportation biofuels, similar developments can be anticipated in other parts of the energy sector, such as in the heat and power production (EC, 2014). If we in the future see similar restrictions on other life style choices that lead to a high (and unsustainable) use of arable land, such as a high meat consumption or feed for recreational horses, it may influence the available feedstock for bioenergy.

There are already some frameworks that biofuel producers can apply to ensure that the feedstock they use is low-iLUC. The Responsible Cultivation Areas (RCA) methodology (Dehue et al., 2010) focuses on what companies and land-use planners can do to minimise iLUC-risk, e.g. by additional production and cultivation in remote areas. The Low Indirect Impact Biofuel (LIIB) methodology developed by Ecofys (2012) in cooperation with several NGOs identifies yield increases, integration of bioenergy and agriculture models, production on unused land and biofuel production from residues as low-iLUC measures. That methodology focuses to a large extent on how the certification process for low-iLUC could be designed. Both methodologies acknowledge that low-iLUC feedstock and the certification process will involve an additional economic cost.

We investigated straw as a potential iLUC-free feedstock in this project. A full technical extraction of straw may lead to a decrease in soil organic carbon and soil quality and an increase in fertilisation requirements. However, when producing biogas and ethanol the residues/by-products can be used as biofertilisers, which can return nutrients and carbon to the soil (Björnsson et al., 2016). Thus, for these biofuels, the removal of residues does need not be a problem regarding nutrient and carbon conservation aspects, as long as the biofertilizer is recirculated to arable land. Results for climate impact when removing more straw, so that soil carbon balance is disturbed, is further discussed in Lantz et al. (2017).

Sweden has great potential for production of residues from forestry, agriculture, industry and society. Together, all of these sources can contribute to a transition to a more sustainable transport system, where the dependence on imported raw materials and fuels is reduced. This study focused on the iLUC-free potential from farmland and showed that there is a large variety of feedstock available from arable land. To bring this feedstock into use, it will be necessary to:

- make it financially attractive to collect unused crop residues
- put unused and fallow land into production
- increase yields in existing ley crop cultivation
- introduce intermediate crops
- use the crops grown on ecological focus areas (EFAs).

Presently, the EU regulation on biofuels is complex (Harnesk et al., 2017), and the uncertainty of future regulation changes can halter investments in iLUC-free biofuel production. It is of high importance that we have transparent and long-term regulations, if we want to increase investments in these types of fuels.

To achieve the target of 70% lower greenhouse gas emissions by 2030 from the transportation sector we need biofuels, but we also need to carry out extensive structural changes that reduce transportation work and we need to use vehicles with higher efficiency, including electric vehicles. In order for Sweden to be a pioneer country in the transition to a fossil fuel free transport sector, we need to include a high realization of domestic biofuel production. We should not shift a dependency on imported fossil fuels, for a dependency on imported biofuels.

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APPENDIX 1

Table A 1. Overview of causal descriptive models for estimating iLUC.

Source	Model type	Strengths	Weaknesses
Schmidt et al., 2015	Biophysical	Wide scope, applicable in many contexts, to any crop and region. Generic framework, simplification with country- and crop-generic approach reduces uncertainty. Consistent with LCA methodology, both consequential and attributional. Accounts for regional- and land category-specific differences in production capacity (NPP). Breaks down iLUC into manageable parts, includes both expansion and intensification effects. Avoids amortisation by time-weighted GWP.	Limited to situation of general net-deforestation (iLUC modelled as time-shifted deforestation). Assumes deforesta-tion until an "acceptable minimum forest area" (protected). Generic approach makes it insensitive to country- and crop-specific factors; usability depends on context of application. In default not suitable in contexts where high resolution is needed. At aggregate level, the "market for production capacity" interprets land/crops as perfect substitutes.
Persson et al., 2014	Biophysical	Flexible methodology that can be adapted to different scales according to precision needed and data available. Simplified framework for average, con-stant LUC effects derived from a dynamic approach. Sensitive to (regular) land use and yield dynamics over time. Limits the influence of allocation in time by calculating average effects over a period where both total production and conversion grow.	Apparently needs low data input, but some factors are difficult to determine beyond case study level. Quantification of proximate drivers of LUC is not an integral part of the model, but required as a data input. No guidance on how to establish causal links between commodities and iLUC. Direct approach overestimates proximate drivers; indirect approach overestimates ultimate drivers and ignores productive interim uses.
Baral & Malins, 2015	Causal descriptive	Structures cause-effect relations in an intuitive and transparent/explicit way (i.e., all effects are attributed to specific causes). Tests several what-if scenarios to identify important parameters in sen-sitivity analysis. Limits the effects cover-ed to what can be understood and track-ed down by stakeholders, e.g. land use effects are attributed to few regions. Allows integration of various data sour-ces and methods to derive reasonable assumptions (e.g. biophysical/ economic data, statistics/ projections, expert opinion).	Strong simplification cannot capture poten-tial "diffuse" price-related feedback mech-anisms over the market. Practically limited to apparent/intuitive effects, omits small effects that may accumulate at an aggre-gate level of analysis. Loses precision by using rough estimates/assumptions to es-tablish the cause-effect chains. Arbitrary allocation period of 30 years not even dis-cussed. Weak assumptions for relaxation to the "natural state" and forgone seque-stration.
Garraín et al., 2016	Biophysical/ Deterministic	Consistent integration of co-products and secondary effects on other markets into the LCA framework: system expansion for food, animal feed and oil market. Acc-urate system expansion based on co-pro-duct properties instead of market value: substitution coefficients regarding ener-gy, protein and moisture content per crop. Simplified and transparent method for crop-specific, constant iLUC factors, largely based on literature, no complex modelling necessary.	Ignores changes in yields due to intensi-fication or use of marginal land. Country-average displacement patterns assume that only one predominantly affected biome type (grassland/forest) experiences conversion. Country-average carbon losses do not adequately represent differences between biomes. Vague assumptions on carbon stock losses due to conversion.

Table A 2, continued.

Source	Model type	Strengths	Weaknesses
Kløverpris & Mueller, 2013	N.a., can be applied to any	Avoids choosing an arbitrary production period for amortisation. Accounts for likely land use dynamics and carbon stock changes in the baseline in a rela-tively simple way, data requirements barely rise.	Methodology reaches limits when large LUC is to be assessed. Yields are held constant over the study period; might be problematic for larger changes in land use where several periods are affected. Vague assumptions about average annual carbon sequestration due to reversion to the natu-ral state.
Overmars et al., 2015	Biophysical/ Causal-descriptive	Comparatively simple, transparent and intuitive methodology. Historical data cover a wide range of factors, including economic influences. Major biofuel feed-stocks and crop origins covered from EU perspective.	Validity of historical land use trends is limi-ted. No control for factors that might not be relevant any more, e.g. differences in land policy. Underestimates iLUC by omit-ting additional emissions from yield inten-sification & lower yield on new cropland. Overestimates iLUC: results based on har-vested area instead of cropped area. LUC allocation based on LHV ignores that by-products are not only used for energy. No discussion on time period, greenhouse gas allocation over several years of production.
Bird et al., 2013	Deterministic	Dynamic baseline, consideration of gene-ral trends in commodity supply/demand: population growth, food calorie con-sumption, harvested area, agricultural area, grazed area, yields and delivery effi-ciency. Simple and transparent account-ing method considering trends on supply and demand side.	Poor methodology; simple regression of each trend against food energy demand as a single driver holds all other variables con-stant. Global iLUC pattern only, carbon loss calculated from national averages -> low resolution of deforestation carbon stock impact. No other ultimate iLUC effect than deforestation considered. Co-products from biofuel production are not consider-ed.

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