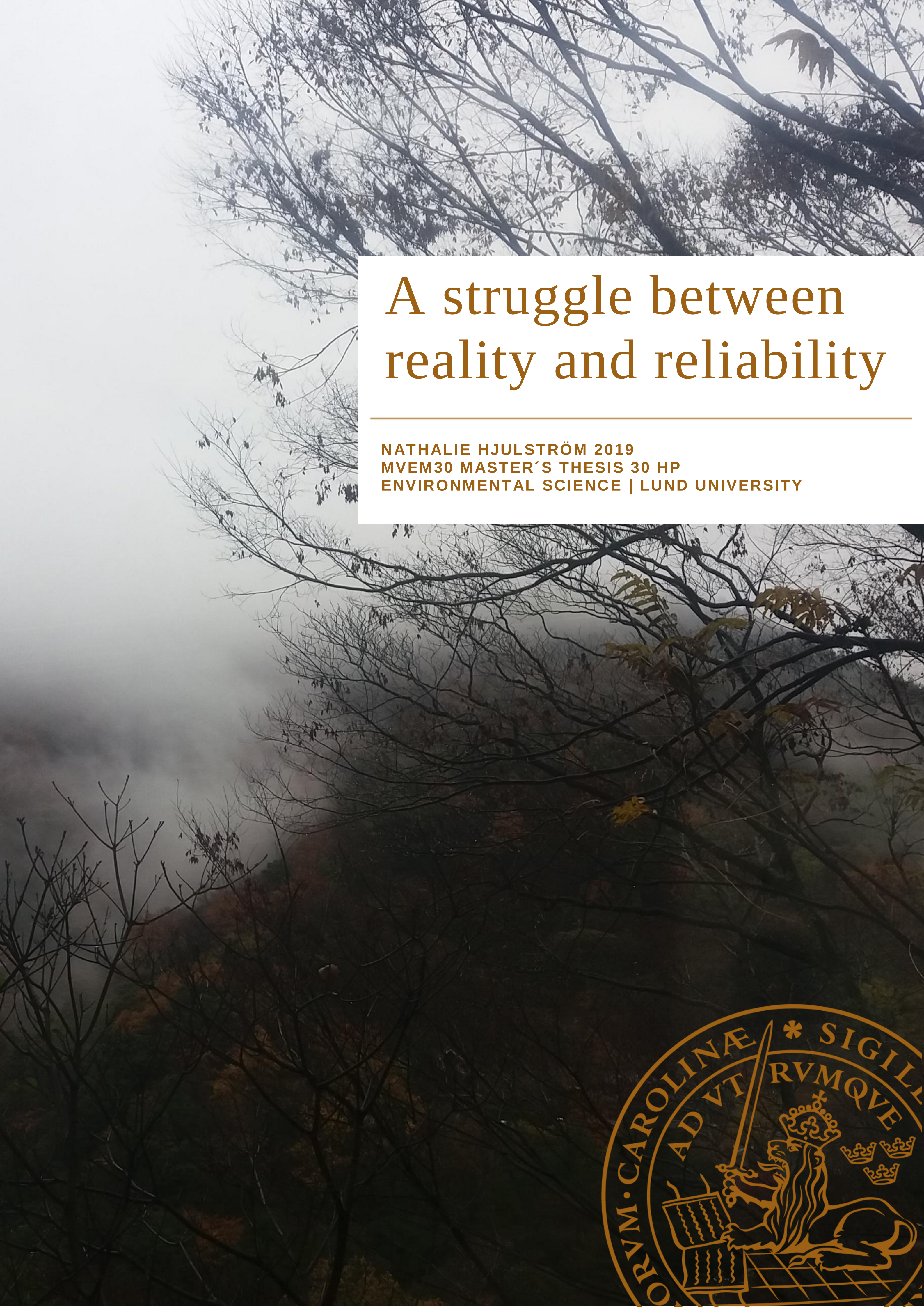

A struggle between reality and reliability

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A struggle between reality and reliability

The uncertainties of including indirect land use change in life-cycle assessments

Nathalie Hjulström

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Abbreviations used in this study:

LUC	Land use change
DLUC	Direct land use change
ILUC	Indirect land use change
LCA	Life-cycle assessment
GHG	Greenhouse gas
CO_2 eq	Carbon dioxide equivalents

Nathalie Hjulström

MVEM30 Master´s thesis 30 hp, Lund university

Tutor: Katrin Molina-Besch, Packaging logistics, Faculty of Engineering LTH at Lund University

CEC – Centre for Environmental and Climate Research
Lund University
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Abstract

Serious questions have been raised about the environmental impacts of biofuels concerning indirect land use change (ILUC) and this concept may also be applied to other products such as bio-based plastics. The purpose of this study is to identify the uncertainties of including ILUC in life-cycle assessments. This study performed a literature review of journal articles examining ILUC. Including ILUC in LCAs of biofuels may have a large impact on the GHG results, although, the range of the impacts of ILUC estimates is vast. The two main models for quantifying ILUC are computable general equilibrium (CGE/GE) models and partial equilibrium (PE) models, which are both agro-economic models that intertwine economics with geodata. Because this type of land use change is indirect and cannot be directly observed, causality is a main concern for the calculations. ILUC models do not contain detailed enough data and require more data on global land cover to become more reliable. Assumptions that provide a simplified depiction of reality are necessary to make ILUC calculations manageable, however, some of them do not correspond with empirical evidence. Emissions from land clearing are distributed over time in ILUC models and deciding the distribution period is arbitrary, yet it has large impacts on the ILUC results. In the ILUC models currently used, there are many uncertainties that have significant impacts for the final result of GHG emissions and the key uncertainties are causality and data. Considering the uncertainties found in this study, it is reasonable to exclude ILUC from LCAs.

Key words: indirect land use change; life-cycle assessment; biofuel, bio-based plastics

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1.Introduction

In life-cycle assessments (LCAs) of products that require large areas of land to produce significant quantities of biomaterial, such as biofuels and bio-based plastics, there is great uncertainty concerning how to quantify some of the environmental impacts (Finkbeiner, 2014; Oladosu & Kline, 2011; Mullins, Griffin & Matthews, 2011). One of the issues is how to include indirect land use change (ILUC), or perhaps excluding it from environmental assessments due to the lack of a scientifically accepted methodology (Finkbeiner, 2014). A simple example of ILUC is when a plot of land first is used to produce food and then changes to produce biomaterial for e.g. bio-based plastics (European Commission, 2019). In this scenario, demand for food has not disappeared and the food that was previously grown there may be displaced to an area with high carbon stock (European Commission, 2019). This *indirect* land use change means that it is very difficult to trace the effect and researchers rely on models that interweave economics and geospatial data to produce an estimate of ILUC.

This study was performed in cooperation with the EU-project “Biodolomer for Life” which consist of three parties, they are GAIA BioMaterials, NSR AB (Nordvästra Skånes Renhållnings AB) and Öresundskraft. GAIA BioMaterials produce biodegradable biomaterials for several different types of products (GAIA BioMaterials, n.d.). NSR AB is owned by six municipalities in Northwest Scania and manages waste as well as recyclables (NSR, n.d.). Öresundskraft is an energy- and communications company owned by the city of Helsingborg (Öresundskraft, n.d.). The objective of the EU-project is to “show how fossile-based and energy intensive plastics and packaging materials can be replaced by Gaia BioMaterials renewable and biodegradable biomaterial Biodolomer” (Biodolomer for Life, n.d.). Because bioplastics require land to produce raw material, that can be the same as for biofuel e.g. maize or sugar cane, the same type of ILUC effects can be attributed to bio-based plastics and that is why this study has reviewed journal articles examining ILUC of biofuels.

1.1 Disposition

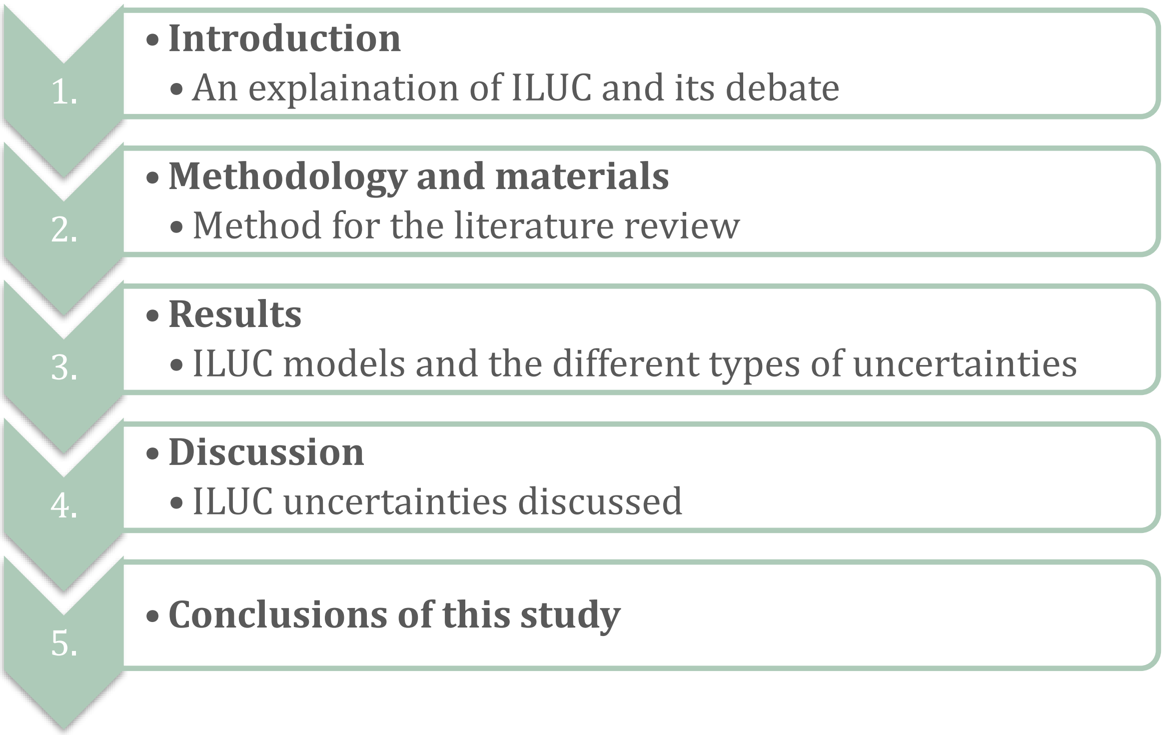

Figure 1. Disposition
This study´s disposition

1.2 Land use change and environmental impact

Land use change is an area which has been widely debated within the scientific community regarding environmental assessments, mostly of agriculturally based biofuels (Gawel & Ludwig, 2011). This has resulted in more practical consequences as policies for biofuels, such as the European Union’s Directive on the promotion of the use of

energy from renewable sources (RED II), which include sustainability criteria for biofuels produced or consumed in the EU. Biofuels from e.g. maize was at first perceived as a possible way to reduce greenhouse gas (GHG) emissions compared to its fossil alternatives.

Later, questions concerning reductions of GHG emissions arose, based on if land use change (LUC) is accounted for in LCAs. Land use change is a term for when a piece of land that previously had different use, changes to fit human demands (European Commission, 2019). Using agricultural land for biofuels does not replace the need for food or feed, the previous agricultural production might relocate to forests or grasslands and this is the indirect effect of land use change (European Commission, 2019).

The question of if it is possible to reduce GHG emissions with biofuels is relevant because forests and grasslands generally absorb a great deal of CO_2 and changing the land for agricultural purposes may lead to a rise in atmospheric CO_2 levels. The following examples aim to make a simple explanation of direct and indirect land use change according to a report from the European Commission (2012), along with explanatory illustration (figure 2). In a scenario of a global agricultural system based on only forest land and grazing land, there is no biofuel production. Starting with biofuel production on grazing land results in direct land use change and can lead to an increase or decrease of soil organic carbon. If it instead is the forest land which is used for production of biofuel, the emissions from direct land use change might be great due to the loss of forest biomass (European Commission, 2012).

A decrease in grazing animals are assumed to have the macro-economic effect of an increase in the price of meat because of the reduction in meat supply (European Commission, 2012). Incentives to increase meat production thereby occurs. A rise in production can be created by intensifying the original production (by keeping more animals per hectare) or to transform other land into grazing land. The last case on transforming more land to meet the demand is a classic example of ILUC and results in this instance is a reduction of forest carbon stocks, because grazing has been extended to forests. It is not as simple as a one-to-one relationship between the area that is converted to produce biofuels and the area that is changed to new grazing land or cropland to compensate for the loss of land to the production of biofuel. The connection between them "depends on the relative productivity of the old vs. new pasture/cropland, markets for co-products and to what extent the macro-economic pressure induces increased productivity and changes in consumption" (European Commission, 2012, p.79). A simple explanation of ILUC is offered by Slade, Bauen and Shah (2009, subsection "Consideration of consequential impacts and land-use change") "Indirect land-use change impacts may arise if increasing demand for biofuels increases commodity prices or displaces the production of other agricultural crops, and this, in turn, causes uncultivated land to be converted to agricultural production".

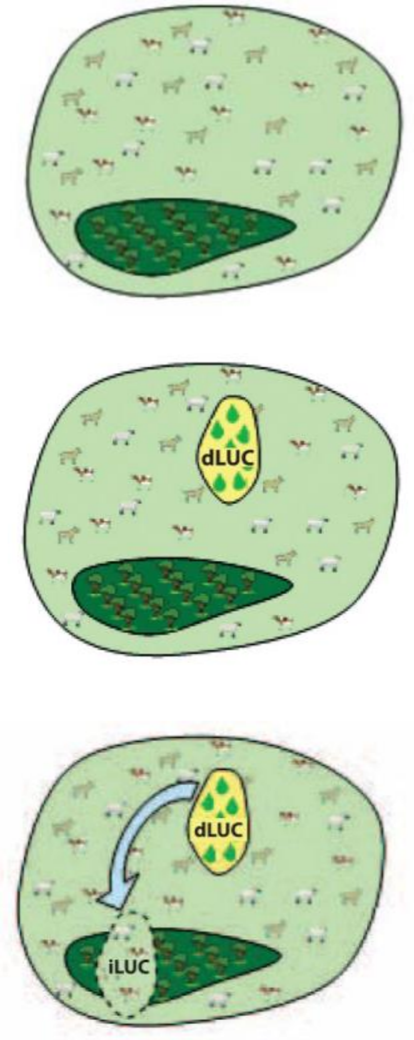

Figure 2. "iLUC" means indirect land use change and "dLUC" stands for direct land use change. The illustrations above are examples of direct and indirect land-use changes arising as a consequence of a biofuel project.

Source: European Commission (2012).

To calculate the effects of LUC there are several different methodologies, some of them will be explained in section 3.1., and there is little consensus concerning particularly the calculation of indirect land use change (ILUC). The concept of indirect land use change is quite new and considering the potential ramifications of ILUC from biofuels, it has not received as much attention in scientific studies as would be expected. The debate concerns how ILUC can be calculated as well as if it should be part of environmental assessments, due to its high uncertainty, or if it is better to exclude it (Verstegen et al., 2016). Despite the uncertainties, many studies encourage more research on ILUC and improving the models used to create estimates (Ostwalda & Henders, 2014; Gao, Skutsch, Drigo, Pacheco, Masera, 2011; Kline et al., 2011).

1.3 The rise of the ILUC debate

The debate regarding ILUC arose around 2008 when studies by Searchinger et al. and Fargione, Hill, Tilman, Polasky and Hawthorne (2008) were published, which were the first to be concerned with the added indirect consequences from biofuels. Before those articles, LCA studies on biofuels that included DLUC had accepted the assumed reduction of GHG emissions from bioenergy compared to fossil. Searchinger et al. (2008) calculated that over 10 years, a designated area of 12,8 million hectares for growing corn in the US, for the purpose of making biofuel, would lead to the need of 10,8 million hectares of additional land for crops across the world and that would predominantly implicate the clearing of forest land. Emissions from only ILUC were estimated to exceed emissions from the gasoline the ethanol was modelled to substitute (Searchinger et al., 2008). Since 2008 there is an ongoing debate about the issues of ILUC effects from biofuels and it is far from resolved.

Plastics affect many people’s everyday lives, as they are used for everything from communication technology to food packages (Spierling et al., 2018). Although production of bio-based plastics is increasing, there is a momentous difference in scale as the international capacity of production was around 1,48 million tonnes in 2014, whereas its conventional alternative supplied 311 million tonnes the same year. Currently, most of the plastics used are fossil based, but concerns about climate change and the limited amount of fossil resources have led to plastics which are instead bio-based, receiving more attention.

The demand for bio-based plastics is increasing as well as the width of how the materials can be utilized, which has raised questions about their performance from a sustainability perspective. New innovative products are generally scrutinized in terms of sustainability and due to this it is necessary that bio-based plastics can demonstrate superiority in aspects of sustainability to be acknowledged as a reasonable substitute for fossil plastic (Spierling et al., 2018).

One relevant aspect of sustainability for bio-based plastics is the question of ILUC effects, since it has created a debate for bioenergy it is rational to assume it will become a larger issue for bio-based plastics as production continues to increase. Due to the similarities of biofuels and bioplastics regarding land use change, the debate about ILUC puts the bioplastics industry in an uncertain situation. ILUC regulation may in the future also apply to bioplastics which means that it is something producers of bioplastics also have to consider.

1.4 The building blocks of an LCA

An LCA is constructed of several parts and they are goal and scope definition, inventory analysis and impact assessment (Hauschild, 2018). To perform an LCA there needs to be a clearly stated goal of it and this serves as the substructure for the scope definition. In the first step there are many boundaries for the study that should be clearly stated. Boundaries in time and space and level of technology used to make the product are some of them. Deciding the functional unit is one of the very first things to do when performing an LCA. Functional unit is a quantitative portrayal of the function or service the assessment is used for, as well as the foundation for deciding the reference flow (Hauschild, 2018).

Scoping the product system, deciding which activities and processes belong to the life cycle of the product also belongs to the first part (Hauschild, 2018). Inventory analysis is the second part of an LCA (Hauschild, 2018). It comprises information concerning the physical flows when it comes to input of products, materials and resources. The inventory analysis also discloses the output of valuable products, emissions and waste from the product system. Life cycle inventory is the result of the inventory and it is a list of quantified physical flows for the product system (Hauschild, 2018).

After the inventory analysis the next step is impact assessment where the physical flows are translated into environmental impacts (Hauschild, 2018). The ISO 14040 standard on LCAs include three involuntary components in impact assessment, but there are two additional components that can be applied in this final section of the LCA. Selection of impact categories, classification and characterization are the first three obligatory elements. Normalization and weighting or grouping are optional according to the standard mentioned above, although they are not uncommon in LCAs (Hauschild, 2018).

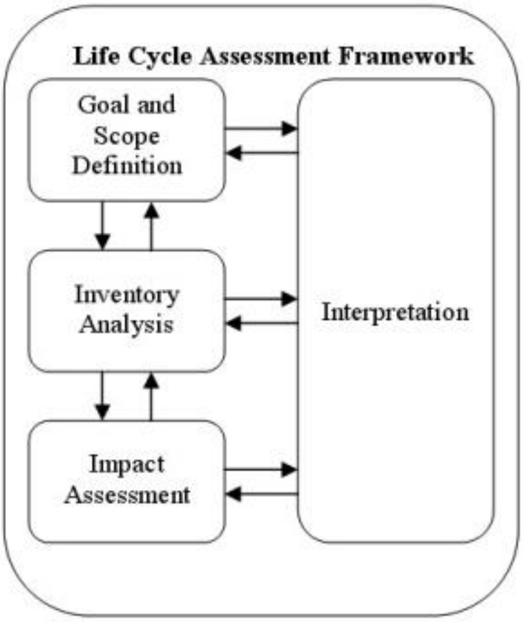

Figure 3. Life-cycle Assessment Framework.
Source: International Organization for Standardization (ISO) (2006)

1.5 Purpose

Indirect land use change is chosen as the study's focus because it is frequently excluded in life cycle assessments of products originating from agriculture, even though land use change has been identified as a critical methodological aspect in life-cycle assessments of biomaterial by Pawelzik et al. (2013). There is a lot of uncertainty around how land use change should be calculated, especially regarding ILUC. Indirect land use change is an underexplored area in research and due to great uncertainties of applying the concept, the purpose of this study is to identify the uncertainties of including ILUC in environmental assessments such as LCAs. The study also aims to give recommendations for companies that work with bio-based plastics on how to approach ILUC in environmental assessments of their products.

1.5.1 Research question

- What are the current uncertainties of including indirect land use change in life-cycle assessments?

1.6 Demarcations

Ethical issues as working conditions and child labor in the collection of agricultural crops for e.g. biofuels or other type of production leading to land use change, are not included in this study. They are very important inquiries, nevertheless this study does not observe the social or economic dimensions of ILUC. Even though much of the material concerning ILUC examines policies, this study does not explore policy for biofuels as these policies do not apply to bio-based plastics. Articles concerning ILUC focus on GHG emissions and there is generally a lack of other parameters in the literature which is reflected in this study through the primary focus on GHG emissions. As this study identifies current uncertainties of including ILUC in LCAs, it does not provide material to determine whether or not ILUC should be included, merely the issues of inclusion. The scientific material on ILUC is currently quite small and this study reviewed 31 journal articles, this implies that certain issues of ILUC may have gone unnoticed. The material was limited to 31 articles due to the time limit of 20 weeks of the course that this study was performed for.

2. Methodology and materials

This chapter includes the process of finding material for the literature review, as well as how the review was performed.

2.1 Literature review

To answer the questions concerning ILUC in LCAs, a literature review of studies examining ILUC has been performed. To complement the scientific studies of the subject, discussion articles in scientific journals were also reviewed to form a more comprehensive understanding of the discussion around how ILUC should be managed in LCAs. A document for databases and search words used was created where all the relevant findings from the searches for articles were placed in, as recommended by Ridley (2012). This structure for the literature review was used from the very beginning to guarantee that the articles would be easily found later and to avoid wasting time repeating the same searches. Another crucial aspect of the document for searches was to ensure reliability of the study in case several searches with different key words were to be used.

2.2 Searching material for the literature review

The material used to perform this study were journal articles found in the database "Web of Science". The search method used was key word searches, with the ones deemed to be the best description of the material of interest (Ridley, 2012, p. 56). Several different words and combinations were tested before deciding the right combination. Although there are more databases other than "Web of Science" that may publish journal articles relevant to the study, the search was confined to one database since it is a very comprehensive one that holds many scientific journals. Using the database "LUBsearch" was also tested because there is more diversity in the material.

There is, however, no function of limiting the studies to purely scientific material, meaning that articles from newspapers etc. were included in the search which would not fulfill the purpose of this study. It was decided that only using "Web of Science" would be the most efficient way of conducting searches and limiting the search to a few keywords used in one single search would result in the highest reliability concerning the material used in the study.

To find articles about the subject, Boolean logic was used along with the key words "indirect land use change" and "indirect land-use change", with the two terms within quotation. Boolean logic means that using the word "OR" between two key terms, in a database which has this function, results in searches made for publications that incorporates either of these terms (Ridley, 2012, p. 57). This was done because of the variations in the spelling of "land use", which is sometimes "land-use". This search gave 222 findings on the 13th of February 2019 in "Web of Science", which was not specific enough. The search was then refined by only allowing articles and using the search bar within the results for "bioplastic* OR biofuel*" which resulted in 146 publications. Again, Boolean logic was utilized by using a wildcard symbol, an asterisk, together with the words to find articles with different endings of the words (Ridley, 2012, p. 57). To narrow down the search further, refined search was used once more with the word "method*" which resulted in 54 articles. However, some articles were removed from this search in "Web of Science" during the time that the review was performed and at the very end of this study the articles had been reduced to 50. Because the review was already being performed when some articles were later removed, one article was added to the 50 that the search resulted in on the 21st of May 2019. An appendix of the articles used is attached at the end of this study.

The articles also had to meet a basic criterion to be part in the literature review. The criterion was an examination of ILUC from agricultural crops in some way, not only a mentioning of it. Due to the uncertainties of ILUC, many articles mention indirect land use change in the abstract but do not investigate it in the actual study. This phenomenon means that a part of the publications found through the search in the database could not be part of the literature review because they would not provide information of relevance. The table below will provide a clear description of the search used to find publications for the literature review.

Table 1: Search process used for the literature review

This study's search process

Database used	Web of Science
Words used in main search	"indirect land use change" OR "indirect land-use change"
Words used in refined search	bioplastic* OR biofuel*, method*
Criterion for the selected articles	ILUC must be part of the study's results

The review was performed with the assistance of an Excel-document consisting of two sheets, one for studies concerning the calculations or methodology behind ILUC and one sheet for studies with a more argumentative approach for or against ILUC. The type of study was first identified and thereafter the information was put in the different categories in the Excel-document. While reading the material for the literature review the technique SQ3R (Survey, Question, Read, Recall, Review) was used as a guide for processing the material (Ridley, 2012, p. 63-65). A Word document with the articles found in the search was used for notetaking during the reading.

3. Results

3.1 Relevance of LUC/ILUC in environmental assessments

The impact of LUC in environmental assessments of biofuels is significant for GHG emissions (Nguyen & Hermansen, 2012). The GHG performance of ethanol compared to gasoline has a wide range of 35 % “better” (when LUC is excluded) to 31-686 % “worse”. The worst result is due to the demand for ethanol when it causes the obliteration of tropical rainforest. Accounting for GHG emissions derived from land use has severe consequences for the optimistic results for ethanol. Nguyen and Hermansen (2012) state that carbon emissions from deforestation means that ethanol is a significant source of carbon emissions, despite the length of the amortization period.

Ostwalda and Henders (2014, p. 540) state that current methodology of ILUC effects are insufficient because applying equilibrium models or standard discount values to indirect effects, which are “un-measurable”, contain large uncertainties. They pose the question if it is cause enough to not use the models or if ILUC estimates should be included, even though they may be far from accurate, to provide an indication of the consequences. There are different opinions in this issue and there are those involved in the debate who find the application of ILUC factors sensible as it means a recognition that these indirect effects are real, despite the values not being low or high enough (Ostwalda & Henders, 2014). Many researchers emphasize the uncertainties of calculating ILUC emissions, but close to all simulations indicate that the indirect effects are significant and should be part of future analysis (Gao et al., 2011).

The carbon intensity of biofuels can rise substantially as a result of GHGs originating from ILUC (Guest & Desjardins, 2017). The range of ILUC factors (net emissions of ILUC calculated in unit gram CO_2eq per MJ fuel) for wheat and corn ethanol is large and varies from –80 to 155 g CO_2eq per megajoule and 7 to 104 g CO_2eq per megajoule. Ranges as large as these imply great uncertainty, but also that ILUC cannot be overlooked (Guest & Desjardins, 2017).

Despite the difficulty of observing and quantifying ILUC, it is relevant for the LCA and uncertainties concerning indirect effects are, to some, not enough to exclude ILUC from LCAs. Not including uncertain aspects such as ILUC may appear to reduce uncertainty in the LCA results, although the actual uncertainty has not been reduced (Guest & Desjardins, 2017). Boldrin and Astrup (2015) argue for the importance of ILUC emissions as they conclude in their article, that the incorporation of emissions from ILUC in environmental assessments is a key element to make a judgement of biofuels general sustainability.

3.2 The different types of models used for calculating ILUC

An important aspect of LUC is that it can solely be empirically observed and assessed regarding the local direct effect (Nassar, Harfuch, Bachion, Moreira, 2011). In evaluations of larger areas, e.g. on a national level, direct and indirect effects need to be assessed via models (Nassar et al., 2011). Neus et al. (2018) proclaim that tracing ILUC is problematic and that it is mostly undertaken by using global computable general equilibrium (CGE) models, together with biophysical components. It should be noted that many of the articles reviewed in this study refer to the term "general equilibrium (GE) models", instead of the term "CGE models", but they appear to refer to the same type of models. CGE models are used because of the ability to include links between production and consumption through all economic regions and sectors (Neus et al. 2018). Khanna and Crago (2012) state that there are two main types of economic models to calculate the consequences of ILUC, they are partial equilibrium (PE) models and computable general equilibrium models (CGE). Overmars et al., (2012) also proclaim that there are two key alternatives regarding the quantification of ILUC, however, they declare these two as modelling and monitoring. Calculations of ILUC through monitoring has its foundation in historical data, whereas models are used for forecasting land use under a baseline together with a scenario of a specific policy (Overmars et al., 2012).

According to Van Stappen et al. (2011) there is an overall scientific consensus regarding applying an economic method to estimate ILUC and studies so far have used general or partial equilibrium models. For an acceptable quantification of ILUC, a GE model should be adopted and the model must include availability of land, patterns of land use, demand and supply of agricultural commodities along with numerous components.

At the present, raw estimates founded on hypothetical situations are the only calculations accessible for ILUC. To forecast the place of relocation for displaced activities an international economic and trade model consisting of national and crop specific data is required (Van Stappen et al., 2011).

3.2.1 Partial equilibrium (PE) models

Some of the models of PE type are the International Model of Policy Analysis and Agricultural Commodity Trade (IMPACT), the Agribusiness Linkage Program Commodity Simulation Model (AGLINK-COSIMO) and the global Food and Agricultural Policy Research Institute (FAPRI-CARD) model (Khanna & Crago, 2012). Models of PE type are multimarket models which contain key crops and livestock production in a regional depiction of a global economy (Khanna & Crago, 2012).

3.2.2 Computable general equilibrium (CGE) models

CGE models simulate effects of a biofuel shock across the entire economy and contain restrictions on capital and labor, links between different sectors and decide all incomes and prices at once (Khanna & Crago, 2012). The CGE models include the Integrated Global System Model (IGSM), the Global Trade Analysis Project (GTAP) model, the Modeling International Relationships in Applied General Equilibrium (MIRAGE) and the LEI Trade Analysis Project (LEITAP) model. The database GTAP is used for the four models of CGE type, although there is a difference in which base year is utilized in calibrations. LEITAP and GTAP are static representations of the economy, while MIRAGE and IGSM are dynamic with their variations in time horizons and time steps (Khanna & Crago, 2012).

3.2.3 Alternative ways for calculating ILUC

To properly account for ILUC Khatiwada et al. (2012) propose using regional models for complete geospatial information on the country in question. Also, patterns of LUC from the production of sugarcane ethanol, together with the cause-effect correlation coming from its source and demand should be part of the models (Khatiwada et al., 2012). In the case of Brazil there is the economic model Brazilian Land Use Model (BLUM), which portrays LUC in six different areas of the country.

A model like that is supposed to convey more exact ILUC effects because it is rooted in real changes of the land. Emission factors and methodologies must be specialized instead of generalized. Restrictions bound by law as conservation plans and attainable land also need to be included correctly in the model.
Due to this Khatiwada et al. (2012) claims that using a causal descriptive approach for GHG emissions together with geospatial information on a country level for land allocation and LUC, may be a good way forward for quantifying ILUC in terms of its GHG emissions for sugarcane bioethanol in Brazil. There are alternatives to the models mentioned in the paragraphs above, which Kim and Dale (2011, p. 3236) demonstrated in their article where they use a "bottom-up", data-driven, statistical approach based on individual regions' land use patterns and commodity grain imports". In this case the purpose was not to measure the potential ILUC effects, but only a question of if ILUC occurs (Kim & Dale, 2011).

As opposed to linking LUC to a rise in demand for specific crop products somewhere on Earth, which is done by ILUC impact models, Ponsioen and Blonk (2012) used a method for quantifying ILUC by analyzing production of certain crops in countries where extensive felling of forest and LUC occurs. Ponsioen and Blonk (2012) recognize that their approach may be arguable due to agricultural actions across the world being entirely linked together. In spite of the interrelations of agricultural activities, they argue that using calculations which are specific to one country is the better option as the relations are too complicated to model and deforestation may be spurred on or hindered by polices from the national government. The study claims that the applied method produces "more sensible and consistent results than currently used methods for calculating the GWP of land use change in carbon footprints" (Ponsioen & Blonk, 2012, p. 125).

3.2.4 Uncertainties in ILUC models

The assumption in PE models are that with the production of biofuels, conditions in the other parts of the economy as well as prices of capital and labor stay the same (Khanna & Crago, 2012). These types of models exclude feedback effects from changes in income that are derived from a change in prices that can impact demand for commodities in different markets. The models focus on a handful or one single sector of the economic sphere and detailed information can be included in order to involve local socio-economic features, although they have a tendency to overvalue ILUC consequences due to the lack of adjustment instruments that span over the entire economy (Oladosu & Kline, 2013).

Even though CGE models include many sectors, a large part of the models do not have detailed geographical information as the Earth is divided into a small number of large similar districts. DLUC and ILUC is not differentiated in CGE models due to the fact that they are unable to trace if a biofuel feedstock was employed as a means for production of biofuel or for another purpose (Khanna & Crago 2012). Because CGE models are based on a structure that compasses the whole economy it means they are appropriate for capturing the wide-spread economic relations which dictate ILUC consequences (Oladosu & Kline, 2013). This also means that the economy-wide capacity of the models confines the number of details that can be included for them to stay tractable (Oladosu & Kline, 2013).

According to some authors, ILUC models overestimate ILUC effects by undervaluing GHG emissions from fossil fuel (in comparisons) and by excluding how biofuels diminish average GHG emissions (Levidow, 2013). Studies have a large range of results from the effect of ILUC which is due to the sensitivity to assumptions and model structure (Khanna & Crago, 2012). The fluctuations in ILUC studies of GHG intensity of biofuel are significant and the models are very intricate which unfortunately means that it is problematic to derive the variations in the estimates to a certain aspect of the models (Khanna & Crago, 2012).

Verstegen et al. (2016) find that uncertainty in projections of ILUC originate, aside from uncertainties in model construction and parameters, from differences in model concepts among the model's similar model chains. It is also important to note that attributional LCAs exclude ILUC as they do not account for indirect economically generated effects which arise due to the reactions on commodity markets (DeCicco, 2012). The majority of models are unable to determine with precision the place where ILUC occurs and results of the dimension as well as the projected location of LUC differ extensively between models (Gao et al., 2011).

3.3 Uncertainties concerning causality

A fundamental issue of ILUC concerns the visibility of the effects, "ILUC remains a highly debatable, yet undemonstrated, concept and certainly one upon which public policies cannot be based" (Levidow, 2013). To measure the consequences of indirect land use change there is a need for specific information of the effects of LUC (Gawel & Ludwig, 2011). There is a problem of causality regarding ILUC which is derived from the fact that a reduction in biodiversity and carbon stock related to LUC from bioenergy is not alone the reason for why the use of land changes.

Kline et al. (2011) similarly mention the lack of data for finding the reason for changes of ILUC. Economic prosperity, demand for agricultural products and population growth are major reasons for diminishing areas of e.g. tropical forests (Gawel & Ludwig, 2011). Nguyen and Hermansen (2012) also emphasize the complication that arises from needing to know the original state of the land that is converted, if it is grassland, forest etc., because that decides the size of the change in carbon stock. The variations in carbon stocks in different type of land is mirrored by the degree of uncertainty of GHG emissions from LUC (Nguyen & Hermansen, 2012).

Verstegen et al. (2016) state that ILUC cannot be directly observed. An example of this is if pasture displaces forest during a time of increase of land for bioenergy crops over pasture, the scenario in question does not have to indicate that the cause of the displacement of pasture is the extended area for crops for biofuels. The deforestation caused by pasture may be unlinked to biofuels. This case illustrates how the indirect consequences of a specific rise in demand is not possible to detect from historical data due to the consequences being interrelated with many different activities from which the consequences are also present in these data (Verstegen et al., 2016). Quantifying the extent of ILUC is an issue due the intricacies regarding the social and economic structures that link the production of biofuel with the conversion of land across the globe (Gao et al., 2011). Oladosu and Kline (2013) also mention that LUC at the local level arise through complicated political and social drivers and that it is essential that they are assessed in the future. Attributing the effects of ILUC is also problematic due to the international scope of the issue (Gawel & Ludwig, 2011). It is possible that a region growing crops for non-edible products previously used the same land for growing food. A rise in the demand for those products can lead to the region being dependent on importing food and thus lead to more DLUC or ILUC in another region (Gawel & Ludwig, 2011).

3.4 Uncertainties concerning data

The actual measurements are only applicable to DLUC because they are observable in the chosen geographical areas for that specific crop (Gawel & Ludwig, 2011). One very important fact is that the results from ILUC studies will not be reliable if the data used is not itself reliable (Kline et al., 2011). Data of high quality for land cover and land use are, despite the necessity of it to make ILUC calculations reliable, not accessible for the related “temporal and spatial scales” to comprehend changes in land use or the consequences of changes in land cover (Kline et al., 2011).

For tools that include ILUC it is a requirement to have information on how much of the LUC that is triggered from which type of product – biofuel, food, feed, or fiber (Gawel & Ludwig, 2011). The amount of increase in crop demand that is achieved by an increase in land area, as opposed to an increase in yield, has to be differentiated and the knowledge on the part that co-products play needs to be developed (Gawel & Ludwig, 2011). Kline et al. (2011) also argue that better data is needed, namely geospatially and temporally unambiguous data sets of high resolution on global land cover with matching biophysical features as carbon stock to enable reports which are less subjective and more consistent. In the study by de Jong et al. (2019) it is stated that models with better spatial and temporal resolution are needed, particularly since the time and place for ILUC and DLUC can fluctuate within the biofuel and counterfactual scenario (de Jong et al., 2019).

In the study by Mullins, Griffin and Matthews (2011) the ILUC emissions factor is the most important parameter, for all the different scenarios used, because of the large increase of emissions from ILUC as well as the great uncertainty from the hefty range of estimates. Economic models which predict ILUC and its related emissions need to be enhanced to elevate the accuracy of forecasting emissions from biofuels. Mullins et al. (2011) notes that evolving ILUC models holds the assumption that the uncertainties regarding ILUC can be diminished on a significant scale with more information, but that there are those who claim that parts of the uncertainty cannot be reduced. Because of the insecure estimates, a range of emissions might be the most advanced result which can be expected from ILUC calculations. Incorporating ILUC effects in LCAs creates controversy and excluding ILUC means biofuels get much better results in terms of GHG emissions (Mullins et al., 2011).

Calculating the environmental impacts of biofuel in terms of deforestation is complicated, especially since it has both direct and indirect effects on LUC (Gao et al., 2011). Gao et al. (2011) identifies the main issues to stem from data, specifically data on biofuels due to the shallowness of geographical precision, which means that it is impossible to relate this to maps of forest clearance. Verstegen et al. (2016) call for more information on the accuracy of data, because the absence of this led them to be forced to apply heavy assumptions concerning the flaws in the maps used for generating the primary land use map as well as the empirical data for calibration.

3.5 Common assumptions in ILUC calculations

Assumptions in ILUC models are simplified, e.g. assuming that actors are driven by maximizing their profit. The real cause for deforestation is however much more complicated than people trying to make as much economic gain as possible, because aspects as land use rights, permission from local authorities and the economic state also affect ILUC (Levidow, 2013). Due to the impossibility of conveying this complex interaction in a model, the result is concentrating it to an only rational economic matter (Levidow, 2013).

Changes in economic markets that are central for predicting consequences of policies concerning biofuels are simulated in models such as FAPRICARD, FASOM and GTAP (Kline et al., 2011). However, the models are not authenticated for assessing LUC and use critical assumptions in addition to simplifications that are in opposition of what has been proven empirically. The mentioned models generally make the assumptions that land is used to maximize profit and that land is owned privately, when the actual situation is that forest land, in the models that are assessed to be affected by ILUC, are almost exclusively publicly owned. LUC is decided by mathematical functions and elasticity components induced by relative international commodity prices which comprises additional conversion of forest land. Nevertheless, the conversion of forest land is largely compelled by intricate relations between various factors at the local level such as political direction and land speculation. Despite that ethanol policies have been in place in the US for over two decades with policies preceded by notification to biofuel producers and that land use as well as production are very dynamic regardless of policies, the models express that US policies on biofuel generates a “shock” in the request for corn ethanol while land use and production remain solid (Kline et al., 2011).

Land is assumed to be in a natural condition or completely exploited, which enables the application of models (Kline et al., 2011). However, it also decides ILUC effects due to the unavoidable shift of production on land or by extensification caused by biofuels. Not even 25 % of the world’s, not forested, arable land is cultivated which means that there is great prospect to enhance the manner in which most of the formerly cleared land is managed. Even though models assume that forests regrow spontaneously where land is not managed by humans, the non-managed arable lands in question actually experience disturbances frequently and annually lead to a burned area of 380 million hectares on average. The consequences of fires and more disruptions are excluded from economic models of LUC (Kline et al., 2011). Models are also different in assumptions about yield and land use forms that are measured (Kløverpris & Mueller 2013).

The study by Searchinger et al. (2008), which started the discussion on ILUC, used scenario studies that required various assumptions which had low scientific support according to Ponsioen et al. (2012). It is appropriate to mention that the article has been extensively challenged due to the uncertainties in the modelling (Gao et al., 2011), and that it is merely an example of the fact that ILUC is considerably more intricate to model than DLUC (Van Stappen et al., 2011). The renowned study founded a very important aspect of the econometric calculation design (the link between the speed of deforestation in a large region and the price of soybean) on exclusively four data points from one source. Ponsioen et al. (2012) acknowledges the importance of similar studies that contribute with some kind of expression of ILUC effects when biofuels are endorsed by policies, but they also conclude that scenario studies currently produce too ambiguous results to use these calculations for including GWP of LUC in carbon footprints of products (Ponsioen et al., 2012). Describing the consequences of ILUC involves intricate models that entwine economy and agriculture and the outcomes of these are widely different due to the assumptions made (Boldrin & Astrup, 2015).

Another important decision for ILUC is whether to use the IWM (integrated world market) assumption or Armington assumption (Khanna & Crago, 2012). The IWM assumption allocates land conversions quite evenly globally and the amount of forestland around the world that is changed to cropland is greater, compared to under the Armington assumption where land conversions are mostly located in the EU and the United States. The difference above might explain the results by Searchinger et al. (2008) because they used the IWM assumption implicating that utilizing more ethanol in the US would have the effect of substantial land use change in India, China and Brazil, while a study by Hertel et al. (2010) estimate a low conversion rate in the named countries. Typically, the yields are reduced in the areas that Searchinger et al. (2008) estimated noteworthy LUC in, which means that larger areas of land are needed to substitute the land that was superseded by corn ethanol, thus leading to a larger ILUC effect (Khanna & Crago, 2012).

Bird, Zanchi and Pena (2013) state that their examination of average crop and animal yields in eight regions and countries suggest great possibilities to increase yields, especially in the least developed regions. Due to this several researchers have amplified the valuations of possibilities for bioenergy from crops, but Bird et al. (2013) also refer to research that gives reason to consider that the valuation may be overestimated. Aspects as using too much irrigation, erosion of soil and increased energy prices can act as restrictions of yield increases, which is why Bird et al. (2013) suggest business-as-usual scenario for yields because they deem it to lead to more realistic results.

Conventional LCAs on bioenergy focusing on GHGs do not take into account that climate impact of GHG emissions rise along atmospheric residence time "and may therefore lead to incomplete conclusions about (relative) system performance and the timing of climate mitigation benefits" (De Jong et al, 2019, p. 428).

3.6 Uncertainties regarding the distribution of GHG emissions from LUC over time

The assumptions of causality are a foundation for measuring the effects of ILUC that have to be attributed to a specific crop or product (Gawel & Ludwig, 2011). To be able to account for this, more assumptions are necessary. Limiting the ILUC consequences to emissions of GHGs means even more model assumptions, like the distribution of the GHG emissions from one-time land clearing over a period of time of growing the crop (Gawel & Ludwig, 2011).

As one of the first articles calculating ILUC, Searchinger et al. (2008), in a way set a standard for how to distribute emissions from ILUC over time by choosing a time period of 30 years. The technique is sometimes referred to as the annualization method (Kløverpris & Mueller, 2013). Kløverpris and Mueller (2013) announce that spreading the emissions over 30 years without a particular reason is undoubtedly an arbitrary choice which impacts the results a great deal. Doubling the time period means ILUC emissions are cut to half compared to the original annualization and cutting the period down to 15 years means emissions are doubled (Kløverpris & Mueller, 2013). Khanna and Crago (2012) also mention that annualization is very important for the ILUC factor when trying to measure GHG intensity per megajoule of biofuel.

Others that underline the importance of spreading the one-time LUC emissions over time are Gawel and Ludwig (2011). Despite the large sensitivity of the outcome from ILUC related emissions due to this type of distribution over time, there is currently no fixed period to use and there is no way of deciding what an appropriate time period would be. It may even be changed to a period of 100 years as Nguyen and Hermansen (2012), despite their choice of using 20 years as "depreciation period", argues that 100 years of annualization could be feasible because IFEU (Institute for Energy and Environmental Research) and Kim et al. grant it as reasonable. This would naturally lead to drastic changes in the results of the calculations of GHG emissions.

To emphasize the importance of LUC in general, GHG emissions from ethanol, using 20 years as annualization, including LUC are two to twelve times higher due to the level of carbon stock change (Nguyen & Hermansen, 2012). When it comes to analyzing the effects of biofuel policies both 20 and 30 years of time is considered acceptable and is practiced (Khanna & Crago, 2012). Annualization, or amortization as DeCicco (2012) refers to it in his article, is the only way that CO_2 emissions related to ILUC from biofuels can be reduced to a low enough value to seem to lead to a reduction compared to fossil fuels. The geographical location of the research institute that conducts studies on ILUC may have an effect on the choice of amortization period because papers from the EU tend to use an annualization period of 20 years and papers originating from the US often use 30 years of annualization (Guest & Desjardins, 2017).

3.7 Sustainability aspects that calculations of ILUC exclude

Even though GHG emissions are very important in the context of ILUC, especially concerning biofuels, there are other environmental effects that should not be forgotten as lack of water, reduced biodiversity, soil degradation and other societal impacts like a raise in food prices (Gawel & Ludwig, 2011; Ostwalda & Henders, 2014). Verstegen et al. (2016) propose error propagation valuation for effects like availability of water and biodiversity. Other than climate concerns, LUC has impacts on biodiversity, socioeconomic circumstances and environmental quality (Van Stappen et al., 2011).

One thing the different ILUC models have in common is that they do not consider the future production of biomaterials and that might intensify significantly ahead (Kløverpris & Mueller, 2013). ILUC factor estimations must be revised down the line because baseline circumstances and additional conditions do not remain the same, but that does not exclusively apply to ILUC effects as other carbon intensity values (for non-renewable fuel sources etc.) also vary with time (Kløverpris & Mueller, 2013).

A feature that is generally not included in ILUC studies is efficiency of delivery, but it is used by Bird et al. (2013). They use it to define the volume of agricultural-based food energy production which takes place in the system and is unused. The assessment is done through the ratio of people’s consumption to the national production net imports and exports. In the case of certain products, it is the degree of food that is wasted.

A low value of efficiency of delivery can for other products signal that production of crops is, instead of being used as food for humans, diverted to feed for livestock or for biofuel. An enhancement in the efficiency value conveys that a greater amount of food energy is available for humans which means that the need to increase the area of production is not as great, leading to reduced ILUC (Bird et al., 2013).

4. Discussion

4.1 The general uncertainty of ILUC

Although ILUC effects cannot be calculated precisely, it does not mean that the concept should be ignored. ILUC models are attempts of mapping and predicting some indirect effects that are likely to be significant in the area of GHG emissions from biofuels (Boldrin & Astrup, 2015; Guest & Desjardins, 2017). The difficulty of quantifying ILUC leads some to argue that measures for avoiding ILUC is better than focusing on the calculations behind it (Finkbeiner, 2014; Verstegen et al., 2016). Verstegen et al. (2016) encourage proactive efforts to reduce indirect land use change, instead of the attention in research being put on calculations of ILUC, despite the difficulties of measuring those efforts.

LCAs should not alone be the base for decision making to reduce environmental impacts, because it is not possible to include all impact categories and acquire a complete depiction of the harms caused by the products. However, it is proven that ILUC can impact the total GHG emissions of biofuels significantly and excluding ILUC from LCAs means that GHG emissions from biofuels are much lower compared to when it is included (Nguyen & Hermansen, 2012; Guest & Desjardins, 2017). Some studies, e.g. Searchinger et al. (2008), have in their results showed that ILUC affects the GHG emissions of biofuels to an extent where they may be the inferior alternative to fossil fuels. This is debatable though, again because of the large uncertainties of the calculations (Gao et al., 2011; Van Stappen et al., 2011). The core is that without evidence that ILUC is insignificant, it cannot be ruled out that ILUC of e.g. biofuel production may lead to potentially immense emissions of GHGs.

Uncertainties of ILUC calculations are large and including them in LCAs may therefor harm the credibility of the LCA. Even though excluding ILUC may give the impression of reduced uncertainty, the real uncertainty is still not reduced (Guest & Desjardins, 2017). Despite the many uncertainties around ILUC, the vast majority of articles reviewed in this study support the improvement of models for estimating ILUC.

Guest and Desjardins (2017, p. 612) conclude that "The LCA community has debated iLUC quite recently and there remains a strong argument to include iLUC in the accounts, especially in terms of jurisdictional renewable fuel regulations."

It should be stated that LCAs that do not include ILUC, still contain several uncertainties. Heijungs and Lenzen (2014, p. 1445) declare in their article that "the last few volumes of the International Journal of Life Cycle Assessment contain papers on uncertainty in LCA, either in recognizing that there is uncertainty or in presenting approaches to manage them". In an LCA, uncertainties can be found in numerous forms in all of the LCA-steps. Uncertainties in an LCA can be found in input data (e.g. CO_2 emissions or fuel consumption) as it may be uncertain due to incorrect measurements or because of fluctuations depending on the day or source. Conducting an LCA also means making assumptions and decisions about system boundaries, time horizon for global warming and so on, which are subject to debate. Using data which varies and is uncertain permeates through the entire LCA and leads to uncertain results (Heijungs & Lenzen, 2014). Considering the uncertainties mentioned above, excluding ILUC from an LCA does not mean that the LCA will produce certain results. Nevertheless, uncertainties in an LCA will be magnified by the inclusion of ILUC due to the many uncertainties concerning the concept.

After all the uncertainties that have been allocated to ILUC models in this study, an expression within statistics seems suitable to describe current research "Essentially, all models are wrong, but some are useful" (Box & Draper, 1987, p. 424). As models are merely representations of reality and cannot depict all aspects, certainly not in the case of such an intricate concept as ILUC, models cannot be expected to be without flaws. However, models also need to provide a certain level of reliability as a justification of using them, meaning there is a struggle between attempting to depict reality in a more comprehensive way and using reliable calculations.

4.1.2 Consequences of the lack of a standardized ILUC model

The uncertainties regarding what type of models are appropriate for calculating ILUC are great and there have been many very different attempts. It is clear that there is no common practice around calculating ILUC, demonstrated by e.g. Kim and Dale (2011) in their article where they use a different approach to ILUC. Short after publication the article received a very critical comment published in "Biomass and Bioenergy" where the assumptions, calculations and the first conclusion were severely critiqued (O'Hare et al., 2011).

There is substance in the critique and the purpose of the article can be questioned since the objective was to test the prediction that producing biofuel from soybean or corn will lead to ILUC due to reduced exports increasing the prices of the crops, thereby creating land use change which can mean releasing immense GHG emissions. Because the purpose was not a matter of scope of the potential ILUC effects, but only a question of if ILUC occurs, the reader does not get full information on the calculations leading up to the result.

The article by Kim and Dale (2011) illustrates one of the very different ways in which ILUC is calculated in research and that despite quick publication of a comment, heavily criticizing many things regarding their examination of ILUC effects, it was still published. Naturally, research may sometimes be very experimental (as in the case of e.g. Kim & Dale, 2011), but the width of variations of ILUC assessments shows a lack of consensus around ILUC that weakens the realization of the concept. Only stating whether or not ILUC occurs, does not provide much useful information as the environmental impacts depend greatly on what type of land is changed. Estimations of how large ILUC emissions might be, gives a more complete representation of the environmental impacts, although a precise quantification cannot be expected.

Despite the importance of an agreed upon period of time that the GHG emissions need to be distributed over, ILUC studies lack a shared terminology regarding spreading GHG emissions from LUC over time. Some examples of the different words are DeCicco (2012) who uses the term “amortization”, while Kløverpris and Mueller (2013) use “annualization” and Nguyen and Hermansen (2012) practice a “depreciation period”. What is of actual importance is not the name of the period but that the choice of the length is arbitrary (Kløverpris & Mueller, 2013). Although, the different terms used is a manifestation of the many variations in ILUC calculations. Considering the variations in language together with the many other variations in quantifying ILUC, expectations of one standardized ILUC model to incorporate into an LCA may not be fulfilled in a near future.

4.1.3 Different models for different situations

If estimations say that most of the ILUC that takes place in a country, originates from the same country, a model of smaller geographical scope as in Ponsioen and Blonks approach (2012), may be a better alternative than the usual GE or PE models. Using calculations specific to one country leads to fewer simplified assumptions as it should be easier to determine links concerning land use change and thereby noticing the causes of ILUC.

Limiting the model to one country also provides a better base for more consistency with actual policies concerning land use rights as well as the potential to use more location specific data on land cover. There is generally a lack of data for ILUC-models (Kline et al., 2011; de Jong, 2019; Verstegen et al., 2016; Gawel & Ludwig, 2011), and reducing the area of the model may facilitate using less averaged data and more accurate data for the specific locations, if e.g. a country´s government decides to expand and release this type of data. Possibly reduced uncertainty concerning data on land cover, may on the other hand lead to different types of uncertainties. As country's economies today are deeply connected to other countries, using a perspective that isolates a country from the rest of the world is questionable. But because of the complexity behind indirect land use change, using economic models that have a global span is still uncertain. For countries that experience a large degree of LUC, a model specific to that country may be more appropriate. However, national models are not available for all countries.

4.1.4 The focus on GHG in ILUC models and what they exclude

Quantifications of ILUC effects in the reviewed articles cover GHG emissions, but leave other important aspects out of the calculations. As the debate around ILUC originally started from questions regarding the sustainability of biofuels in terms of GHG emissions, it is logical that these emissions are what ILUC models are built around. The focus on climate can be justifiable due to the acuteness of climate change. Proceeded emissions of GHGs will lead to further warming of the Earth and raise the likelihood of "severe, pervasive and irreversible impacts for people and ecosystems" (IPCC, 2014, p. 56).

Gawel and Ludwig (2011), among others, mention the importance of not ignoring aspects such as reduced biodiversity due to ILUC. Currently Earth´s sixth mass extinction is taking place and the loss of biological biodiversity is considered one of the biggest serious environmental problems triggered by human activity (Ceballos, Ehrlich & Dirzo, 2017).

Only focusing on GHG emissions will not meet the United Nations (n.d.) Sustainable Development Goals as they include e.g. protecting biodiversity, which is part of goal 15. Even though climate is a crucial issue, it does not imply that other issues such as reduced biological diversity are less important and can be ignored. Of course, the complexity of ILUC models are great and that is why e.g. assumptions that simplify reality are needed to make the models manageable. Adding aspects like biodiversity or socioeconomic consequences poses an extraordinary challenge for already extremely complicated calculations. ILUC models cannot include all relevant aspects of sustainability and prioritization must occur.

4.2 The key issues of including ILUC in LCAs

Land use change is only possible to observe empirically and assess in terms of the local direct effect and indirect effects require the use of models (Nassar et al., 2011). This, as in the lack of causality, is most likely the greatest issue of quantifying ILUC. Since ILUC cannot be directly observed, quantifications rely on models which in turn rely on many assumptions, both due to lack of data and the many factors influencing ILUC. Improved data on global land cover with information on carbon stock is requested in research to enhance ILUC models (Jong et al., 2019; Kline et al., 2011). The main issues according to Gao et al. (2011) originates from data. More data on land cover globally, along with information on what type of products the crops are intended for, would imply that the connections between land use change in one area, leading to land use change in another area (ILUC) could become less difficult to detect. More data would result in the use of fewer assumptions which would reduce some of the model uncertainty.

Some of the assumptions used when calculating ILUC are questionable. The assumption in ILUC models that forests regrow naturally, even though it is quite common that forest fires occur in the relevant areas of land and thereby emit GHGs annually (Boldrin & Astrup, 2015), is one of the assumptions that may not lead to correct results. The regrowth of forest and the burning of forest have opposite effects in terms of climate impact. Because of this, the assumption cannot be used and expected to lead to correct estimations of ILUC GHG emissions. More detailed data on land cover may lead to this particular assumption not being used, which would very slightly improve the reliability of the models.

Even with complete data on land cover, the issue of causality would mean that e.g. deforestation could not be attributed to biofuel crop expansion somewhere else. Deforestation is affected by aspects such as land use rights, permission from local authorities and the economic situation (Levidow, 2013). This means that despite the potential link between increased crop land for biofuel production and deforestation, it cannot be determined as the cause (Verstegen et al., 2016). Even though ILUC is something that occurs in reality, it is thus far only in theory that it can be traced and assessed. This is an inherent issue of ILUC, hence the term *indirect* land use change. The lack of causality regarding ILUC is thereby in the center of all the uncertainties. Without clear causality it is uncertain if reliable scientific models for indirect land use change can exist, and if not, research may instead be spent on other aspects such as direct land use change.

4.3 The current state of ILUC research

It is noteworthy that the literature search used in this study comprises close to a fourth of the articles related to "indirect land use change" in the database "Web of Science", indicating the strict limitations of research of ILUC at this point. Of course, the use of a different database may have led to more articles on ILUC, but "Web of Science" include many different scientific journals and is a well-known database in the general field of science. Nevertheless, important and illuminating studies may have been excluded due to the choice of search words and database. As this study does not cover all the available material on ILUC, there may be recent studies that provide better solutions for ILUC calculations than the studies reviewed here.

The reason why it is still a shallowly researched area, more than a decade after the publication of the first articles seriously raising the question of ILUC, is probably due to the complexity of the concept. There are several reasons for why ILUC models still have so many uncertainties and this is probably linked to the two key issues identified in this study: causality and data. Considering the current lack of research on ILUC, further research on the subject is needed to state if it is even possible that the uncertainties identified in this study can be significantly reduced in future calculations. Studies that examine methodology of different ILUC models in a detailed way and compare them are also needed as this study has a general approach to the uncertainties of including ILUC in life-cycle assessments. Considering the uncertainties found in current ILUC research, especially causality, future research should be guided by a troubling question: *Will there ever be a reliable ILUC model?*

4.4 Recommendations for the industry of biomaterials

While direct land use change can be worked with more proactively, indirect effects are difficult to manage. With new products such as bio-based plastics there is the societal requirement of proving its sustainability compared to its fossil counterparts, which is often a burden for innovative companies trying to break into the market. Providing evidence for a new product that is intended to have better environmental performance than the original product, is of course of large importance to secure the choice of the best alternative.

In a scenario where ILUC is included in the LCA of e.g. bio-based plastics, a range of ILUC estimates, instead of a final number for the calculation, is suitable considering the many uncertainties. One alternative is to also offer two LCA results, one where ILUC is excluded and one where it is included. The part of the LCA which has ILUC excluded should be the one that is primarily promoted as the regulations including ILUC (EU RED II) only applies to biofuels and not bio-based plastics. The many uncertainties of ILUC calculations is however the more important argument against fully including ILUC in an LCA. One version with ILUC can at least create an awareness of the indirect effects of the products. It may appear unconventional to provide two results within one LCA as the core of an LCA is to achieve a compilation and simplification of the impacts of the product. However, this may be a pragmatic approach that works for regulators and companies that want an inclusion of ILUC in LCAs, despite the difficulties of quantifying it.

5. Conclusions

There are numerous uncertainties in ILUC models that have critical influence on the end results. Uncertainties take the shape of the many alternatives of calculating ILUC, instead of one standardized method that can produce reliable results. The arbitrary choice of the distribution period of GHG emissions is another uncertainty which has a large impact for ILUC emissions as doubling the time period means emissions are halved. The number of assumptions used in ILUC models could be reduced with more data, but due to the complexity of ILUC, assumptions are currently used which do not reflect reality well. Some of the assumptions are immense simplifications of very complex occurrences as deforestation and some even contradict empirical evidence.

The two key uncertainties regarding ILUC found in this study are causality and data. Causality is a basic fundament when trying to calculate something, but there is a lack of clear causality for ILUC. Due to the many factors influencing LUC, proving that land use change in one place is an indirect effect of land use change somewhere else is very difficult. Although ILUC models are not complete, they have drawn attention to the important issue of indirect land use change.

If ILUC is included in an LCA of e.g. bio-based plastics, it should be presented as a type of alternative LCA and clearly differentiated from the regular LCA (meaning ILUC excluded), due to the many uncertainties regarding ILUC. The most realistic option for LCA-practitioners is however, probably to simply exclude ILUC from LCAs. In respect of all the uncertainties found in this study, excluding ILUC from LCAs is under current circumstances highly reasonable.

Ethics

This study was performed in cooperation with the EU-project “Biodolomer for Life” which consist of three parties, they are GAIA BioMaterials, NSR (the municipal waste company in Helsingborg) and Öresundskraft (the municipal energy company in Helsingborg). One ethical issue that can arise when working on assignment by external parties is that the author put too much emphasis on the project party’s interests by skewing the study to produce results they will be pleased with. In this case it would be to focus on the benefits of bioplastics, instead of researching it through the critical lense that is the foundation of science. During the semester when this study was performed, the author kept in mind that the primary objective was to present a scientific thesis that would be accepted by the university and secondly providing the project parties with a study of interest to them.

As this study was made in association with Öresundskraft the author will receive a type of salary from the company (this is customary for the company) after the thesis has been approved by Lund University. When agreeing to write this report in cooperation with the EU-project, this was not known to the author and the knowledge did not change the author’s mindset in terms of firstly contributing to research instead of producing something that pleases the parties.

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Appendix – Articles in the literature review

The following list comprises all the journal articles that were used in the literature review. The numbers represent their order in “Web of Science” as they were sorted by date. There are 31 articles in total and the last one in the list is not numbered because it vanished from the database at the end of the study.

1. Using dynamic relative climate impact curves to quantify the climate impact of bioenergy production systems over time

8. A carbon footprint of HVO biopropane

10. Impact of uncertainty in indirect land-use changes and life-cycle carbon intensity for biofuels under climate legislation: a case study of British Columbia

11. A confirmation of the indirect impact of sugarcane on deforestation in the Amazon

13. What can and can't we say about indirect land-use change in Brazil using an integrated economic - land-use change model?

16. GHG sustainability compliance of rapeseed-based biofuels produced in a Danish multi-output biorefinery system

17. Policy change, land use, and agriculture: The case of soy production and cattle ranching in Brazil, 2001-2012

19. Indirect land use change - Help beyond the hype?

21. Making two parallel land-use sector debates meet: Carbon leakage and indirect land-use change

22. Ethanol expansion and indirect land use change in Brazil

23. A method for estimating the indirect land use change from bioenergy activities based on the supply and demand of agricultural-based energy

24. A dynamic simulation of the ILUC effects of biofuel use in the USA

26. Baseline time accounting: Considering global land use dynamics when estimating the climate impact of indirect land use change caused by biofuels

27. EU criteria for sustainable biofuels: Accounting for carbon, depoliticising plunder

28. An alternative approach to indirect land use change: Allocating greenhouse gas effects among different uses of land
30. Accounting greenhouse gas emissions in the lifecycle of Brazilian sugarcane bioethanol: Methodological references in European and American regulations

31. Calculating land use change in carbon footprints of agricultural products as an impact of current land use

32. Biofuels and carbon management

33. System expansion for handling co-products in LCA of sugar cane bio-energy systems: GHG consequences of using molasses for ethanol production

34. Direct and indirect land use changes issues in European sustainability initiatives: State-of-the-art, open issues and future developments

35. Sources of corn for ethanol production in the United States: a decomposition analysis of the empirical data

36. Comment on "Indirect land use change for biofuels: Testing predictions and improving analytical methodologies" by Kim and Dale: statistical reliability and the definition of the indirect land use change (iLUC) issue

38. The iLUC dilemma: How to deal with indirect land use changes when governing energy crops?

39. Indirect land use change for biofuels: Testing predictions and improving analytical methodologies

40. Indirect land use change emissions related to EU biofuel consumption: an analysis based on historical data

41. Assessing deforestation from biofuels: Methodological challenges

42. Identification of 'Carbon Hot-Spots' and Quantification of GHG Intensities in the Biodiesel Supply Chain Using Hybrid LCA and Structural Path Analysis

44. Policy Implications of Uncertainty in Modeled Life-Cycle Greenhouse Gas Emissions of Biofuels

45. Life cycle assessment of selected future energy crops for Europe.

49. The greenhouse gas emissions performance of cellulosic ethanol supply chains in Europe

Measuring Indirect Land Use Change with Biofuels: Implications for Policy