Influence of Indirect Land Use Change on the GHG Balance of Biofuels – A Review of Methods and Impacts

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Abstract: The greenhouse gas (GHG) balance or carbon footprint of biofuels, generally calculated by life cycle assessments (LCA), is heavily influenced by the modeling of land use changes (LUC). This includes direct land use changes (DLUC) and indirect land use changes (ILUC). Various methodical approaches for the integration of ILUC in LCA have recently evolved. In this study several approaches for calculating ILUC and the effects on GHG balance are compared. These are economic modeling, deterministic modeling and regional modeling. Papers published on this topic since 2007, when the ILUC debate began, are reviewed considering the following main criteria: methodological approach, uncertainties of assumptions, and the level of the GHG emissions due to ILUC. The results show that the existing approaches lead to strongly divergent results. This is due to uncertainties about relevant assumptions, e.g. the methods of linking commodity prices to ILUC, assumptions about yields, soil carbon contents, and the effect of by-products. These uncertainties and other methodological inconsistencies, e.g. the allocation issue with respect to displacing vs. displaced crops, imply that further research is needed and that current methods are not robust enough for adoption in regulation.

Keywords: *Biofuels, Greenhouse-gas balance, Life cycle assessment, Indirect land use change, EU policy*

1. Introduction

The worldwide expansion of biofuel production is being driven by several forces; these include, first and foremost, rising oil prices, promotion of a secure energy supply, and rural development [1]. In the European Union (EU), the reduction of GHG emissions in the mobility sector has been another important factor, leading to national policy objectives designed to increase the biofuels share ([1, 2]). To ensure that biofuels achieve a significant reduction in GHG emissions, the Renewable Energy Directive (RED) indicates that a life cycle GHG emissions reduction of roughly 35% as compared to fossil fuels is necessary; otherwise, biofuels will not be counted towards attainment of the quota. By 2017, this increases to a 50% reduction vs. fossil fuels [3]. Other regulations, e.g. the US Energy Independence and Security Act (EISA) of 2007, include similar reduction targets [4]. These objectives are met by most of the biofuels if LUC are not considered [5]. In 2007, however, in the context of increasing food prices, LUC linked to biofuel expansion became a topic of public discussion; the same year, EISA directed the US government to develop a LCA for biofuels that includes DLUC and ILUC [6]. The 2009 RED similarly directs the European Commission (EC) to investigate “the inclusion of a factor for indirect land-use changes in the calculation of greenhouse gas emissions” [3]. As a consequence of such political pressures, but also a growing interest in research into LUC issues, a number of ILUC studies have recently been published (e.g. [5, 7-16]).

Biofuel production-related DLUC occur when a previous land use especially a natural habitat is converted to bioenergy crop production. The conversion of grassland, tropical rain forest or peat bogs into agricultural land will generally lead to a release of additional carbon dioxide over several years or even decades [17]; these GHG emissions are often referred to as the “carbon debt” of biofuels. Depending on the previous land use, the time needed to repay this carbon debt through annual savings in GHG emissions vs. fossil fuels can range between zero and 423 yr [17]. Feedstock cultivation on degraded lands with low carbon contents, on the other hand, can lead to a sequestration of carbon dioxide (e.g. [5, 18]). According to the IPCC [19], emissions due to LUC are generally allocated across the yields of 20 yr when calculating the emission factor for DLUC; however, since carbon contents depend not only on land use but also on tillage methods (e.g. [7,20,21]), soil texture, and hydrological and climatic conditions [22], the use of default emission factors, such as those provided by the EC, is quite imprecise − there is a lack, in particular, of reliable data on GHG balances for biofuels cultivated on degraded land [23].

ILUC occur when biofuel feedstock cultivation replaces other crops and, consequently, natural habitats are then converted to arable land to meet the demand for the displaced commodities [8]. Inclusion of ILUC in GHG balances is more difficult than with DLUC because of the high system complexity: ILUC are tied to global market dynamics. Some scientists assume that if a crop is displaced, the prices for this crop will increase and farmers will react by creating new arable land [24]; however, because of increasing global market prices, ILUC can occur anywhere in the world – not only in the country where biofuels are being produced ([8, 9]); in such situations, measuring these effects at the regional level is not sufficient. Likewise, national regulations, e.g. customs, subsidies or trade restrictions, also influence prices and trade flows and thus ILUC [25]; hence, a consideration of global prices alone is also not sufficient. Moreover, biofuel production is a multi-product system: by-products, such as dried distillers' grains with solubles, also accrue; these can substitute for fodder crops and thus reduce total land demand ([26-28]). Furthermore, forces other than agricultural expansion, such as timber harvest and infrastructure development (e.g. road building), also drive LUC [7]. ILUC-specific methodologies are thus needed. Currently three basic approaches to quantify ILUC exist: economic models, i.e. partial or general equilibrium models, that provide for calculation of ILUC (e.g. [10,11]); deterministic or descriptive-causal models, which attempt to estimate ILUC based on a set of simplified assumptions (e.g. [5]); regional models that try to take into account regional influences on ILUC [25].

Purpose of this work is to present a systematic overview of the body of literature in the area of ILUC research and to assess its influence on the GHG balance of biofuels. Therefore in the present article, these different approaches for calculating ILUC and the effects on GHG balance are described and compared.

2. Methodology

For this purpose the relevant literature (since 2007) relating to this topic was identified and evaluated; some grey literature was also considered when appropriate. The following three main criteria for evaluation were considered: methodological approach, uncertainties of assumptions, and the level of the GHG emissions due to ILUC. For the purpose of comparing the various approaches, some conversions were necessary; in these cases, conversion values (e.g. carbon contents) were taken from the original literature. The study further addresses the question and extent of ILUC integration into EU policy and poses questions for further research and development. A clear response to the question of the extent to which ILUC influence the GHG balance is not offered, but the study does address their relevance; the advantages and disadvantages of the various methodological approaches are also indicated.

3. Results

3.1. Economic modeling of ILUC

Both partial-equilibrium models (e.g. FAPRI, AGLINK, IMPACT, CAPRI) and general-equilibrium models (e.g. GTAP, LEITAP) are used to project ILUC [12]. Partial-equilibrium models are based on linear relationships between prices, demand, and production in the agricultural market, whereas general-equilibrium models model the whole world economy (e.g. interactions of the agricultural sector with chemical industries) [12]. In general, economic modeling of ILUC follows three main steps. First, the economic model is given a so-called biofuel shock or policy shock, i.e. biofuel production is increased; the model projects the effects of nationally increased biofuel production on global commodity markets and on additional land requirements. In this step, the model also provides indications as to the countries in which additional land will need to be converted. In the second step, LUC are then mapped to specific land-cover types (e.g. grassland, forest), based on historical patterns of LUC. Finally, biophysical models are used to project the GHG emissions from land use conversion. The size of the shock allows GHG emissions to be attributed to a specific quantity of biofuels. Nearly all studies calculating ILUC by means of economic modeling found that ILUC significantly influence the GHG balance of, at a minimum, first-generation biofuels ([10-13]). Current investigations indicate that second-generation biofuels could lead to a negative ILUC effect [29]. Since the various models used different shocks respectively, it has not been possible to compare results for recent years; therefore, at the direction of the EC, modelers calculated the crop area changes for specific biofuels scenarios [12]. The results show that the range of crop area changes is quite high: for the EU biodiesel scenario, for example, the values range between 242 and 1928 kha Mtoe^{-1} (see Table 1) [12] .

Table 1. Minimum and maximum values of LUC calculated with different economic models (source: authors, based on [12])

Scenario	Minimum		Maximum	
	(kha Mtoe^{-1})	Model	(kha Mtoe^{-1})	Model
EU biodiesel scenario	242	AGLINK	1928	LEITAP
EU ethanol scenario	223	IMPACT	743	LEITAP
US ethanol scenario	107	IMPACT	863	LEITAP
Palm oil scenario	103	GTAP	425	LEITAP

These deviations are caused by assumptions about input data made at each stage of the modeling. Many assumptions are uncertain and therefore differ among the models [9]. First, the extent to which farmers will react to rising prices by increasing yields through irrigation or fertilization is uncertain [24]; whether extra emissions due to the use of additional fertilizers are accounted for is also uncertain [12]; moreover, feedstock yields vary among the models, particularly in expansion areas [12]; the extent to which reductions in food consumption will take place as a consequence of increasing food or fodder prices is also unknown. Likewise, the share of additional crops saved by by-products differs among the models; one reason for this are differences in the methods of calculation: in GTAP and LEITAP, by-products are accounted for by substitution on the basis of relative prices; other models, such as CAPRI, account for them through physical replacement ratios [12]. Additionally, controversy exists about the extent to which production is shifted from countries with high yields to relatively less developed countries with lower yields [12] and about the share of forest and grassland conversions [9]; and, finally, as mentioned previously, emission factors related to LUC are also uncertain. To characterize ranges for the GHG emissions of different scenarios, we multiplied the ILUC values in kha Mtoe^{-1} taken from Edwards. et al. [12] (see table 1) and carbon dioxide emission factors using three different values for soil C emissions: 40 tC ha^{-1} as an average value and 10 and 95 tC ha^{-1} as lower and upper values (cf. [11, 12]). Fig. 1 shows that the range for the EU biodiesel scenario, in particular, is quite large, whereas those of the EU and US ethanol scenarios as well as that for palm oil are narrower. Results for the EU ethanol scenario range between 14 and 309 g CO_2 MJ^{-1} due to

LUC. Since the default carbon footprint of fossil fuels is set at 83.8 g CO_{2e} MJ^{-1} in RED, it can be assumed that this scenario and likewise the EU biodiesel scenario will not lead to a 35% GHG reduction in comparison to fossil fuels.

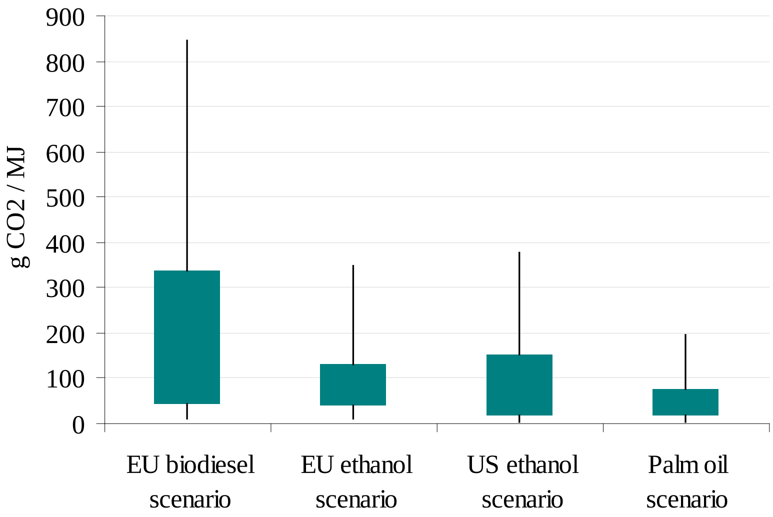

Fig. 1. Range of CO_2 emissions due to LUC calculated on basis of results of various economic models Maximum and minimum LUC values resulting from economic models in ha $Mtoe^{-1}$ [see Table 1] were multiplied with typical C emission factors 40 tC ha^{-1}[error bars: 10 tC ha^{-1}, 95 tC ha^{-1}] – authors' calculations, based on Edwards et al. [12].

3.2. Deterministic modeling of ILUC

The second main approach is called deterministic or descriptive-causal modeling. These models are simplified calculations based on explicit assumptions and are usually realized with a spreadsheet calculator. In general, these models use cause-and-effect logic to describe system behavior. One example of this approach is the ILUC factor developed by the Institute for Applied Energy, in Germany [5]. A crucial assumption in this model is that ILUC can be estimated by looking at the exported products relevant for the bioenergy sector, e.g. soy, corn (maize) and palm oil. Calculations are based on 2005 product exports, but for the purpose of simplification, only key regions, such as Argentina, Brazil, the EU, Indonesia, Malaysia, and the USA, are considered; these countries are responsible for more than 80% by mass of the global trade in the respective commodities [5]. Using the mass of commodities traded divided by the respective country-specific yields, the area needed to produce these products was calculated. From the sum of all land use for agricultural exports, each country's proportionate share could be derived – the "world mix." Next, additionally needed areas were combined with country-specific assumptions about the specific DLUC associated with the production of the export commodities. Following the application of conversion factors from IPCC, the interim results were then weighted according to each country's share of the "world mix," resulting in an ILUC factor of 13.5 t CO_2 $ha^{-1}a^{-1}$ [5]. This means that 1 ha of bioenergy feedstock production displaces 1 ha of previous production. The authors suggest three different levels of ILUC (25%, 50%, and 75% of the theoretical ILUC factor), as they anticipate yield increases and assume that a share of the expansion occurs on degraded lands [5]. Fig. 2 breaks down the level of CO_2 emissions by type of biofuel, country of production, and prior land use. The high level of GHG emissions when ILUC are included means that most biofuels will not achieve the GHG reductions called for in the RED [5]. Compared to the results of economic modeling (see Fig. 1), the results for CO_2 emissions due to DLUC, plus the differing ILUC factors calculated with this approach, are low for biodiesel but in the same range for ethanol if calculated with 40 tC ha^{-1}.

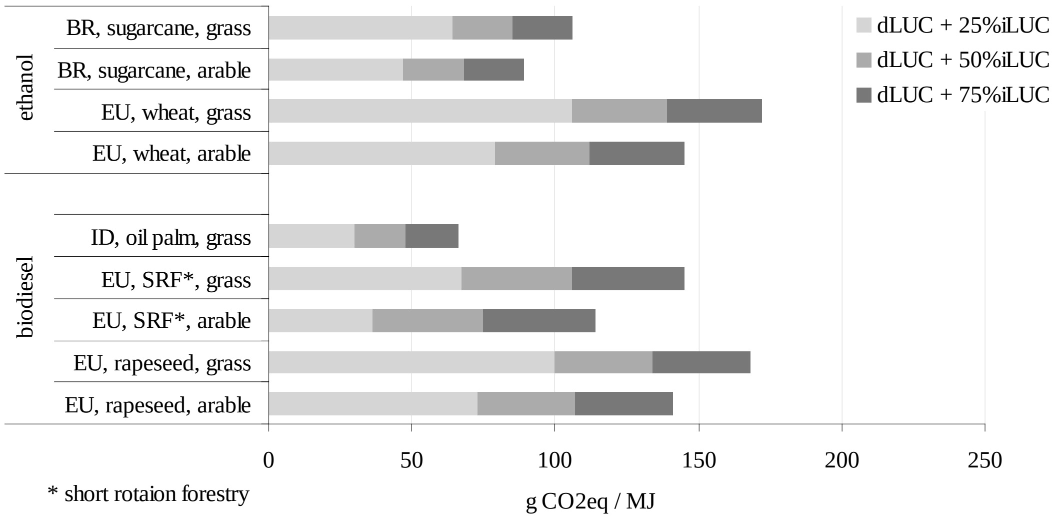

Fig. 2. CO_2 emissions calculated on basis of a deterministic model (figures from Fritsche et al. [5]).

Another deterministic model, developed by Plevin et al. [9], attempts to characterize a robust range of ILUC. For this purpose, the authors include four main parameters in a reduced-form model: net displacement factor (NDF) (ha converted land / ha biofuels), average emission factor (Mg CO_{2e} ha^{-1}), production period (yr) and fuel yield (MJ ha^{-1}yr^{-1}). Setting an upper and lower value for these parameters, based on the literature, the ILUC emission factor for US corn ethanol ranges between 10 and 340 g CO_{2e} MJ^{-1}, which is similar to the range as calculated according to Edwards et al. [12] (see Fig. 1). The results suggest that the NDF accounts for the major part of the variance in the ILUC factor; it includes the effects mentioned above, e.g. price-induced yield increases, relative productivity of land converted to cropping, price-induced reductions in food consumption, and by-product substitutions [9].

3.3. Regional modeling of ILUC

In Germany, another method has been discussed: regional modeling. This approach was developed, first, in response to criticism that other models do not properly consider the effects of state regulation on the global agricultural market; these can take the form of subsidies, customs duties, and trade restrictions (bans on import/export, etc.). Second, the deterministic model of Fritsche et al. [5] is limited to LUC due to product exports ([5,25]) and thus does not consider ILUC effects due to domestic trade, which, according to Lahl [25], must be included as internal trade is quantitatively more important than global trade. Lahl [25] suggests the following method for regional modeling: first, all LUC in a country and for a specific period must be ascertained. Country-specific CO_2 emissions (E^RLUC) are then calculated for the respective carbon stocks in vegetation and soil, before and after conversion. In order to calculate the share of the various biofuels in total emissions, the change in biofuel production is divided by the change in agricultural production in total and multiplied by E^RLUC. Next, the portion of total emissions due to DLUC is subtracted, and finally, the remaining emissions are allocated to the "originator," which can be separate farms or regions. In some cases a correction factor for by-products or transnational effects must be included. To determine whether transnational effects are relevant for a specific country, one should look for a drop in agricultural import levels for recent years and an absolute value of the reduction in agricultural imports higher than the absolute value of the increase of agricultural exports [25].

An application of this model is not yet known. A method of economic modeling that combines regional aspects with economic modeling was applied to the biofuels sector in Brazil [10]. Methodologically, a land-use change model was linked with a partial equilibrium model of the agricultural sector economy and a dynamic global vegetation model. Using these models, it was determined that in Brazil ILUC influence the GHG balance of biofuels much more than DLUC [10].

4. Discussion and Conclusions

LUC are of central importance for the GHG balance of biofuels. For the purpose of GHG mitigation, the EC is directed to consider inclusion of an ILUC factor in the calculation of GHG emissions of biofuels. Currently, three main approaches, economic modeling, deterministic modeling and regional modeling, exist for calculating ILUC. The results of these methods vary greatly – by a factor of more then ten, but nearly all methods indicate that ILUC increase GHG emissions significantly. With respect to the relevance of ILUC, they are thus unambiguous and call into question the viability of biofuels as a climate protection instrument. Many of the results suggest that most of the currently available biofuels will not reach the GHG reduction targets of the RED after inclusion of ILUC. The effect of biofuel specific ILUC factors may be critical with respect to their attainment of the mandated 35% reduction in GHG emissions vs. fossil fuels; this in turn is decisive for whether a specific biofuel is to be included in the intended biofuels share of total fuel consumption; thus care needs to be taken with the development of such a factor.

The deterministic model from Fritsche et al. [5] indicates that oil palm biodiesel and sugarcane ethanol are accompanied by lower ILUC effects than biodiesel produced from rapeseed and ethanol from wheat and corn. Results from economic models exist for only a few biofuel scenarios; thus it is not yet known whether deterministic and economic models will lead to corresponding results for specific biofuels. Characteristic of all ILUC modeling is that input data and assumptions are often uncertain. Some uncertainties are present in all of the methodologies, in particular, assumptions about CO_2 emission factors for various LUC; feedstock yields, particularly in expansion areas; extra emissions due to fertilizing to increase yields; and the share of extra crops replaced by by-products. In some models, by-products are accounted for by substitution on the basis of relative prices; other models account for them through physical replacement ratios [12]. It is possible to set default values, e.g. CO_2 emission factors, or calculation types, e.g. for the consideration of by-products as in RED [3]; this would lessen the deviation between the outcomes of the different models but also limit possible results. Additional uncertainties exist specific to the type of model. For economic and deterministic models, this includes assumptions about the extent to which production is shifted from countries with high yields to relatively less developed countries with lower yields, the share of forest, grassland and wetland that will be converted, and the levels of reductions in food consumption that occur as a consequence of increasing food or fodder prices. Furthermore, economic models do not take into account market distortions due to national policy [25]. Missing or dubious land-use rights in specific countries may also affect ILUC. This is not taken into account in economic and deterministic modeling. For the deterministic model from Fritsche et al. [5], the main question is whether it is sufficient to calculate ILUC on the basis of exported products or whether internal trade should also be included. Regional modeling can probably provide more precise information about real ILUC effects in specific countries; it can also be a suitable method if countries or farms that allow ILUC are to be sanctioned. However, availability of regional data is a precondition for this method and applications of the regional methods remain largely unknown. Each of the current models thus has its pros and cons.

Before establishing a specific method for calculating ILUC or setting default ILUC factors via regulatory policy, these methods should first be improved and applied to various scenarios and regions. Information and data about ILUC effects in specific regions, especially, are still lacking and need to be further explored. Some theoretical considerations are also necessary before ILUC should be accounted for in policy regulation: From the point of view of LCA, a precondition for the comparison of two products, e.g. biofuels and fossil fuels, are consistent boundaries for both systems; therefore, when calculating GHG balances including ILUC, other indirect effects arising from the production and use of biofuels and fossil fuels, e.g. price-induced increases or decreases in fuel consumption (cf. [30]), should be analyzed and similarly included. Furthermore, in most of the current methods the product previously cultivated does not receive any of the GHG emissions due to DLUC if it is displaced; once again, from the point of view of LCA, this is questionable because all environmental impacts should be allocated on all accruing products in the systems being analyzed.

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