

Are models suitable for determining ILUC factors?

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Are models suitable for determining ILUC factors?

Summary

The present sustainability criteria of the European Union for biofuels include minimum values for reducing greenhouse gas emissions. These reductions are based on a greenhouse gas balance which includes all the steps in the production chain for biofuels. Indirect emissions, however, are not included. One of the outcomes of the political debate surrounding the indirect impact of biofuels is an exploration of the possibility of using emission factors in greenhouse gas balances to take into account the emissions caused by indirect land-use change (an ILUC factor). Analysis using models is one way to derive such factors.

To derive the ILUC factor (or factors) the model to be used needs to take into account the interaction between a new biofuel production chain and the dynamic global system. An ILUC factor is a characteristic of this interaction itself and not of the biofuel, and it varies in time. Other essential aspects to be included in the model are physical land use in all world regions, the impact of by-products (feed) and the consideration of agricultural intensification, agricultural area expansion or change in consumption. Although a range of models includes these aspects, how they respond to intensification, expansion and consumption change still varies widely.

There are various reasons for this variability:

- The models currently used differ in the way how area and intensification changes are implemented;
- The set up of the reference determines the demand for agricultural products and thus agricultural area in the reference. This influences the balance between expansion, intensification and consumption.

This paper presents a survey of a series of (specific versions of) models and their results, which may potentially be suitable for this kind of analysis.

1. Introduction

Indirect land-use change (ILUC) emissions could contribute substantially to the greenhouse gas balances of biofuels based on energy crops. These have not been included in the sustainability criteria of the EU. The European Commission is studying various options for dealing with these ILUC emissions. One of the options is to include a factor for indirect land-use change (ILUC) impacts in the sustainability criteria for bio-energy. However, such a factor cannot be directly measured. ILUC emissions have to be derived with rather complicated calculations.

In the political debate surrounding bio-energy the idea of including an extra factor (or factors) has introduced models as a possible instrument for this. Although models cannot distinguish between direct and indirect effects, these are the only instruments for comparing different scenarios or “two different worlds”: a world with a bio-energy policy and one without. Such comparisons show the final land-use impacts which, in turn, can be used to derive the indirect impacts¹. However, models will never be able to represent reality perfectly. Models, by definition, provide a simplified version of the world which means that every model has its pros and cons. The models used in this debate were originally set up to analyse or explore the impact of various policy options, rather than to support the determination of emission standards.

In this policy paper we evaluate which modelling features are really necessary to derive the indirect impacts of bio-energy. We discuss the results of different model studies and finally suggest ways in which model results may be useful in defining ILUC factors. Most of the models considered here are in a continuous process of improvement. Therefore, it has to be emphasised that specific conclusions refer to specific versions of the models and studies (see Tables 1 and 2).

¹ As indicated above, models cannot distinguish between direct and indirect impacts, nor do they include sustainability criteria to prevent direct land-use effects, for example the prohibition to obtain bio-energy from highly biodiverse grassland. If we assume that bio-energy crops are only cultivated on existing agricultural land, all *final expansion* impacts will be equal to the indirect impacts.

Properties of models, analyzing indirect land use change

Table 1

Model	General features		Bio-energy chain		Endogenous ...			Emissions from ILUC		References
	Type	Sectors	Types of bio-fuel crops	By-products	Expansion	Intensification	Consumption change	Emissions from fertiliser use	CO ₂ land conversion	
<i>DART</i>	GE	All	WT, MA, OS, VO, SC, SB	No	No	Yes	Yes	No	No	Kretschmer et al., 2008
<i>EPPA</i>	GE	All	not specified, 2nd generation	No	No	No	Yes	No	No	Reilly and Paltsev, 2009
<i>GTAP</i>	GE	All	WT, MA, SC	Yes	Yes	Yes	Yes	Yes	partly	Lee, 2005; Taheripour, 2008; Hertel et al., 2008; Birur et al., 2008.
<i>GTEM</i>	GE	All	2nd generation	n/a	No	No	Yes	No	No	De Vries, 2009
<i>LEITAP</i>	GE	All	VO, WT, MA, SC, SB, 2nd generation	Yes	Yes	Yes	Yes	No (but Yes via IMAGE)	No (but Yes via IMAGE)	Eickhout et al., 2009
<i>MIRAGE</i>	GE	All	bioethanol and biodiesel	Yes	Yes	Yes	Yes	No	partly	Vain et al., 2009; Al-Riffai, 2010
<i>AGLINK /COSIMO</i>	PE	Agriculture	VO, WT, MA, SC, SB, 2nd generation	Yes	Yes	Yes	Yes	No ²⁾	No ²⁾	OECD, 2008; De Vries, 2009.
<i>CAPRI</i>	PE	Agriculture	WT, MA, OC, OS, VO, SB	Yes	No ¹⁾	Yes	Yes	Included in DNDCC-Europe	No	Britz et al., 2007; Leip et al., 2008.
<i>FAPRI</i>	PE	Agriculture	bioethanol, biodiesel	Yes	Yes	Yes	Yes	Yes	Yes	Searchinger et al., 2008; Fabiosa et al., 2009; Dumortier and Hayes, 2009; Dumortier et al., 2009.
<i>GLOBIOM</i>	PE	Agriculture Forestry	1st generation, 2nd generation	Yes	Yes	Yes	Yes	Yes	Yes	De Vries, 2009; Havlik et al., 2010
<i>IMPACT</i>	PE	Agriculture	SC, SB, MA, WT, OC	No	Yes	Yes	Yes	No	No	Pers. Com. S. Msangji, 2009; De Vries, 2009
<i>G4M</i>	Allocation, coupled to GLOBIOM	n/a	not explicit	n/a	Yes	n/a	n/a	No	Yes	De Vries, 2009
<i>GCAM</i>	IAM & PE	Energy, Agriculture, GHG emissions	2nd generation	No	Yes	No	Yes	No	Yes	Wise et al., 2009; Brenkert et al., 2003
<i>IMAGE</i>	IAM, coupled to any GE or PE ³⁾	n/a	WT, MA, OS, SC, 2nd generation	n/a	Yes	n/a	n/a	Yes	Yes	Leemans and Van den Born, 1994; Eickhout et al., 2009

WT = wheat, MA = maize, OC= other cereals, OS= oil seeds, VO = vegetable oil, SC = sugar cane, SB= sugar beet

1) The total agricultural area is fixed within CAPRI. Crop area can be expanded on fallow land.

2) A separate model, SAPIM (no global coverage), has been developed that deals with fertiliser emissions. CO₂ from land conversion can be calculated outside the model.

3) The LEITAP model has often been used to model economic drivers for the IMAGE model

All the processes and features crucial to the modelling of ILUC factors will be addressed in the course of this paper. In addition, we will compare 14 prominent models in the bio-energy or climate debate with respect to these crucial processes and features. The models and their specific properties are listed in Table 1. The organisation of this paper is as follows:

1. Overview of the general features of the models used to analyse bio-energy policies;
2. Important features in the implementation of the bio-energy chain in the models;
3. The response of area, consumption and yield to bio-energy production;
4. Discussion of the results of final land-use change and the expected emissions per unit of energy of the different models and the reasons for the variation;
5. Suggestions on how to use models to define ILUC factors for policy purposes.

2. Crucial model properties for the calculation of ILUC effects

2.1 General features of the models

The major systems that are affected by bio-energy production are the global economic and bio-physical systems. To analyse all the different impacts of bio-energy policies properly, the economic and bio-physical systems need to be combined in one modelling framework. Indirect impacts are, among others, caused by economic relationships between regions and therefore can occur anywhere in the world. In turn, changes in trade lead to changes in regional agricultural production. The final land-use change and its impact, for example, land-use emissions, occur in the bio-physical domain.

Overview of the models compared

Over the last decade several research groups have separately developed global economic or bio-physical models to look at bio-energy. Table 1 gives an overview of these models and their properties. Some of the models compared have been combined and/or integrated to cover both the socio-economic and the bio-physical systems (such as LEITAP/IMAGE or GLOBIOM/G4M). Other research groups have included one or more bio-physical aspects in their economic models, for example, GTAP-AEZ, MIRAGE or IMPACT. We will start with a description of the economic models and then consider the bio-physical models.

The economic models compared in this paper can be divided into two categories: General Equilibrium models and Partial Equilibrium models. Partial equilibrium (PEs) models take into account one or more sectors of particular interest (e.g. the agriculture, forestry or energy sectors; see Table 1).

General equilibrium (CGE) models take into account all sectors of the economy. These models, therefore, calculate the impacts of increasing production in one sector (and thus more use of inputs, such as labour and capital) on production costs in other sectors. The indirect effects of bio-energy production on the inputs (e.g. labour or energy) of other sectors (e.g. the impact of bio-energy production on the energy sector), can thus be appropriately evaluated using

general equilibrium models rather than partial equilibrium models. Since land is only used in the forestry and agriculture sectors, in principle, these sectors are sufficient for modelling the indirect land-use change impacts (e.g. the GLOBIOM model takes both into account). To calculate the impact on the price of crude oil, for example, at least the energy sector and the agricultural sector have to be included. When all sectors are included this reveals one of the most important limitations of CGEs, that is, the need to limit sectoral and regional disaggregation and the level of institutional detail. For example, the number of agricultural products in CGE models seldom exceeds ten (De Vries, 2010).

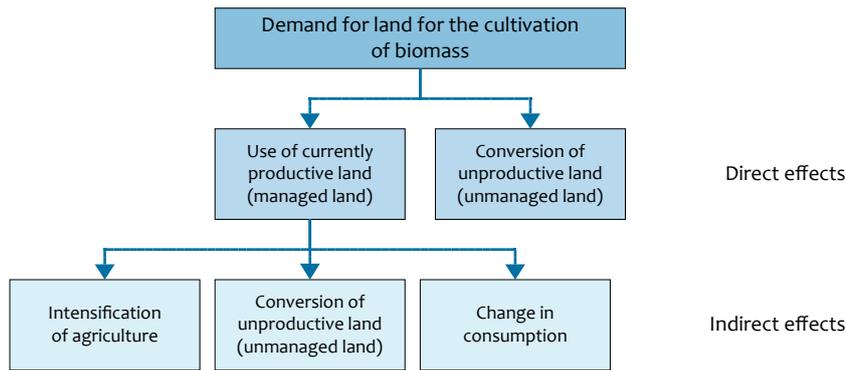
The last three models in Table 1 are bio-physical models. All these bio-physical models include an economic module (GCAM) or have been combined with an economic model (G4M to Globiom and IMAGE to LEITAP) to be able to include economic considerations when assessing land-use allocation and bio-physical effects such as emissions.

2.2 The bio-energy production chain

Different assumptions and choices in the bio-energy production chain lead to a wide variation in the final results of these models, for example, final additional land use needed per unit of energy. The more area needed per unit of energy (see 'demand for land for the cultivation of biomass' in Figure 1), the more the production of other crops will be replaced or displaced. One of the most important factors is the assumed yield of bio-energy crops, that is, direct area utilised to produce one GJ. If an energy target is applied to the model (e.g. the EU bio-energy target), the model will select the kind of bio-energy crops produced and their origin. Besides the assumed yields of these crops in the chosen regions, the allocation to crop type and region define the amount of area needed to produce one GJ. The type of crop and the origin can also be enforced in the model. In such an experiment only the assumed yield, the change in yield and the technology are important. These aspects may change over time. The selected crop mix will depend on two main features 1) the energy crops incorporated in the model, and 2) the accounting of by-products. Where a model is free to choose crops and regions, it should take physical land use in all world regions into account to ensure that the final impacts are based on all direct land-use impacts (globally).

Second-generation crops and by-products

One of the aspects in the crop mix is whether the model includes second-generation bio-energy crops and to what extent these crops are used to produce bio-energy. In reality, the mix of crops will depend on the technology available and the profitability of a particular energy crop and its by-products. This is one of the reasons why it is very important to include by-products in a model. Another reason is that the by-product produced with the bio-energy crop will make land utilised for feed production somewhere else redundant. In the GTAP model the implementation of by-products saved up to 25% of forest area in major energy crop producing regions and 50 to 70% of pasture area in these regions (Taheripour et al., 2008).



Indirect land-use effects of bio-energy production

Overview of the models compared

Models used for longer term climate change projections, in particular, take second-generation crops into account. The GCAM model, for example, uses purpose-grown second-generation crops (besides crop residues and municipal solid waste) to produce bio-energy. At the moment, the GCAM model does not take energy from first-generation crops into account. By-products have been included in more and more models in recent years and several modelling groups are currently working on this issue (see Table 1). Until recently, the LEITAP and MIRAGE models, for example, did not include by-products. A version which includes by-products has recently been developed. Earlier publications with results from the same models may be based on versions which did not yet include by-products. Examples of models which still do not take by-products into account are EPPA and DART. The EPPA model is a longer term projection model that focuses on climate analysis and therefore on second-generation bio-energy crops. By-products do not play a major role in this kind of analysis, however, in light of the indirect land-use change under current bio-energy policies, they do.

Not all the models compared here take physical land use in all world regions into account. The CAPRI model, for example, includes the supply of agricultural commodities from other world regions than Europe, but land use in other world regions is not taken into account in the analysis. Increasing the supply from Brazil does not induce an indirect effect due to land use in this model.

2.3 Response of area, consumption and yields to bio-energy production

General overview

The demand for land in the bio-energy production chain brings about changes in several regional and global systems which results in an indirect land-use change or final land-use change in models. Consequently, an appropriate model needs to include the economic considerations for the three routes shown in Figure 1: change in consumption, agricultural intensification or expansion of agricultural land. It is important to include by-products because these may replace feed production that was previously grown elsewhere.

Currently productive land will be used for the production of bio-energy or unproductive land will be converted for this purpose (see Figure 1). If currently productive land is used there will be an indirect effect in the agricultural sector (or any other sector that occupies that land). The supply of the commodity currently produced (e.g. a food crop) will change and a simultaneous process will define changes in consumption, prices and production. Depending on the cost and opportunities for producing the commodity (in this case, the food crop) somewhere else, a new equilibrium will be created with either the same production as before or less consumption. If the quantity of the commodity produced (i.e. the food crop) remains stable it can be produced, either on 1) 'new' agricultural land (expansion), or 2) existing land where yields will be increased by using more external inputs (intensification) (left-hand side of Figure 1). If the quantity of the commodity produced (i.e. the food crop) is reduced the consumption pattern will change (right-hand side of Figure 1). Depending on specific parameter settings, the consideration of change in consumption, expansion and intensification will differ from one model to another.

Overview of the models compared

The processes that define indirect land-use change, that is, by-products, change in consumption, land expansion and agricultural intensification, are shown in Table 1 for all models. Combining the economic and the bio-physical systems is crucial in the step from direct land-use impacts to final land-use impacts. Intensification or expansion is an economic consideration with bio-physical limits and feedbacks. To include the economic consideration the model needs to be able to change consumption and increase production per hectare substituting the factor input land by capital or labour. In addition, the model needs to be able to expand the agricultural area. The bio-physical limits and feedbacks that should be included are the amount of area in a particular region and the suitability of that area for producing crops. The way intensification is included differs between the models. Some models can substitute land by capital or energy (e.g. LEITAP and GTAP), others have price impacts included in their area calculations (for example FAPRI).

The expansion of agricultural area is one of the features added in recent years. The LEITAP/IMAGE model combination

uses a land-supply curve for each region that indicates the cost for expansion which can be weighted against the cost for intensification. Final production is calculated based on gridded bio-physical information from the IMAGE model (Eickhout et al., 2009). The GTAP-AEZ model uses bio-physical information per Agro-Ecological Zone (AEZ) type in each region and, to a limited extent, can substitute forest area by agricultural area in each region/AEZ combination (Hertel et al., 2009). Production per area has been defined per region/AEZ combination. Agricultural area cannot be expanded in the DART model. Incorporation of land supply is one of the most urgent improvements for this model (Kretschmer et al., 2008). The MIRAGE model uses a combination of the LEITAP/IMAGE land-supply-curve approach and the approach from the GTAP-AEZ model (Valin et al., 2009). In the CAPRI model the total agricultural land in the EU cannot be expanded but crops can be grown on fallow land. These types of land act as a kind of buffer in this model (Britz et al., 2007).

3. Model results

3.1 Model results for final land-use change

Table 2 shows the results of the final land-use impacts of bio-energy demand from the different models as extra area per extra unit of bio-energy. The range in results can partly be explained by the various critical properties that need to be included in the models: by-products, land expansion, consumption change and agricultural intensification. To give as complete a picture as possible we have added the studies analysed by Ecofys (Ecofys, 2009) to the list. A more extensive description of these results can be found in that report.

The third column in Table 2 shows the average area needed to produce one TJ of energy without taking into account any adjustments in supply or demand. The numbers represent the world averages in 2020 without accounting for by-products. There are considerable differences between the models. The results depend on the mix of crops used, the use of second-generation biofuel crops and the increase in the yield of biofuel crops. The GCAM model, for example, uses only second-generation biofuel crops (Table 1) which is the reason for the small area needed for one TJ in this case. The difference between the MIRAGE and LEITAP models is significant, since this model pair is one of the best to compare to each other. One of the reasons for this is that in the MIRAGE model especially sugar cane is used to produce bio-energy, whereas in the LEITAP model, oil crops are the major supplier of energy.

Comparing the third and fourth columns gives us an impression of the mechanisms involved in direct and final land-use change. The AGLINK/COSIMO model provides some scenarios in which solely the demand for one specific product from a specific region has been increased by 1Mtoe. Note, for example, that the final impacts of the AGLINK/COSIMO E27VL case amount to only 16% of the direct impacts, while in the BRASCA case the final impacts represent 64% of the direct impact. This is due to the use of by-products from oil seeds, the final land-use change is only part of the direct land use per MJ bio-energy. This illustrates the impact that the properties

of the bio-energy crops selected by the model have on the final land-use change, and the importance of by-products.

The significance of the origin of crops in turn indicates the sensitivity of the results to changes in trade regimes. See the differences between the two scenarios of the MIRAGE model, for example, one assumes the current EU mandate with the current trade settings (MEU_BAU) and one with full, multilateral, trade liberalization (MEU_FT) (Al-Riffai et al., 2010). In the second scenario, the United States and the EU completely open their markets to ethanol produced abroad. In the last case more sugarcane instead of sugar beet has been used to fulfill the EU bio-energy mandate.

The possibility of agricultural land expansion is, of course, very important in determining final land-use change. The DART model does not take land expansion into account and the CAPRI model looks only at land expansion in Europe. These models, therefore, show the smallest values for final land use. These versions of the models are thus not suitable for calculating ILUC factors. Although the CAPRI model can be used to calculate land use impacts within Europe, results of indirect impacts in the rest of the world are limited to changes in production. All other models do provide for agricultural land expansion.

Other features that define the difference between direct and final land-use impacts are changes in consumption and in agricultural intensification. All the models in Table 2 take into account consumption changes and almost all of them account for agricultural intensification. The differences in the impact of direct land use on final land-use change between models that include by-products, consumption change, land expansion and intensification will be caused by how the model responds to the last three processes. Table 2 shows the share of former consumption, expansion and intensification for the major bio-energy crops in some of the particular cases. Note that because of the way the calculations have been carried out here, the share of former consumption may be high where the use of by-products is without consequences, because the by-products could still be consumed where the product is also used for energy. The share of land expansion depends on the origin of the crops used and probably also on how land expansion and the consideration of expansion or intensification is implemented in the model. More than a quarter of oil crops in the BioEU scenario of the LEITAP/IMAGE model combination, for example, originate from Brazil. Since this is a land-abundant region, land expansion would be a better solution for the model to choose rather than intensification. Therefore, the price impact, and thus the impact on consumption is probably less than in the E27VL case of the AGLINK/COSIMO model, a fixed case in which all oil seeds originate in the EU. In this case, the share of former consumption is more than 50%.

3.2 Model results for indirect emissions

The discussion surrounding indirect land-use change was prompted by the finding that the emissions released by indirect land-use change could substantially decrease or even offset potential greenhouse gas savings from bio-energy. The land-use emissions resulting from different models and analyses may differ due to the regional allocation of final land

Final land-use impacts in different models and scenarios

Table 2

Model	Scenario	Final land-use impact (ha/TJ)			Share of feedstock used for biofuels from...			References	Scenario name
		Direct land use (ha/TJ)	By-products	Biofuels used	Land expansion	Former consumption	Intensification		
DART		25.2	0	LY	no	yes	yes	Kretschmer, Peterson and Ignaciuk, 2008	10Q
EPPA			11.9	HY	no	yes	no	Reilly and Paltsev, 2008	Level 1
GTAP	2001-2006		11.5	LY	yes	yes	yes	Hertel, Tyner and Birur, 2008	2001-2006
GTAP	2006-2015		20.7	LY	yes	yes	yes	Hertel, Tyner and Birur, 2008	2006-2015
GTAP ⁽ⁱ⁾			4.1	LY	yes	yes	yes	Ecofys, 2009	LCFS
LEITAP/ IMAGE	OECD bio-energy policies	35.7	30.1	LY	yes	yes	OS=91% CG=8%	pers com. LEI/own calculations	BioOECD
LEITAP/ IMAGE	EU bio-energy policy	35.5	34	LY	yes	yes	OS=0% CG=56%	pers com. LEI/own	BioEU
MIRAGE	EU bio-energy policy, trade liberalization	7.3	3.8	HY	yes	yes	OS=92% WT=15% SC=7%	pers com. LEI/own	MEU_FT
MIRAGE	EU bio-energy policy	9.9	3.1	HY	yes	yes	SB=1% SC=75%	Al-Riffai et al., 2010	MEU_BAU
AGLINK/ COSIMO	Sugar Cane from Brazil	6.8	3.3	HY	yes	yes	SB=4% SC=8% SC=30%	Al-Riffai et al., 2010	BRASCA
AGLINK/ COSIMO	Coarse Grains from USA	30.6	12.5	LY	yes	yes	CG=38%	pers com. Von Lampe,	USACG
AGLINK/ COSIMO	Oilseeds from EU	30.6	4.1	LY	yes	yes	CG=9%	pers com. Von Lampe,	EZ7VL
CAPRI		23.5	0.4	LY	yes	yes	OS=54%	pers com. Von Lampe,	
FASOM/ FAPR ⁽ⁱ⁾	USA bio-energy policy; Corn ethanol case		3.7	LY	yes	yes	yes	Burrell (eds), 2009	RFS-com ethanol
FASOM/ FAPR ⁽ⁱ⁾	USA bio-energy policy; Biodiesel case		10.1	LY	yes	yes	yes	EPA, 2010	RFS-soy-biodiesel
FASOM/ FAPR ⁽ⁱ⁾	USA bio-energy policy; Sugar cane ethanol case		4.2	HY	yes	yes	yes	EPA, 2010	RFS - sugar cane ethanol

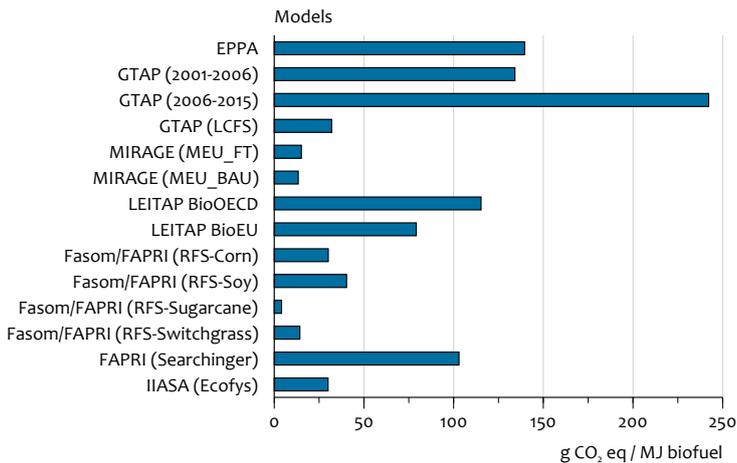
Model	Scenario	Direct land use (ha/TJ)	Final land-use impact (ha/TJ)	By-products	Biofuels used	Land expansion	Share of feedstock used for biofuels from...	References	Scenario name
FASOM/ FAPR ⁽¹⁾	USA bio-energy policy; Switch grass case		2.1	yes	HY	yes	Former consumption yes	EPA, 2010	RFS – switch grass ethanol
FAPR ⁽¹⁾		11	9.2	yes	LY	yes	80% 20% ²⁾	Searchinger et al., 2008; Ecofys, 2009	
GCAM		5		no		yes	no	Wise et al., 2009	
IIASA ³⁾			4.1	yes	LY	yes	39% 34% 27%	Fischer et al., 2009; Ecofys, 2009	

HY = particularly High energy Yielding crops have been used in this scenario (sugar cane and second-generation crops); LY = Particularly Low energy Yielding crops have been used in this scenario (food crops); WT = wheat, CG= coarse grains, OS= oil seeds, SC = sugar cane, SB= sugar beet

¹⁾ These studies and values were taken from the Ecofys study (Ecofys, 2009).

²⁾ Estimated by Searchinger for the Ecofys report (Ecofys, 2009).

³⁾ Only values for international bio-energy production excluding USA are shown (originating from the FAPRI model).



Land-use emission impacts of models that include land expansion

use (where land-use changes take place), the assumed carbon stock at these places and the time period over which it will be released.

Figure 2 shows the indirect emission impacts for all models that provide results on land-use emissions. To meet the emission reduction target, the total emissions of a bio-energy product should not exceed 84 g CO₂ eq/MJ. We have used an allocation period of 30 years for land-use emissions. The allocation period for the emission impacts of direct effects in the EU Renewable Energy Directive is currently 20 years. Applying this shorter period would increase the indirect emissions as shown in Figure 2 by 50%, and therefore make bio-energy even less attractive in terms of greenhouse gas savings.

Most models define land allocation in global regions, sometimes with an extra dimension for climatic zones (AEZ), as in the GTAP or MIRAGE models. Only the IMAGE model uses a higher resolution for land-use allocation (grid cells of 0.5 by 0.5 degrees). The two Integrated Assessment Models (IMAGE and GCAM, see Table 1) take into account carbon pools and fluxes, which results in emissions when land-use changes occur. In the other analysis, emission factors are applied for deforestation and land management.

Compared to the results of final land-use change, the models with large results in final land-use change also have high land-use emissions. There is one exception: the results from the LEITAP/IMAGE model combination are comparatively small, especially for the EU scenario. This is due to the fact that 30% of the land expansion needed to meet the European bio-energy directive (bioEU) takes place within the EU. It has been anticipated in the analysis that a lot of agricultural land that had previously been set aside in western Europe could easily be taken into production again. Therefore, the related emissions are fairly small.

4. Discussion and conclusions

Uncertainties in future yields

Assumptions regarding future developments in technology, especially yield increases and better conversion of crops to energy, are of great importance in defining the direct and related indirect land use for bio-energy. The higher the yield the less area is needed to produce one unit of energy. On average, yields for cereals and coarse grains have been growing by 2% per year globally (own calculations FAOSTAT). A 1% increase in yield of any crop towards 2020 would imply a 10% decrease in the direct effects measured in ha/TJ. However, since yield growth greatly depends on factors other than purely technical ones, such as the political stability in a region, this remains a highly uncertain aspect. Yield growth may be the result of increasing inputs (labour, capital and energy) or the development of high yielding varieties. It is very difficult to define the share of these components in past yield developments. This is one of the reasons why it is very uncertain what part of increasing yield in the future can be assigned to the extra demand for bio-energy, for example, or to policy favouring research and development.

The impact of climate change on yields is another uncertainty which could even be reinforced where the emission impacts of bio-energy production are greater than conventional energy sources. The land-use emissions caused by the conversion of unmanaged land to agricultural land will have an additional impact on climate change. Climate change in turn will have its impact on yields and therefore on land use. Models which take into account these processes are the integrated assessment models, such as the IMAGE and GCAM models (Leemans and Van den Born, 1994; Brenkert et al., 2003). However, up until 2020, the impact of climate change on yields is expected to be small and therefore this feedback has been disregarded in the rest of this analysis.

Uncertainties in trade

In the economic models compared here, current trade preferences and modelled production costs define the amount of bio-energy that will be imported into a region. The

CGE and PE models use parameters based on a calibration of past developments that define the share of imported products in a region or assume the commodities of all origins to be homogenous. These ratios can change but only to a limited extent. In reality, such ratios could change more quickly due to a sudden change in circumstances of a climatic, economic or political nature. It should be remembered that such changes can hardly be modelled with the CGE and PE models. Besides this, changes in international agreements on trade policies (WTO) will influence future trade opportunities, as shown by the MIRAGE scenarios. As we have seen, the final land-use change greatly depends on the crop used and on the location where it is produced (e.g. different AGLINK/COSIMO cases and LEITAP/IMAGE scenarios).

JRC study

To avoid the uncertainties in trade and crop mix, ILUC factors could be defined per crop and per region. A way to set up this analysis might be to analyse the impacts of an extra 'obligatory' production of a particular bio-energy crop in a particular region. Such a study is currently being coordinated by the EU's Joint Research Centre, the Institute for Environment and Sustainability, in which modelling groups have been asked to perform marginal experiments with an additional production of 1 Mtoe for each specific bio-energy crop. However, 1 Mtoe is not even 1% of the extra supply that would be needed to comply with a 10% bio-energy target for the transport sector. The extra land use and emissions are not necessarily linear with the amount of energy demand. Therefore, the set-up of such a study should provide for an extra production that is realistic in terms of its order of magnitude. Besides this, an integrative analysis is needed which implements all crop-region combinations that meet the future sustainability criteria, to avoid impacts that have been overlooked due to a partial analysis of crop-region combinations.

Conclusions

Models can be a helpful tool for deriving ILUC factors. However, the selection of models to be applied and the way to derive such ILUC factors must be carefully chosen. Furthermore, the method to derive ILUC factors needs to take into account how and in what context these factors will be used. Even if these considerations are taken into account, the ILUC factor of a certain crop will strongly depend on global developments outside its production chain.

Currently, the political debate aims at including (crop-specific) ILUC factors as an additional element in the existing sustainability criteria, that is, the criteria to ensure that bio-energy crops will lead to a reduction in greenhouse gas emissions. For this purpose models or model combinations that deliver information for such an ILUC factor need to have the following components:

- include land use in all world regions;
- include major by-products;
- include the economic considerations relevant to intensification, agricultural land expansion and consumption change.

These aspects have been included in the models GTAP, LEITAP, MIRAGE, AGLINK/COSIMO and FAPRI. However, even

where crop/region combinations are included in a model, the final land-use impacts, and thus the emission impacts, will depend on the behaviour of the model in relation to the third element: the share of intensification, agricultural land expansion and change in consumption in the total feedstock for bio-energy. This behaviour is governed by the way these elements are implemented in the model.

Besides, the model response depends on the assumptions applied in the reference or baseline. These assumptions are crucial to the final land-use and emission impacts. Where the demand for agricultural land is increasing in the reference, extra demand for bio-energy crops will put more pressure on expansion than if the demand is decreasing in the reference. We have discussed some of the uncertainties, such as yield developments and trade preferences. Although uncertainties around this second aspect could be avoided with an appropriate model set-up, there are many more uncertainties with other policy assumptions, particularly as some of them are set to change in the coming decade, for example, the Common Agricultural Policy of the EU, or bio-energy mandates in other regions. Besides policy assumptions, assumptions on the development of the oil price and global macro-economic developments will also be major drivers of results in the reference and thus of the emission impact of bio-energy.

So, while such a study as currently coordinated by JRC is very useful to provide a first estimate of indirect land-use change and emissions of bio-energy it does not remove the most important uncertainties in model analyses: the dynamic environment in which the bio-energy policy takes place. These uncertainties are governed by technological advances and yield increases, as well as by changes in global trade and bio-energy policies. Taking a short time horizon and repeating such an analysis every few years could help to reduce these uncertainties and keep abreast of changes in the global agricultural system. An extra integrative analysis besides the crop-region analyses should reveal impacts that have been overlooked in the partial analysis. Additionally, monitoring is needed to assess the actual indirect land-use change for bio-energy, and ultimately to correct the model-based ILUC factors.

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Colophon

Responsibility

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