Methodologies accounting for indirect Land Use Change (iLUC): assessment and future development

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ABSTRACT

Land demand is constantly increasing due to increasing population and consumption patterns. When new land is required land use changes are triggered, causing several environmental and social impacts. Particularly debated is the assessment of indirect Land Use Change effects. Several methodological approaches have been proposed for carrying out the assessment. In this paper we reviewed state-of-the-art iLUC models and classified them in two main categories: economic models and deterministic models. Five models have been selected and compared according to fifteen criteria covering modeling framework, impact categories assessed and models' transparency.

The results show that, within a Life Cycle Assessment approach, progresses have been made in Economic General Equilibrium and Deterministic Models and a combination of those can achieve a markedly robust assessment of iLUC. There are still wide margins for improving current models. In particular, there is room for improving precision of data, identification of marginal land and inclusion of a broader range of impact categories.

Keywords: Land Use, indirect Land Use Change, Life Cycle Assessment

1. Introduction

Land demand is increasing due to population growth, demanding food, feed and pasture land. Land use is also caused by demand of fibers, fuel wood and more recently industrial scale biofuels. The result is a constantly rising environmental and social impact. Land use has long been underestimated or ignored in environmental assessment techniques (Lindeijer 2000) but is increasingly being included in impact assessments. Land Use Change (LUC) impacts have recently been introduced in environmental (Banse et al. 2008) and economic analysis (Hertel, Rose, and Tol 2009B). The debate around LUC effects accelerated with the publication of two articles by Fargione et al. (2008) and Searchinger et al. (2008). Until then, the term LUC was mainly referring to direct Land Use Change effect (dLUC), such as greenhouse gas (GHG) emissions, caused by a change in land use, where the change is taking place. Fargione et al. (2008) and Searchinger et al. (2008), instead, investigated the relevance of indirect LUC (iLUC) effects: a change in land use caused indirectly as an upstream consequence of a direct LUC taking place somewhere else in the world. ILUC and dLUC were defined in standards only in 2012 (ISO/TS-14067 2013).

Different approaches and models have been proposed in recent years to solve those controversies but a broad consensus on them still needs to be reached. The controversies include the theoretical framework as well as ways to model the complex global land use dynamics; in particular, difficulties related to: understanding and modeling where land LUC takes place; establishing the relationship between demand of agricultural products and land use changes; accounting for the effect of by-products; the overall level of uncertainties caused by the multiple modeling assumptions (Marelli, Mulligan, and Edwards 2011). The first rather high GHG emissions esteems cause by iLUC rouse a high concern (Fargione et al. 2008, Searchinger et al. 2008); further researches contributed to a progressive downsizing of the estimated effects: in a recent work Dull et al. (2013) show that the estimated LUC GHG emissions from corn ethanol gradually decrease in newer studies. Refined and improved models predict a lower iLUC impact compared to earlier esteems; some authors conclude that iLUC emissions might even be irrelevant (Kim and Dale 2011); other studies still prove how the existence of iLUC effects have neither disappeared nor can be considered as negligible (USA-EPA 2010). Indeed, with the current ethanol and biodiesel production trend, increasing population and pro-capita consumption, it seems difficult to challenge the hypothesis that iLUC is taking place. Tyner et al. estimated that only in the USA a third of corn ethanol production is intended to ethanol (2010). In the meantime, the annual yield growth rates are stationary or decreasing while crop demand is increasing, leading to a constant increase in crop prices (Brandão 2012). Yet, the challenges in estimating the magnitude of LUC and related effects are numerous and models still future a relevant degree of uncertainties, mainly related to data availability and modeling constraints.

The goal of this paper is to underline recent improvement upon models and the aspects that still remain hotspots. Following an extensive review, five models have been chosen to assess their characteristics according to a set of fifteen criteria including: completeness of scope; impact assessment relevance; scientific robustness and certainty; transparency, reproducibility and applicability. For each criterion the models' performances were compared and scored relatively to each other. The data required for reviewing and scoring the models were obtained from scientific literature and models' reports. Since a complete product/process assessment is usually carried out within the framework of Life Cycle Assessment (LCA), this paper reviews iLUC models as part of a more comprehensive LCA framework, in which the modeling results are included, independently of the model used for their assessment.

2. Methods

The review criteria used to assess the performances of the five selected models are reported in Table 1. The criteria were built on the work of Hauschild et al. (2013) modifying the assessment categories and relative criteria to fit the purpose of the current review. The models criteria were grouped in four categories.

Table 1. List of criteria: the criteria are grouped in four categories. Each criterion is meant to answer a specific question reported on the right.

A - Completeness Of Scope	**How in detail does the model covers the environmental mechanisms associated with land use changes?**
i - Dataset	What is the underlying dataset of the study?
ii - Land Classification	Which types of land are classified by the model?
iii - Origin of Marginal Land	How the location of the identified marginal land type is identified?
iv - Co-product	How is the effect of co-product accounted for?
v - Distribution of Emissions	How is the time of GHG emissions associated to the activity?
B - Impact Assessment Relevance	**To what extent are the critical impacts of LUC included and modeled in accordance with the current state of the art?**
vi - Non GHG Emission	Which non-GHG emissions are considered?
vii - Other non-Environmental Impacts	Which non-Environmental Impacts are considered?
C - Scientific Robustness And Certainty	**Does it represent state of the art, can it be validated against monitoring data, and are uncertainties reported?**
viii - Peer-review	Is the model peer-reviewed/presented in peer-reviewed articles?
ix - Uncertainties	Are scenario and model uncertainty taken into account?
x - Updating	How can the model be updated/further developed?
xi - Science-Based	Are the data and assumptions consistent with a science-based approach?
D - Transparency, reproducibility and Applicability	**How accessible are the model, the model documentation and the applied input data? Are the models applicable to different contexts?**
xii - Documentation	Is the model documentation published and easily accessible?
xiii - Input Data	Are the input data publicly available?
xiv - Applicability	Can the model be applied to other contexts/products?
xv - Transparency	How transparent is the reviewed documentation?

According to their main characteristics, existing LUC models have been grouped in three types: Economic Equilibrium Models (EEM), Deterministic Models (DM) and Normative Models (NM); they differ in the extent they address iLUC modeling challenges and the approach used. EEM are divided in Partial Equilibrium models (PE) and Computable General equilibrium models (CGE). Normative Models are simplified approaches, based on rules, established 'norms', not necessary scientifically justified, but based on statistical metadata or normative assumptions. Due to their more simplified nature they have not been considered for comparison with other models. They are however discussed in section 3.

An accurate review following the criteria introduced above was completed for five among EEMs and DMs (Table 2): a modified version of the CGE model GTAP (GTAP 2014, Hertel, Rose, and Tol 2009B) named GTAP-AEZ, the PE model Common Agricultural Policy Regional Impact (CAPRI 2012), the EU Joint Research Center (JRC) hybrid model (Hiederer et al. 2010) and two DM (Bauen et al. 2010, Schmidt et al. 2013). These models were selected after a broad review of the existing literature to cover a wide range of different approaches.

Table 2. Models selected for comparison and description of models' typology

Model	Model type	Selected iLUC Models
Economic Equilibrium model (EEM)	Partial Equilibrium (PE) model	CAPRI
	Computable General Equilibrium (CGE) model	GTAP-AEZ
	Hybrid CGE-PE model	EU-JRC
Deterministic Model (DM)	Participative model	Bauen et al.
	Avoiding type allocation of emissions	Schmidt et al.

GTAP is a global network of researchers coordinated by Purdue University, developing models and databases used also in other CGE models (e.g. IMAGE, LEITAP); CAPRI model is an agricultural sector PE model developed by the European Union (EU) research fund for policy impact assessment in the EU. The EU JRC developed an harmonized spatial dataset integrates data obtained from the CGE model IFPRI-MIRAGE and the PE model AGLINK-COSIMO; the hybrid model expressly assesses GHG changes (including soil) caused by the production of biofuels; Bauen et al. (2010) is a regional DM commissioned by the UK department of transport to assess the GHG emission associated with iLUC caused by biofuel production; through a more transparent and participative approach, it attempts to overcome previous models' limitations by consulting a panel of experts and stakeholders in the development process. The model developed by Schmidt et al. (2013) is a flexible DM, applicable to any land or crop in any location in the world, overcoming a frequently used normative assumption used to distribute emission over time; a similar approach is also proposed by Kløverpris and Mueller (2013).

The performances of the five selected models were scored through a paired comparison analysis: for each criterion, the models were compared against each other and ranked by assigning a comparative value ranging from 1 to 5.

3. Results and discussion

According to the criteria introduced in Table 1, the models were assessed and compared. The results of the comparison are schematically presented in the Table 3.

The final score are expressed as an average and shows considerably homogeneous values, with the exception of the JRC and Bauen et al. models; this is due to the scope of those models, restricted to a regionalized analysis of the biofuel sector. EEMs are generally more robust with regard to the group of criteria 'A': the average score obtained by EEMs for the first four criteria is in fact 2.9 (3.1 excluding the hybrid JRC model), while the average score obtained by the DMs for the first four criteria is 2.5. EEMs show a lower average score when the JRC model is included because the JRC model does not account for the effect of co-products (criterion iv). The calculated average excluded criterion v (Distribution of emissions) from group 'A' because the value for this criterion are rather imbalanced between EEMs and DMs; this is simply due to the fact that EEMs provide an iLUC GHG emission factor but do not suggest a methodology to handle the distribution of the emissions. In the compared EEMs this aspect is left to the results' users. To some extent EEMs consider the issue outside the scope of iLUC modeling and as a general problem to be dealt with anytime emissions' impacts are accounted.

It can be observed that the robustness gained by EEM through the complex methodological framework (group of criteria 'A') tend to be lost in the group of criteria 'D', reflecting a loss of transparency and clarity and traceability of the model. The average score obtained by EEMs in group of criteria 'D' is in fact 2.9 (3.0 excluding the JRC model), while the average score obtained by the DMs is 4. The trend is especially visible in the traceability of the input data (criterion xiii) and overall transparency of the model (criterion xv). The smaller score obtained in criterion xiv (Applicability) by the JRC and Bauen et al. models reflect instead their regional scope and the focus restricted focus to biofuel production. Model uncertainties (criterion ix) are also more difficult to assess in complex EEMs than DMs. On the other hand, because of their complexity, EEMs and the respective databases are generally maintained by large scientific networks or institutions and are more likely to be updated and peer-reviewed.

Group of criterion 'B' shows a very interesting result: at present, the focus of iLUC models (including the compared models) is almost exclusively restricted to GHG emissions impact; among the compared models. CAPRI is the only case in which an attempt is made to assess other environmental impacts than GHG emission, namely, water quality impacts and impacts on biodiversity. There are however other consequences triggered by increasing land use, both environmental (Wicke et al. 2012), social and economic. In life cycle analysis of LUC they are often not included, or only partially (Gawel and Ludwig 2011). The inability to include a full range of impacts caused by iLUCs is a notable limitation of current iLUC models. A more thorough analysis might in fact leads to very different results, suggesting different development patterns than the one indicated by current analysis.

From a LCA perspective, it might be argued that iLUC models concerns data inventory modeling rather than impact assessment and that broadening the range of iLUC impacts is an impact assessment problem rather than an inventory one. Moreover, data collected for quantifying LUC GHG emission (land classes, marginal land, yields etc.) are in some cases the same underling data necessary for a broader impact assessment. If occupation of new land (forest land) and its location are identified for example, it might be relatively easy to assess the consequent loss of biodiversity. Nevertheless, impacts on biodiversity are always pointed out as the most serious when occupation of new land is concerned and comprehensive iLUC models are not consistent if their scope do not included its assessment; yet, to broaden the assessment to further environmental aspects as soil depletion, water use, and non-environmental as social and economic impact, the collection of further data is unavoidable and a the goal and scope of the model needs to be radically reformulated.

Table 3. Results of the paired comparison analysis applied to the five selected models.

A - Completeness Of Scope	**CAPRI**	**GTAP-AEZ**	**JRC**	**Bauen et al.**	**Schmidt et al.**
i - Dataset	3	4	4	2	2
ii - Land Classification	3	5	3	2	5
iii - Origin of Marginal Land	2	2	3	2	4
iv - Co-product	3	3	0	3	0
v - Distribution of Emissions	1	1	1	3	5
B - Impact Assessment Relevance					
vi - Non GHG Emission	2	0	0	0	0
vii - Other non-Environmental Impacts	1	0	0	0	0
C - Scientific Robustness And Certainty					
viii - Peer-review	5	5	3	3	0
ix - Uncertainties	1	3	0	2	4
x - Updating	5	5	3	0	3
xi - Science-Based	4	4	4	4	5
D - Transparency, reproducibility and applicability					
xii - Documentation	5	3	5	4	4
xiii - Input Data	2	1	2	4	5
xiv - Applicability	3	5	2	1	5
xv - Transparency	3	2	2	4	5
Average score	**2.7**	**2.9**	**2.1**	**2.1**	**3.1**

Regarding group of critera ‘C’, EEMs obtain and average score of 3.5 while the average score of DMs is 2.6. Generally, the assumptions behind the models are motivated through science-based argumentations (criterion xi) with the exception of the allocation of GHG emissions flows associated with LUCs over an arbitrary period of time followed by Bauen et al (criterion v). Distributing GHG emission over time is a widely used normative approach but, as such, non-scientifically justifiable. Acknowledging this limitation, Bauen et al. DM calculates the iLUC GHG emission factor considering different allocation time (30 and 100 years). Schmidt et al. DM instead proposes a science based alternative approach, avoiding a normative assumption (criteria v and xi), further discussed in section 3.2. CAPRI and GTAP models have been peer reviewed in scientific journals articles available on the model webpage. The DM by Schmidt et al. is currently under review. Peer-reviewed version of JRC and Bauen et al. models have not been found but their development involved multiple stakeholders and panels of experts. With the exception of Bauen et al. the models are periodically updated but the JRC model does not directly assess uncertainties; yet, the PE and CGE models upon which is based have been both peer-reviewed and show models’ sensitivity to main assumptions.

A further discussion is presented in the following subsections.

3.1. Economic models

EEMs are distinguished between PE and CGE models: PE models represent only a specific subset of economic sectors for a country or region, with no link to other economic sectors, giving an incomplete but rather detailed picture of it. On the contrary, CGE models account for the entire economic flow among different production sector within an economic system (national or global). However, completeness entails an increasing complexity and a loss of details in the model; the representation of land uses, land use alternatives and emissions cannot be sufficiently detailed for modeling land use change. For this reason CGE models are usually expressly modified to suit the model of iLUC. Complexity also adds to CGE models uncertainties difficult to estimate (Dunn et al. 2013).

3.1.1. CAPRI model

Economic models have usually a national level of data aggregation; in some cases efforts have been made to further regionalize models: CAPRI (Common Agricultural Policy Regional Impact) divides the EU territory in about ca. 250 NUTS2 sub-regions (CAPRI 2012). Data are mainly drawn by FAOSTAT, OECD and the Farm Accounting Data Network (FADN). Land use change data are drawn from EUROSTAT land use and land cover data but no particular plausibility check is carried on this datasets. Land uses are classified according to the LUCAS survey, which means 36 crop land classes and 2 of permanent grass rearranged according to the crops present in CAPRI. Since CAPRI has been built to model agricultural activities, forest land, water and urban areas are all aggregated in category 'Other' (criterion ii). Obviously the difference between an urban area and a forest land is rather big. This is of course a limit when modeling LUC. Other than GHG emissions indicator, CAPRI features indicator accounting for ammonia emissions, NPK leaching, water balances, and nitrate concentration in water and chemical emissions. The model also accounts for by-products of land-requiring product by means of physical replacement ratios. Alternatively, other CGE models accounts for by-products by substitution based on relative prices, as the GTAP model, which includes corn ethanol DDGS as a co-product.

3.1.2. GTAP-AEZ model

The Global Trade Analysis Project (GTAP) develops databases and CGE models which have recently seen improvements (GTAP version 8 database has been released in 2012) aiming at assessing LUC impacts. For this purpose it has further been regionalized, linking it to agro-ecological zones (AEZ) model (Fischer et al. 2012): since land types differs, land substitutability is possible only among zones showing similar characteristics (Hertel et al. 2009A). GTAP-AEZ is a special version of the model suited for estimating land use changes. The biofuel sector is here better represented through disaggregation of corn and sugarcane ethanol, and biodiesel, the three major biofuels. Environmental issues, such as climate change, resource use and technological progress in agriculture, are better pictured by dynamic models; GTAP-Dyn, a dynamic version of GTAP (Ianchovichina and Walmsley 2012) aims at projecting future land use change patterns linked at growth rate in each world's regions to identify the marginal land. Forest dynamics are accounted integrating the Global Timber Model (Sohngen and Mendelsohn 2006) while land heterogeneity is limited by the use of AEZ and land mobility across uses by the Constant Elasticity of Substitution (CET) function, estimating land supply elasticity. The CET function simulates the competition for land in economic models through the parameter 'σ', elasticity of land transformation. GTAP database is built upon the integration of several datasets on crop harvested area, production and yields (FAO 2006, Monfreda, Ramankutty, and Foley 2008). However, accounting at global scale for interaction among different economic sectors and regions poses some problems and for this reasons GTAP database aggregates in eight sector all crop productions.

3.1.3. EU JRC model

The hybrid model based on a CGE, PE and geographical information was developed by the Joint Research Center (JRC) of the EU (Hiederer et al. 2010). To calculate the GHG emissions from LUC the model use the cropland demand data acquired by CGE model IFPRI-MIRAGE and the PE model AGLINK-COSIMO. Moreover, the model spatially allocates agricultural land demand: combining different datasets to estimate existing cropped areas, land availability and land suitability they predict the geographically location where the land use change may occur (the location of the marginal land) and create a land suitability map. The model provides precise results with regards to GHG emissions by iLUC since it also includes soil properties information (such as carbon content) drawn from the Harmonized World Soil Database. However, the land demand spatial allocation module also increases the overall complexity, assumptions and consequently, the model uncertainties; at present, uncertainty analyses of the JRC model have not been undertaken (Hiederer et al. 2010). Due to the considerable number of assumptions (economic trends, market variables) and the complexity of model's framework (CET function, prices elasticity etc.), EEM results are rather complex: the extent to which they depend on the assumptions are not intuitively understandable (Nassar et al. 2011). The use of prices and price elasticity to determine yield change and cropped area variations in EEM does not reflect the role that other factors, such as technological and infrastructure constraints, yearly harvest capacity, trade agreement and other factors may play in determining those changes; even when these factors affect prices, price response is not visible in the short term. Yet, the complexity of the EEMs does not broaden the spectrum of the analysis and aspects as land degradation and biodiversity are generally not included in these models.

3.2. Deterministic Models

Alternative approaches to EEMs are causal-descriptive or Deterministic Models. DMs provide a simpler and more transparent framework than EEM where those data can be applied. They describe the future states of a system based on cause-effect relationships observed through statistical and historical data. They tend to have a more simple approach than EEMs (Nassar et al. 2011). That reduces the computational effort, data requirement and makes them conceptually easier to understand. Nevertheless, DMs do not necessary exclude economic aspects driving the supply/demand patterns: in some cases DM also includes market information such as cross-price elasticity of products, making them hybrid models, able to draw from different approaches. According to current market trends and assumptions on agriculture supply/demand trajectories, they forecast future production and consumption patterns. From this scenario, future land uses and origin are estimated.

3.2.1. Bauen et al. model

On behalf of the UK's Department of Transport Bauen et al. (2010) developed a DM to assess iLUC from five biofuels, taking into account future yield and area changes' trends, products substitutability and the effect of co-products; data were extrapolated from databases through statistical analysis of historical trends. A peculiar characteristic of this study is that future predictions were estimated consulting a panel of expert and stakeholders, to integrate their views in the assessment and guarantee a more democratic approach compared to the economic models' approach. Cederberg et al. (2011) used a deterministic approach to assess the impact of beef production in Brazil. This regional focus and product-oriented model make it unfit for application to different contexts, a limit generally observed in many DMs. As Bauen et al. (2010), also Cederberg et al. only account for iLUC GHG emissions effects. Within the LCA framework DMs are also distinguished between models using averages of historical data and future oriented models; the latters may also use historical data but to predict future trends, which can also diverge from historical patterns. This difference is also reflected in the LCA approach chosen, Attributional (A)LCA or Consequential (C)LCA (Sanchez et al. 2012). The dispute between ALCA-CLCA is beyond the scope of this paper; however, thorough discussions upon details of the two approaches are present in the scientific literature (Weidema 2003, Schmidt 2008, Thomassen et al. 2008, Finnveden et al. 2009, Rehl, Lansche, and Müller 2012).

3.2.2. Schmidt et al. model

A limit of iLUC models, regardless of the approach used, is the time allocation of the emission over an arbitrary period of time, generally 20 years (Fritsche, Hennenberg, and Hünecke 2010, IFPRI 2010) or 30 years (Bauen et al. 2010). Since this choice has no scientific bases, Schmidt et al. proposed an alternative DM approach, avoiding time allocation of emission, similar to the approach proposed also by Kløverpris and Mueller (2013). Kløverpris and Mueller model (2013) is applicable to any phenomenon causing LUC, based on current trends and future predictions of land uses. The starting point is the principle that land uses baseline is dynamic rather than static therefore in a region with expanding agricultural area, further occupation of land is seen as "accelerated expansion" and in a region with decreasing agricultural area as a "delayed reversion" (Kloverpris and Mueller 2013). As Kloverpris and Mueller (2013), Schmidt et al. (2013) avoid time allocation of emission considering an increasing land demand as a dynamic baseline; the result is only a time shift in the emission profile and consequently in the measured Global Warming Potential (GWP) effect. Doing so, the GWP is caused from the accelerated expansion of land and the resulting effect is accounted only in the specific year the activity 'land occupation' is taking place; therefore, the emissions do not need to be allocated over an arbitrary period of time. In accordance with a LCA framework Schmidt et al. see "Land" as an input to a process creating an output (the product), as in LCA is treated any other process's input. Schmidt et al. (2013) model is a more comprehensive model than Kløverpris and Mueller (2013). Based on global statistics (FAOSTAT, FAO) and IPPC guidelines, the model is applicable to all crops and regions in the world. Despite being a DM, it does not refrain from drawing upon different toolboxes: economic tools, such as cross-price elasticity tables, are used to identify product substitute and calculate the related environmental consequences (e.g. GHG emissions impact measured by GWP). The authors draw from bio-physical relations and statistical data to identify the marginal land and the share of land intensification. The model assumes that changes in land uses are a consequence of change in land demand; land is treated as any other LCA input and land productivity (the reference flow) is measures in Net Primary Productivity (NPP) (Haberl et al. 2007). The result is DM tending towards a hybrid approach. The limit of this approach is that its validity is limited by the hypothesis that land demand is constantly increasing worldwide: despite at present this is globally a valid hypothesis, it will inevitability fall at some point due to the fact that land is a constrained resource and, if not contained earlier, land demand will be in the end constrained by land availability.

3.3. Normative Models

The last type of modeling approach is the most simplified Normative Model explained above. Flynn et al. (2012) for example proposed a NM based on IPCC national GHG inventory methodologies to assess LUC impacts from crops. The model is intended to be applied in context where complex process-based spatial models to feed agro-economic models are not available, such as in developing countries, and when information on crop origin and growing conditions is limited. The model allows to convert per ha emissions from LUC to a per-ton of product basis (Flynn et al. 2012) but the analysis is restricted to the top 20 producing countries of the assessed product, and a single yield value is assumed for each county. Generally, NMs are intrinsically based on normative assumptions, regardless of whether those being scientifically justifiable or not. NMs are hence suitable for simple applications, such as for illustrative or didactical purposes but are not suitable to support policy making or decision making processes, where more accurate, scientific-sound analysis are required.

A normative approach is also adopted in calculating the iLUC factor by Fritsche et al.(2010), obtained dividing the share of land for biofuel production in 25% as coming from intensification of "set free" land, with a zero displacement risk, and 75% from "new land" representing the actual iLUC factor. This simplified solution to quantify the GHG emissions associated to iLUC is paid by a least reliable result since the factor is calculated ignoring the complexity of cause-effect relationships triggered by LUC. Normative assumptions can be found also in non-normative models: the distribution of GHG emissions over an arbitrary period of time of 20 or 30 years described above can be found for example both in analysis using DM and EEM. Searchinger et al. (2008) for example, used for their model the FAPRI-CARD PE model but assumed bioenergy as the only source of iLUC, since ethanol is a relatively new product demanding a large amount of land, therefore responsible for increasing the global land demand compared to usual trends. This normative assumption is not completely true as land demand is caused by any conventional agricultural activity (Nassar et al. 2011) as well as increasing demand of conventional agriculture products, urban sprawl, forest fires, logging etc.

4. Conclusion

There are very diverse solutions to model iLUC in literature. Considerable progress has been made to adapt EEMs and DMs to capture the complex dynamic of land use changes. Transparency is usually inversely proportional to complexity but complexity of models is to some extent necessary to compensate for the lack of primary data. New studies aiming at collecting global land use and yield data will in the future help reducing complexity. Currently few hybrid economic models, linked to bio-physical and geographical models, can provide scientific sound and accurate picture of iLUC. They are however complex, and computationally intensive and are therefore recommended for large scale applications, such as policy making. For small scale applications, such as LCA of product or processes for companies or small institutions, DMs provide a more useful picture of the cause-effect relationships and product chain. Time allocation of emissions can however be avoided also by EEM using the approach proposed bt Schmidt et al. (2013). A substantial limitation of current model is the inability to include the full range of impacts caused by iLUC since the focus is generally restricted to GHG emissions impact. More comprehensive analysis might show very different results and suggest completely different development patterns. It is therefore in this direction that future research should be addressed.

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