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Summary

Motivated by the conclusions from various modelling studies, modifications to the bioenergy sector regulations are under way in Europe and in the USA to account for emissions from indirect land-use change (ILUC). Despite their influence on the policy-making, evaluations of the capacity of numerical models to estimate ILUC are sparse. To address this void, this paper reviews recent developments in land-use modelling, with a particular focus on the solutions adopted to estimate ILUC due to biofuel production. As indirect effects of bioenergy result from the interplay of various mechanisms, their modelling is a major challenge for land-use science. In recent years, numerical models have been significantly upgraded to provide a more comprehensive vision of the agricultural system. This has been performed by improving the representation of land supply and the biofuel production process in general equilibrium models (e.g., GTAP, MIRAGE, DART). At the same time, modelling systems coupling partial equilibrium models with CGE (e.g., KLUM@GTAP) or economic modules with spatially explicit models (e.g., MAgPIE, GLOBIOM, LEITAP), and modelling architecture combining land-use and life-cycle assessment models (e.g., FASOM/FAPRI/GREET) have been developed. In spite of these advances, some limitations remain and uncertainties are still numerous.

Keywords: Indirect, Land-Use Change, Modelling, Biofuel

JEL Classification: O13, Q15, Q16, Q17, Q18, D58

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1 Introduction

Attracted by the potential benefits of biofuels to (i) mitigate greenhouse gases (GHG) emissions, (ii) support the agricultural sector and (iii) secure the energy supply, the large scale exploitation of biomass for energy has been implemented despite uncertainties regarding its effective environmental impact. Thus far, the principal uncertainty concerned the emission of nitrous oxide that results from fertiliser use [Crutzen et al., 2008]. Studies conducted by Searchinger et al. [2008], and Fargione et al. [2008] introduced an additional potential factor environmental impact of biofuels. Assuming that food demand is price inelastic, any increase in the production of biomass fuel generates a rise in crop prices and creates an incentive to extend cultivated areas. The indirect land-use change (ILUC) concept refers to the displacement of crops (food and non-food) or pastures on uncultivated land, such as fallow or forest land, resulting from the use of feedstock for biofuel production.

Using the worldwide agricultural model FAPRI [Devadoss et al., 1989], Searchinger et al. [2008] provide estimates of ILUC that raise concerns regarding large-scale biofuel production. This initial analysis has prompted an intense debate among sustainable development experts. In particular, some errors and/or gaps that could potentially invalidate the analysis were noted by Wang and Haq [2008]. To settle the debate, the European Commission and the U.S. Environmental Protection Agency (EPA) conducted several studies based on numerical models. On the whole they confirm Searchinger et al. findings. However their results are associated with large confidence intervals [U.S. Environmental Protection Agency, 2009, Edwards et al., 2010].

Following these conclusions, modifications to bioenergy sector regulations are under way in Europe and in the USA to account for emissions from ILUC. Despite the potentially serious implications of such modifications for the future of the biofuel industry, evaluations of the capacity of numerical models to estimate ILUC are sparse. To address this void, this paper reviews recent developments in land-use modelling, with a particular focus on the solutions adopted to estimate ILUC due to biofuel production.

The first section outlines the ILUC modelling specifications. The second section describes the main characteristics and limitations of traditional approaches for land-use modelling. Against this background, the third section reviews recent advances in numerical models of land-use. The fourth section presents their remaining limitations, and the last section concludes the paper.

2 Modelling ILUC

Estimation of ILUC is a difficult task because such changes are not directly observable. Furthermore, ILUC theoretical functioning is complex, as they result from the interplay of various factors, e.g. prices or the type of feedstosck used. Schematically, GHG emissions from ILUC can be computed by multiplying (i) the area of cropland or pastures at the global scale that is displaced on uncultivated land due to increased biofuel production by (ii) a GHG factor estimated for each hectare of land converted. However, this apparently simple calculation is challenging, as it involves four main disciplinary fields: economics, agronomy, engineering and climatology.

The size of land conversion results from the interrelation between economic behaviours and agronomic parameters. The former component determines the effect of farming an additional hectare of feedstock for biofuels on agricultural prices, and consequently, on the cultivation of new lands. As suggested by Searchinger et al. [2008], the price-impact of biofuel is all the greater than the demand for food is inelastic. Its extent is also governed by agronomic mechanisms, such as crop yield response to the incremental production of biofuels and the substitution of biofuel by-products for feedgrains. These two mechanisms mainly depend on the type of plants used to produce bioenergy. For example, some plants exhibit higher yield (e.g. sugar cane, sugar beet) while others provide more by-products (e.g. soybean, wheat). For this reason, it is necessary to account for these different plant types and for their specificities. Attention must also be given to the biofuel production process – from grain (first generation) or from lignocellulosic materials (second generation) – that naturally crucially impacts these mechanisms. Because ILUC relates to biomass production leakage between the different regions of the world, a global representation of processes encompassing a detailed description of international trade is necessary.

The GHG factor depends on two main drivers:

- The nitrogen fertiliser used in the production process causes emissions of nitrogen oxide (NO and NO_2), a greenhouse gas with a high warming potential;
- The type of land converted plays a prominent role in the extent of the carbon debt. Tropical rainforests or peatland rainforests store high levels of carbon, while the conversion of marginal croplands releases lower levels of carbon into the atmosphere [Fargione et al., 2008].

These two elements vary greatly across the different regions of the world. Each region may differ in its land cover, storing more or less carbon, as well as its climate and technological itineraries, requiring more or less nitrogen fertiliser and irrigation. For this reason, international flows of agricultural goods must be tracked as precisely as possible and geographical specificities must be accounted for.

Beyond the representation of these various mechanisms, another difficulty relates to the tensions already present in the agricultural system, which may influence the effect of an increase of biofuel production. These tensions essentially relate to arable land availability, tensions on water, and energy and fertiliser prices. Agricultural policies and global changes in food demand and diet composition, because they determine pressure on land, must also be part of the analysis. Also, because agricultural markets are not independent from the larger economy, particularly concerning energy prices, or labour and capital availability, a link to a general equilibrium representation provides a higher degree of relevance. Finally, in order to provide a relevant accounting of GHG emissions, energy and physical fluxes have to be correctly accounted for, as it is performed in life-cycle assessments (LCA).

3 Limitations of traditional land-use models

Land-use change was traditionally represented by two types of tools: economic models, mostly inspired by the Ricardian theory, and geographic models linking land cover changes to a definite number of explicative variables related to location and characteristics of land. In these approaches, each type of model was designed within the framework of particular disciplines, and economic and geographic features were quite separately represented.

3.1 Geographic models

Among large-scale geographic models, which are best suited to address the ILUC issue, Heistermann et al. [2006] distinguishes between empirical-statistical models and rule-based models. The former category estimates the most important biogeophysical and socio-economic drivers of land-use through multiple regression methods. The CLUE model framework [Veldkamp and Fresco, 1996] is an example of a model using this method. It is composed of several modules that estimate the total area needed for different land-use types and the production of each country on the basis of GDP, population size (which is estimated using a specific module), consumption pattern and international prices. Subsequently, the area of each land-use type in a given grid cell is the result of scale-specific regression equations, where the biophysical and socio-economic conditions and the conditions at higher grid scales are the explanatory variables.

Rule-based models rely on causal chains, elaborated based on theory or expert knowledge, and linking land-use change to economic, geographic and biophysical variables. The land-use module of the Integrated Model to Assess the Global Environment (IMAGE) [A.F. Bouwman and Goldewijk, 2006] exploits this method. Following a rule accounting for crop productivity, proximity to existing agricultural land, distance to road and water, land-use types are allocated within a grid, at a 0.5 by 0.5 degree resolution, in each region of the world until the total demands, resulting from economic and demographic variables, are satisfied.

Overall, this type of model allows for an accurate analysis of the spatial structure of land uses, by describing the neighbourhood effect or hierarchal organisation of land and by providing results at a high resolution level. However, land-use allocation is generally based on the assumption that observed spatial relations between land-use types and potential explanatory factors, representing currently active processes, remain valid in the future [Heistermann et al., 2006]. Economic behaviours, implying potential modifications of allocation rules, rarely received particular attention. From this perspective, using spatially explicit models to explore future driving forces of agricultural transitions is of limited interest.

3.2 Economic models

Economic model have been used because they take into account optimisation behaviours of agents in allocating land-use. Such models can be either in partial equilibrium, considering only a subset of markets, where the remaining markets are parameterised or in general equilibrium, where all markets are explicitly modelled and are assumed to be in equilibrium in every time step.

Partial equilibrium models (PEM) can provide an explicit description of the agricultural sector while accounting for adjustments of land-use allocation in reaction to price signals. To do so, they generally calculate endogenous prices resulting either from supply demand equilibrium – see, e.g. FASOM [Adams et al., 1996], AGLINK [Adenauer, 2008], AGLU [Sands and Leimbach, 2003] or IMPACT [Ryan, 2003] - or from the effect of policy instruments, as in the ESIM model [Banse et al., 2007]. Then, they determine the reaction of agents to prices in two ways: by maximising consumer and producer surpluses (FASOM, AGLU) or by solving a system of behavioural equations, relying on elasticity parameters and response functions linking crop yields, cultivated areas and food demand to prices (ESIM, AGLINK, and IMPACT).

This detailed representation allows for a great flexibility in modelling the impact on agriculture of structural variations, but it lacks coherence with respect to the rest of the economy. The computable general equilibrium model (CGE) can include additional details at the macroeconomic level by connecting agricultural markets to the rest of the economy. This provides a more relevant representation of intensification possibilities in the agricultural sector by computing labour and capital scarcity costs, as well as employment opportunities in other sectors. Macroeconomic closure is also of great interest to describe features that are closely related to energy markets, such as biofuel production or exploitation costs (fermentation, machines...). Golub et al. [2010] stress the importance of general equilibrium insights to represent the by-products channel.

However, the integration of biofuels in CGE presents two major difficulties. First, in the classic CGE representation, land is modelled as homogeneous and perfectly mobile production factor. Hence, any increase in demand for land for one specific use (e.g., crop or forestry) is met as long as land remains, but without consideration of their adequacy for the intended use. This assumption tends to overestimate the potential for heterogeneous land to move across uses, or, in an equivalent formulation, the land supply elasticity. Second, unlike macro econometric models, CGEs are not estimated, but calibrated using a social accounting matrix (SAM). A SAM is a balanced matrix that summarises all economic transactions taking place between different actors of the economy in a given period (typically one year). It is assumed that a SAM of a certain year represents an equilibrium of the economy and that the model is calibrated in such a way that the SAM is a result of the optimising behaviour of firms and consumers in the model. These SAMs are generally provided by the Global Trade Analysis Project (GTAP), but with regards to biofuels, the data are not as precise as for the other sectors for two reasons. First, they are not represented explicitly in the SAMs, but aggregated with other sectors (e.g., fossil fuels) ; second, bioenergy production was until recently not widespread, and was primarily driven by a variety of governmental supports that are not well represented in the SAMs [Kretschmer and Peterson, 2010]. For these reasons, these matrices do not give the appropriate information from which realistic biofuel trends could be projected, and as such, they cannot be used for the study of ILUC.

4 Solutions to meet ILUC modelling challenges: toward integrated land-use models

4.1 Representing biofuel in CGE

To solve the problem of misrepresentation of biofuels, the MIT Emissions Prediction and Policy Analysis (EPPA), a recursive-dynamic multi-regional CGE model, uses an innovative methodology for incorporating biomass production Reilly and Paltsev [2008], Melillo et al. [2009]. Based on the GTAP dataset, EPPA uses additional data for greenhouse gas and air pollutant emissions based on EPA inventory and projects. The GTAP data are further disaggregated to include latent technology, i.e., energy supply technologies that exist but are not active in the base year of the model, generally because they are not yet fully profitable (e.g., 2nd generation biofuel). Two technologies that use biomass are introduced: electricity production from biomass and liquid fuel production from biomass. They are described by their cost structure (composed of capital, labour, land and intermediate inputs from other industries), and their competitiveness level with existing technologies -

endogenously computed by the model - determines their market share.

Biofuels are represented in the DART model [Kretschmer et al., 2008] using a comparable methodology. This model is a recursive dynamic CGE model, solving a sequence of static one-period equilibria for future time periods connected through capital accumulation and relying on GTAP 6. In this database, the refined oil products category has been disaggregated into motor gasoline and motor diesel to better account for the substitution possibilities between these two products and biofuels [Kretschmer and Peterson, 2010]. Corn production has also been separated from the "cereal grains neglected" category because corn is an important feedstock for the production of bioethanol. Bioenergy technologies are modelled as latent technology. As it is performed in Reilly and Paltsev [2008], technologies are described through their cost structure, including feedstock, electricity, and a value-added composite of capital and labour. Mark-ups are also added to account for the difference between production and prices. This methodology allows for a fairly realistic representation of the biofuel sector but can be problematic as the technologies being only latent, there are few exchanges at the calibration year. For this reason, the projection of future trends can only be performed using strong assumptions. For example, Kretschmer et al. [2008] assumed that bioethanol trade takes place only between Brazil and the industrialised countries and small initial shares of biodiesel exports are included in Malaysia and Indonesia, where they believe that export potentials exist.

Following an alternative solution, improvement of biofuels representation has been brought to standard CGE model GTAP [Powell et al., 1997]. In this version designed for the analysis of energy markets and environmental policies, called GTAP-E [Burniaux and Truong, 2002], the nested production structure has been modified to include a capital-energy composite factor amongst the other traditional production factors of labor, land and natural resources. This factor is further disaggregated to represent all substitution possibilities (modelled by elasticity parameters) between biomass ethanol and petroleum products.

This implicit representation of biofuels, through the production factor, without an explicit economic sector, has rapidly been refined. In subsequent modelling experiments, the SAM has been directly disaggregated to add new bioenergy sectors. Using International Energy Agency sources, the GTAP-BIO model [Taheripour et al., 2007] introduces three new commodities (ethanol from food grains, ethanol from sugarcane and biodiesel from oilseeds) into the GTAP database.

The Mirage model [Decreux and Valin, 2007], developed at CEPII for trade policy analysis, was also modified to explicitly address biofuels issues and their consequences on land-use change [Bouet et al., 2009]. Like the EPPA model, MIRAGE is a general equilibrium model relying on the GTAP database. From this database, six new sectors were added: the liquid biofuel sectors (ethanol and biodiesel), the major feedstocks sector (maize, oilseeds used for biodiesel), the fertiliser sector, and the transport fuels sector.

CGE have also been refined to account for the use of by-products. In Taheripour et al. [2008], the GTAP-E model is modified to incorporate the possibility of producing multiple products. Hence, the grain ethanol and biodiesel industries can produce both main- and by-products (dried distillers grains with solubles for ethanol and soy and rapeseed meals for biodiesel), the latter goods being substitutes for feed grains in the livestock industry. Trade-offs between main- and by-products are represented in the supply and demand side, respectively, using constant elasticity of transformation and constant elasticity of substitution. By comparing model outputs with and without by-products, Taheripour et al. show that their incorporation into GTAP-E significantly reduces the impact of biofuel production on agricultural production and prices. The MIRAGE model was also modified to account for by-products from ethanol and biodiesel production but, in contrast to GTAP-E, they are represented as a fixed proportion of production.

4.2 Improving land supply representation in CGE

As mentioned in section 3.2, considering an homogenous and perfectible mobile land factor prevents accurate representation of land supply. To overcome this issue, CGE models have extensively used agro-ecological zoning (AEZ). This method consists of disaggregating a parcel of land into smaller units according to its agro-ecological characteristics, such as moisture and temperature regimes and soil type [Batjes et al., 1997]. The use of AEZ data by CGE has been facilitated by its integration in the GTAP database. The database now includes 18 AEZs, covering six different lengths of growing period spread over three different climatic zones (tropical, temperate and boreal). Land-use activities include crop production, livestock raising, and forestry. This extension of the standard GTAP database permits a better evaluation of the potential for shifting land-use amongst different activities [Lee et al., 2005].

Golub et al. [2008] describe the integration of this extended database in the recursive-dynamic framework of the GTAP model and its advantage for representing land supply mechanisms. The land rent is firstly disaggregated in each region across 6 of the 18 AEZs and for 3 agricultural activities (crops, ruminants and forestry). Then, the elasticity of land supply for each activity is computed based on these land rent shares. Finally, the mobility of land across uses within an AEZ is constrained via a constant elasticity of transformation frontier.

Other CGE models, such as MIRAGE, also use the GTAP-AEZ database. In its modified version, land-use change arises from two effects: substitution, which involves the modification of crops distribution on existing arable land, and extension, which involves the conversion of non-arable lands (forests, savannah) into arable lands. The substitution effect results from the optimisation behaviour of producers, computed for each AEZ, while the extension effect is determined from an exogenous land evolution trend based on historical data, cropland prices and the elasticity of cropland extension.

The LEITAP model uses an alternative method to improve the representation of land supply [Eickhout et al., 2008, Verburg et al., 2009]. This general equilibrium model is an extended version of GTAP that includes an enhanced representation of the land and agricultural markets. For example, some key features of the Common Agricultural Policy are introduced (e.g., agricultural quota). More fundamentally, LEITAP incorporates land supply curves computed by the Terrestrial Vegetation Model (TVM) of IMAGE on a 0.5 degree resolution. These curves are a function of land rental cost and are parameterised by price elasticity of land supply calibrated on data from the IMAGE model. Land supply functions are such that if land is abundant (resp. scarce), any increase in demand for agricultural land will lead to rather large (resp. small) land conversion to agricultural use and to modest (resp. large) increases in land rents.

4.3 Coupling models

A convenient way to overcome the problem of misrepresentation of agricultural sector specificities is to directly integrate the advantages of the various approaches (i.e., the precision of small scale models and coherence of large scale ones) into the same modelling framework. This is usually done by coupling general or partial equilibrium models with spatially explicit models that include insights on biophysical processes. In such an architecture, the dedicated model computes patterns of agricultural production and land allocation. These results are included in the economic model as exogenous parameters, and are used to update the calibration data. In turn, the economic model provides the land-use model with information on new production conditions.

The goal here is to break with the segmentation that exits amongst the economic, geographic and biophysical analytic frameworks characterising traditional land-use models and to build numerical models with a strong multidisciplinary orientation. In contrast to pure CGE, which do not link economic values to physical quantities, the advantages of such an approach is to establish a consistent relation between both types of variables and to guarantee that projections will be realistic from both points of view. In addition, coupled systems allow for a relevant representation of multi-scale effects, as processes are represented at both high and small resolution.

The Model of Agricultural Production and its Impact on Environment (MAgPIE) is a distinctive example of such a multidisciplinary approach [Lotze-Campen et al., 2008]. This mathematical programming model describes economic behaviour by minimising the total cost of production for a given amount of regional food energy demand, and has been designed to be coupled with the Lund–Potsdam–Jena dynamic global vegetation model (LPJmL) [Bondeau et al., 2007]. In contrast with CGE using an AEZ representation, which remains a coarse description of the biophysical system, this integrated tool entails a full description of the dynamic processes linking climate and soil conditions, water availability, and plant growth at a detailed geographic scale worldwide. In addition, MAgPIE is able to endogenously represent yield and water use evolution.

A comparable multidisciplinary methodology has been undertaken by the IIASA Global Model cluster [Havlík et al., 2011]. This numerical tool uses the bottom-up partial equilibrium GLOBIOM, which relies on the recursive dynamic structure of FASOM (see section 3.2 for more detail), to determine production and consumption levels, trade flows, and prices. These values are then conveyed to the Global Forestry Model (G4M), which compares the net present values of forestry and agriculture to determine land-use change decisions. Crop yields and soil organic carbon stock are extracted from the Environmental Policy Integrated Climate (EPIC) model according to 4 management systems (high input, low input, irrigated, and, subsistence). The results are finally downscaled to homogenous response units (HRU), i.e., spatial units where altitude, slope and soil are assumed to be similar. This HRU concept assures consistency in integrating biophysical features into the economic land-use optimisation model.

The advantages of such coupled approaches have been demonstrated by Ronneberger et al. [2009], using the KLUM@GTAP model that combines the global agricultural land-use model KLUM and GTAP-EFL. This latter model is refinement of GTAP-E in terms of industrial and regional aggregation levels. The KLUM model allocates land into spatial units (0.5x0.5 degree grid for Europe) by maximising the expected profit per hectare under risk aversion, according to crop price and potential yield. Geographic location and biophysical heterogeneity of land is represented by using spatially explicit potential productivities, calculated by the crop growth model EPIC (Erosion Productivity Impact Calculator). Thus, contrary to the AEZ methodology, land is not classified by its differing productivity, but each spatial unit is associated with a given productivity. This provides a more precise land allocation and a more realistic representation of land transitions. For its part, GTAP-EFL provides crop prices and management induced yield. The relevance of the coupling was tested by comparing the results of the coupled system with those of each of its components taken separately. This analysis reveals significant differences between the simulations of KLUM@GTAP and of the standalone models, which according to the authors, "strongly supports the hypothesis that a purely economic, partial equilibrium analysis of land-use is biased; general equilibrium analysis is needed, taking into account spatial explicit details of biophysical aspects."

However, to bring general equilibrium insights, it is necessary to overcome some inconsistencies within the coupled system. Equations in the general equilibrium models are actually generally formulated in terms of value. In contrast, partial equilibrium models address quantities to accurately reflect biophysical features. This means that in this architecture, both models work with two separate price systems. In KLUM@GTAP, this discrepancy has great practical consequences. Notably it makes land quantity data incomparable between GTAP-EFL and KLUM. As a consequence small absolute changes in the area of "other crops" in KLUM translate into large absolute changes in GTAP-EFL [Ronneberger et al., 2009]. This problem can be solved by completely recalibrating the coupled system. This is however a complex task that can face data issues (lack of data on land prices...). For this reason, Ronneberger et al. simply decrease the responsiveness of GTAP-EFL to changes in land allocation.

4.4 Inclusion of land-use models outputs in LCA

Traditional models also suffer from a relative disconnection from engineering studies. Examples in the literature of studies integrating outputs of land-use models in LCA are scarce. This disconnection between the modelling and the environmental assessment communities mainly stems from two reasons. First, LCA are typically static simulation models describing a production system without regard for production scale and time dimension, while land-use models perform a projection throughout a certain period of time with a given evolution of the production. Second, LCA usually describe the exchanges between a production system and its environment, while land-use models are best equipped to describe the expected consequences of a change of production on the environment.

In spite of these restraints, some initiatives attempt to reconcile LCA and land-use modelling approaches. From the distinction made by Rebitzer et al. [2004] between the attributional LCA, focusing on the exchanges between the production system and its environment, and the consequential LCA, which estimate the change in the environmental system resulting from a change of the production scale, the EPA has developed a new methodology for assessing biofuel environmental impacts. This methodology is oriented toward the second definition, and links LCA and land-use models [U.S. Environmental Protection Agency, 2009]. It relies on a set of numerical tools to provide a comprehensive estimate of GHG emissions:

- The GREET model quantifies emissions at each step of the biofuel production process;
- Emissions due to land-use, exports and livestock market changes are estimated using the FASOM model. This model actually presents the advantage of covering a

wide range of production possibilities and accounts for the main GHG emitted by agricultural activities;

- While FASOM predicts land-use change in the U.S. agricultural sector, FAPRI estimates land-use change in other countries due to the response of international agricultural production to changes in commodity prices and U.S. exports. These estimates are based on historic responsiveness to changes in price in other countries. Using MODIS satellite data, FAPRI also predicts the types of land that will be converted into crop land in each country, and calculates GHG emissions associated with land conversions;

- The EPA-developed Motor Vehicle Emission Simulator (MOVES) estimates vehicle tailpipe GHG emissions. It also represents the impact that greater renewable fuel use may have on the prices and quantities of other sources of energy, and the greenhouse gas emissions associated with these changes in the energy sector.

As previously mentioned, the difficulty in accounting for ILUC emissions relates to their time dependency, which does not fit with the traditional framework of LCA. To overcome this difficulty, the EPA uses the net present value for emissions as a common metric.

5 Remainnig limitations

Prompted by European and U.S. regulators, several numerical evaluations have been undertaken using some of the previously described models [Edwards et al., 2010, U.S. Environmental Protection Agency, 2009, Laborde and Atlass Consortium, 2011]. On the whole, these studies confirm that ILUC could account for a significant part of biofuels emissions. However they also call attention to the uncertainty that remains in spite of the efforts to improve numerical models.

Laborde and Atlass Consortium [2011] list a large panel of uncertainties surrounding ILUC estimates. Among them, the estimations of the crop yield response to food price and of the price-elasticity of demand for food are of prominent importance because these two factors drive the most fundamental mechanisms respectively from the production and the consumption side.

Yield reaction to price was one of the major bone of contention in the controversy that followed the articles by Searchinger et al. and Fargione et al.. Biofuel proponents argued that higher production of biomass fuel would lead to higher crop prices, which in turn would spur higher yield.

However, though the literature provides evidence of a positive yield response in the long run, there is no consensus on its magnitude: estimates range from 0.22 to 0.76 for corn in the U.S. over the period 1951-1988 [Feng and Babcock, 2010]. Moreover, these values cover a period too far in the past to be used in modern models and should be updated to account for structural changes that affect agriculture since the end of the eighties (e.g. growth in farm size...). There is also no consensus on the effect of a positive yield response to crop price. Feng and Babcock [2010] actually show that higher yields will not necessarily limit cropland expansion. Unless output prices sharply decrease, yield growth increases profits in a given area and prompts the cultivation of land of poorer quality. This assertion is corroborated by Keeney and Hertel [2009] who demonstrate, using a modified version of GTAP (see section 4.1 for more details), that yield increases allows the U.S. agricultural export sector to regain some of their competitiveness in foreign markets and may lead to more land-use.

More work is also needed to assess the evolution of food consumption in response to price. Within models, food consumption is driven by demand functions reflecting price and income elasticities. The limitations of such functions are described in Yu et al. [2003], which also propose a new type of demand function that could be advantageously generalised to other models. In typical demand systems, the price elasticity of plant food calories is assumed to be small and negative, while for animal products, it is set to be negative and greater than that of plant food. A meta-analysis of price elasticity of meat estimations confirms that it is significantly smaller than zero; the median price elasticity across the 4 142 recorded estimates is -0.77 [Gallet, 2009]. However, this analysis also suggests that with a standard deviation of 1.28, such estimations are surrounded by large uncertainties.

Beyond these issues, the development of comprehensive models incorporating a large number of parameters raises the question of data quality. Well-designed models are actually not sufficient if they are based on flawed data. Meta-analysis of elasticity parameters estimations are frequent and provides interesting insights. However, evaluations or comparisons of databases are scarce, so there is little information on their quality.

6 Conclusion

Modelling indirect effects of bioenergy is a major challenge for land-use science because of its complexity and its potential influence on decision-making. In recent years, numerical models have been significantly improved to provide a comprehensive vision of the agricultural system. This has been performed by improving the representation of land supply and the biofuel production process in general equilibrium models (e.g., GTAP, MI-

RAGE, DART). At the same time, modelling systems coupling partial equilibrium models with CGE (e.g., KLUM@GTAP) or economic modules with spatially explicit models (e.g., MAgPIE, GLOBIOM, LEITAP), and modelling architecture combining land-use and LCA models (e.g., FASOM/FAPRI/GREET) have been developed. Both methodologies have advantages and drawbacks. Coupled systems guarantee a coherent relation between economic values and physical quantities but lose the price consistency that characterises CGE.

Despite these efforts, numerical models do not completely provide a robust assessment of ILUC, as their results are surrounded by large confidence intervals reflecting the numerous sources of uncertainty. Among them, the yield and food demand responses to price appear to be of particular importance and need specific attention from modellers.

A precise understanding of lack of robustness of models remains elusive, as the mechanisms at play in such models are complex, and their interaction with exogenous assumptions are less explicit as they become increasingly sophisticated. A pitfall of current modelling practices is that numerical tools become a black box. For this reason, transparency and simplicity should be privileged as much as possible. Additionally, the great variety of parameters used in the models makes inter-comparison more difficult. For this reason, each model should provide an extensive description of its methodology and assumptions, along with a description of its strengths and limitations. From there, meta-analysis and model inter-comparisons could be useful to understand models divergence and to guide the political decisions. Finally, in addition to evaluation of models' performance, insights on the quality of underlying database are also necessary.

More fundamentally, the role played by models in decision-making raises the question of their appropriate use. Their value added is to provide a consistent vision of the studied sector by combining complex equations and various databases. In this context, they are able to represent interconnection between mechanisms at different levels and to shed light on potential unintuitive system effects, such as indirect land-use changes. However, to build a coherent framework each model relies on a theoretical structure and on several categories of assumptions whose choice requires some subjectivity [Peace and Weyant, 2008]. The diversity of approaches to modelling ILUC that were presented in this review is a stunning example. For this reason, one should not expect from models robust predictions and definite answers but rather policy assessments guaranteing internal consistency with insights on potential unexpected effects.

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