EC project ENER/C1/428-2012 - LOT 2

Assessing the land use impact of EU biofuels policy

Description of the GLOBIOM (IIASA) model and comparison with the MIRAGE-BioF (IFPRI) model

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1. Introduction

The European Commission assigned Ecofys, IIASA and E4tech for a project to quantify Indirect Land Use Change (ILUC) associated with conventional and advanced biofuels consumed in the EU. The GLOBIOM[1] partial equilibrium model, developed by IIASA, will be used for this purpose. This model has a focus on land use change dynamics resulting from agriculture and forestry.

Until now, the MIRAGE-BioF model developed by IFPRI has been the most extensively used model to quantify ILUC effects from EU biofuel policies. This model was applied through several reports and articles[2] and has been used by the European Commission in their legislative proposal on ILUC and accompanying Impact Assessment, both published in October 2012[3].

This document provides a detailed comparison of main features of the GLOBIOM and MIRAGE-BioF models, their respective strengths and limitations, written from the perspective of the GLOBIOM model. The version of GLOBIOM used for the comparison is the model as it stands at the start of this project.[4] We compare this with the version of the MIRAGE-BioF model as used in the IFPRI 2011 study for the European Commission.[5] The purpose of this document is not to argue that one of the two models is better than the other, but merely to give an insight into how GLOBIOM works, partly by comparing it with MIRAGE-BioF.

The main features of both models are presented, focusing on data and mechanisms that play an important role in the assessment of land use change impacts of biofuels. The following aspects are discussed in detail: the representation of bioenergy processing chains and their co-products, the dynamics of land use change and the response of agricultural yield or food demand to change in domestic and international market prices. These aspects are taken into consideration when presenting GLOBOM and comparing it to MIRAGE-BioF in this report (Figure 1).

[1] www.globiom.org

[2] Bouet et al., 2010; Al-Riffai et al., 2010, Laborde, 2011, Laborde and Valin, 2012

[3] SWD(2012)344 final

[4] Note that this version features a detailed representation of the European Union and may differ from some earlier standard versions used for global level assessments.

[5] The model may have been changed in the course of other projects in the meanwhile but no documentation was accessible on these changes at the time of writing this document.

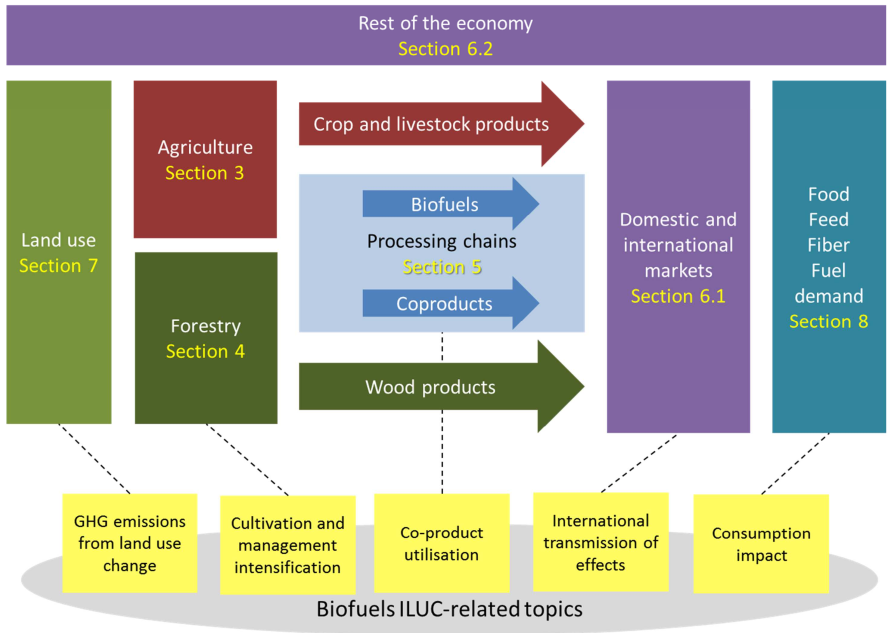

Figure 1. Main steps in the biofuel supply chain, how they relate to the model description in this report and what their associated ILUC issues are

The following questions will be addressed in this document:

1) How does the model represent the important elements of the ILUC debate?
2) What advantages can GLOBIOM bring?
3) What are the current shortcomings and how can they be addressed?

This document is intended as a background document for all stakeholders involved in the biofuels ILUC debate. Models are complex and the use of technical terms is inevitable at times, however this document aims to clearly describe the GLOBIOM model, outline the main differences between this and MIRAGE-BioF as well as note any implications to interested stakeholders. Experienced readers can find more technical information in the appendices. A full technical documentation of the model will also be made available separately during our ILUC modelling project.

2. Summary of differences between GLOBIOM and MIRAGE-BioF

GLOBIOM and MIRAGE-BioF belong to two different families of economic models. None of the two models is a priori superior to the other, but depending on the topic addressed, some characteristics can be important. GLOBIOM is a model designed to address various land use related topics (bioenergy policy impacts, deforestation dynamics, climate change adaptation and mitigation from agriculture, long term agricultural prospect). MIRAGE-BioF, besides its use for biofuel policies, is generally used to assess trade policy impacts and impacts of agricultural policies on income and poverty in developing countries. The main differences between GLOBIOM and MIRAGE-BioF are summarised in Table 1. More technical descriptions can be found in Appendix A.

Table 1. Main differences between GLOBIOM and MIRAGE-BioF

	GLOBIOM*	MIRAGE-BioF*
Model framework	Bottom-up, starts from land and technology	Top-down, starts from macroeconomic accounts
Sector coverage	Detailed focus on agriculture (including livestock), forestry and bioenergy (Partial equilibrium)	All economic sectors represented with agricultural sector disaggregated (General equilibrium)
Regional coverage	Global (28 EU Member states + 25 regions)	Global (1 EU region + 10 world regions)
Resolution on production side	Detailed grid-cell level (>10,000 units worldwide)	Regional level, with land split into up to 18 agro-ecological zones
Time frame	2000-2030 (ten year time step)	2004-2020 (one year time step)
Market data source	EUROSTAT and FAOSTAT	GTAP economic accounts, harmonized with FAOSTAT
Factor of production explicitly modelled	More detailed on natural resources (land, water)	More detailed on economic resources (labour, capital, land)
Land use change mechanisms	Geographically explicit. Land conversion possibilities allocated to grid-cells taking into account suitability, protected areas.	Aggregated representation. Substitution of land use at regional and agro-ecological zone level. Allocation of agriculture and forest land expansion across other land covers using historical patterns
Representation of technology	Detailed biophysical model estimates for agriculture and forestry with several management systems Literature reviews for biofuel processing	Input-output coefficient from GTAP database or national statistics at regional level. Literature reviews for biofuel processing
Demand side representation	One representative consumer per region and per good, reacting to the price of this good.	One representative agent per region adjusting its consumption between different goods depending on prices and level of income
GHG accounting	12 sources of GHG emissions covering crop cultivation, livestock, land use change, soil organic carbon based on advanced accounting framework. Peatland emissions based on IPCC default emission factors.	Only land use change emissions. Deforestation and soil organic carbon calculated with default IPCC emissions factors. Peatland IPCC emission values revised upward based on Edwards et al. (2010).

** GLOBIOM version with disaggregated EU as at the start of this project. MIRAGE-BioF as in Laborde (2011).*

As a model specialised in land use based activities, GLOBIOM benefits from a more detailed sectoral coverage, backed by a solid representation of production technologies and a geographically explicit representation of land use[6] and associated greenhouse gas emission flows (see Figure 2). GLOBIOM is a partial equilibrium model, meaning that the only economic sectors represented in detail are agriculture (including livestock), forestry and bioenergy. In MIRAGE-BioF, all sectors of the economy are represented but with a more limited level of detail on the supply side representation due to the top-down approach.

Many of the modelling issues raised during the previous ILUC assessment can be more easily and accurately addressed in GLOBIOM. Some GLOBIOM characteristics that differ from MIRAGE-BioF include:

- A more precise representation of land use change dynamics
- The robustness of biophysical relations for production, conversion and substitution processes
- The level of detail in the description of available technologies
- The representation of non-linear responses on land (for instance, fallow land can be used, but only up to a certain maximum level).

[6] By geographically explicit, we refer to the fact that the model makes allocation of production based on precise geographical data on land characteristics (> 10,000 spatial units).

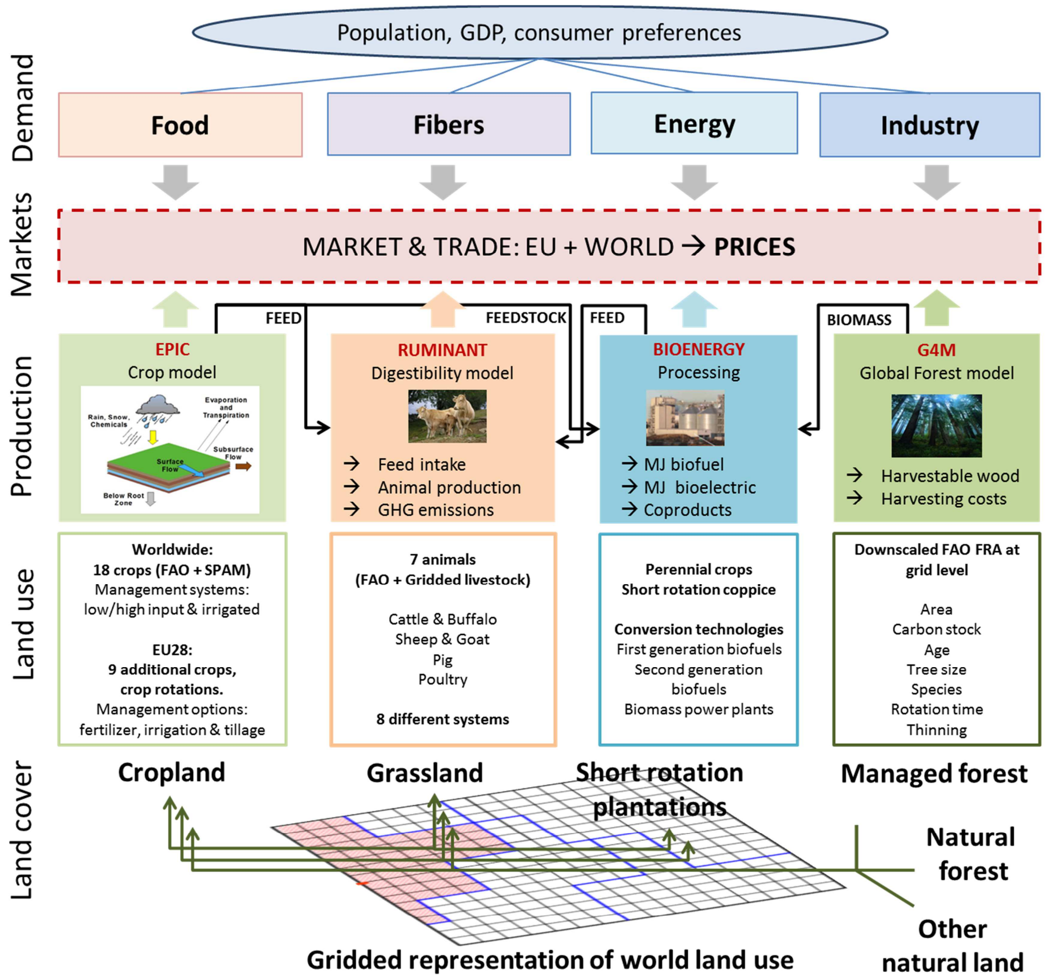

Figure 2. Overview of the GLOBIOM model structure

While GLOBIOM can address many modelling limitations raised in the ILUC debate, a limitation of GLOBIOM is the fact that it does not have some of the mechanisms that are present in MIRAGE-BioF, such as the macroeconomic effect of bioenergy policy on the fuel market or population income. These effects are discussed in more detail in section 6 and the appendices, where it will also be argued that they are expected to remain of second order when compared with drivers of indirect land use change, as explained in chapter 6.

Beyond differences in modelling frameworks and their capacity to describe mechanism at play, a main challenge in ILUC modelling remains the treatment of uncertainties on parameters that are independent from the model used (behavioural parameters, emission factors, future technologies). These uncertainties will receive much attention during our ILUC modelling project. A range of confidence will be established for emission factors on the basis of literature review and other available information. Sensitivity analyses will be performed on the behavioural parameters considered as the most critical for the final results (for instance, yield response or land conversion costs).

3. Representation of agriculture and yield development

As a model specialised on land use issues, GLOBIOM benefits from a greater level of detail in its representation of agriculture, with a larger number of crops and livestock systems represented than in MIRAGE-BioF. This increases the number of biofuel feedstocks that can be modelled, and allows for a more precise description of crop and livestock interaction, including co-products utilization. Like in MIRAGE-BioF, yields are sensitive to prices and farmers can intensify their production in response to market signals.

3.1. Crops

GLOBIOM represents 18 crops globally and 27 crops for the European Union. The full list of crops covered is detailed in Appendix B. Harvested areas are based on FAOSTAT statistics but are spatially allocated using data from the Spatial Production Allocation Model (SPAM).[7] In the case of the EU, crops are allocated across NUTS2 regions using data from EUROSTAT. This setting provides a very detailed framework compared to the previous modelling with MIRAGE-BioF, where Europe was represented as a single region and the number of crops more limited. MIRAGE-BioF relies on a modified version of the GTAP 7 database[8] that only contains 8 crop aggregates. IFPRI extended the number of these crops to 11 by disaggregating oilseeds and singling out corn (see full list in Appendix B).

The aggregated approach of MIRAGE-BioF is too coarse to trace all single crop substitutions, but allows a mapping of the total global harvested area. In GLOBIOM, the crop level approach is more precise but, as all crops are not represented, a small fraction of harvested areas is not explicitly modelled. Cultivated area currently represents in GLOBIOM around 84% of the total harvested area in the world. Harvested area for the non-covered crops is kept constant.[9] Global harvested area amounts to 78% of land classified by FAO as “Arable land and permanent crop” category, which shows the importance of abandoned land, idle land and temporary meadows in the definition of this category. The advantage of the GLOBIOM approach is that this “not harvested” arable land is also explicitly represented in the model. The standard assumption for model projections is to keep this area constant. However, modifications can be proposed in the course of this project to represent more complex dynamics (for instance, decrease in fallow land).

In GLOBIOM, yields for all locations and crops are determined in a geographically explicit framework by the Environmental Policy Integrated Climate Model (EPIC) The yields are distinguished by crop management system and land characteristics by spatial unit.[10] They are however rescaled by a same factor to fit FAOSTAT average yield at the regional level, in order to catch other managements parameters not supplied to EPIC or other cause of yield mismatch. This approach with differentiated

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[7] See You and Wood (2008) and http://mapspam.info/

[8] The Global Trade Analysis Project (GTAP) database is a large database describing the world economy and compiled using national statistics and global trade datasets. This database is formatted to satisfy certain properties of consistency on economic accounts in order to be used by computable general equilibrium models, a class of macro-economic models to which MIRAGE-BioF belongs. For more details see Narayanan et al. (2012) and the GTAP website www.gtap.org .

[9] The five most harvested crops in FAOSTAT nomenclature subject to this assumption in GLOBIOM are in decreasing order: other fresh vegetable, coconuts, olive, coffee, natural rubber.

[10] EPIC is run over a large number of spatial units covering the global land cover (over 200,000) that are then aggregated for model runs into around 10,000 larger units. See Appendix B for more details.

yields is different from the one in MIRAGE-BioF that assumes a homogenous yield within a region and agro-ecological zone.

Different crop management systems are distinguished in GLOBIOM. At the world level, four technologies can be used (subsistence, low input rainfed, high input rainfed and high input irrigated). In Europe, a larger set of options is available, with two different levels of fertilizer input, two levels of irrigation, and three different levels of tillage. EPIC has additionally been run for a large combination of different rotation systems for all NUTS2 regions.[11] This therefore allowed a more precise simulation of the yield achieved through optimisation of rotations, a practice well observed in Europe. Input requirements for each system and location are determined by EPIC (quantity of nitrogen and phosphorus, irrigated water). At the base year, production cost for these systems (i.e. all input costs plus the farmer margins) are calibrated using FAOSTAT producer price data at the national level, assuming that all units within the country supply the market at this price.

The representation of crop production is therefore much more detailed than the one used in MIRAGE-BioF, which is also consistent with FAOSTAT but has a more aggregated description at the regional level for output and at the agro-ecological level (AEZ) for land distribution.[12] The production structure in MIRAGE-BioF relies on a single aggregate production function at regional level, describing how output can be obtained from various production factors and intermediate consumption interactions (see Box 1). The description of the link between output and land is therefore not based on any biophysical model and relies on a simplified relation of substitution between inputs. A specific treatment of fertilizer input has however been added to better represent the saturation effect of yield in case of excessive addition of fertilizer.[13]

Additionally to production of grains or fibres, GLOBIOM also represents the production of straw for some of the major crops (barley, wheat) and corn stover. Only a part of the residues produced is considered available because of the role of residues for soil fertilisation. The residues removed are currently used in the model by the livestock sector but the effect of using these agricultural residues as biofuel feedstock will be explored in the project. Only one rate of residue removal is currently considered but if deemed appropriate, the effect of changing this rate on the nutrient cycle and carbon sequestration could be further explored in the course of this project, using the EPIC model. Agricultural residues are not represented in the version of MIRAGE-BioF used in Laborde (2011).

3.2. Livestock

GLOBIOM is one of the most refined global models in its representation of the livestock sector. It includes in its dataset all relevant information from the Gridded Livestock of the World database[14] and represents eight animal types spatially distributed, and producing seven animal products (see Appendix B for the list of animal and products). This allows for a more precise representation of the links between livestock production, feed requirements and the link to land through grazing needs.

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[11] NUTS (Nomenclature of Units for Territorial Statistics) is the standardized format for administrative divisions in the European Union. The level 2 of NUTS (NUTS2) corresponds to 271 regions in Europe.
For more information see http://epp.eurostat.ec.europa.eu/portal/page/portal/nuts_nomenclature/introduction

[12] More information on the GTAP-AEZ framework can be found in Lee et al. (2007). This framework relies on aggregation of input data from Ramankutty et al. (2008) database.

[13] See appendix 4 of Al Riffai et al. (2010).

[14] See Wint and Robinson (2007)

Livestock productivity for ruminants (buffalos, cows, sheep, goats) is estimated in GLOBIOM on the basis of animal feed ration using RUMINANT, a digestibility model.[15] The use of this model ensures consistency between the livestock sector input (grass, grains, stover, etc.) and output under different management systems.[16] For monogastric animals (pigs, poultry) the same consistency has been achieved using the results of a literature review to identify feed conversion efficiencies under two management systems (industrial and smallholder). Production costs for these systems are all based on FAOSTAT producer prices for product output and for grains input.

Grazing needs of ruminants depend on the rearing management system. For instance, cattle under mixed temperate systems spend a longer period of the year in stables and have lower grazing needs than cattle under extensive grazing management. A grassland map indicating levels of biomass production in the different regions is used to determine possible stocking densities of animals. The link between animals and land is therefore fully consistent, allowing the need for additional land in response to changes in the livestock sector to be traced.

This level of detail and consistency is an important asset when compared with the more simplified representation of the livestock sector in MIRAGE-BioF, where only two types of animals are distinguished: cattle and other animals (derived from the three sectors present in GTAP: cattle dairy, cattle other and other animals). A caveat of the GTAP approach is that animal numbers are not explicitly represented which makes the calculation of the feed requirement more complex.[17] Feed intake and conversion efficiencies are derived from the input/output relations observed in the economic statistics of the sector as a whole. Each sector is only represented through one aggregated production function, similar to the approach for crops.

3.3. Dedicated energy crops

In addition to the crops mentioned in section 3.1, GLOBIOM also contains yield information from EPIC to simulate deployment of dedicated energy crops, such as switchgrass and miscanthus. Because these crops are not cultivated at large scale in the base year, only their production potential is represented in the model. The use of the EPIC model to estimate the biophysical characteristics of the crops provides information on the suitability of land in different locations, as well as the fertilizer and water requirements.

Woody biomass can also be supplied on agricultural land using short rotation coppice. In the current version of the model, all short rotation woody biomass production is described through a single sector of short rotation plantation (section 4.1) that can be deployed on agricultural land or on other types of land.[18] Several types of management and yield can be distinguished in the course of this project to better characterise yield as a function of rotation time. These dedicated energy crops and woody biomass sectors in agriculture are not represented in MIRAGE-BioF.

[15] See Herrero et al. (2013)
[16] Eight production systems are used that are based on the classification from Seré and Steinfeld (1996)
[17] Animals in GTAP are assimilated to capital for these sectors.
[18] See Havlik et al. (2011)

3.4. Yield responses and intensification

The response of agricultural yield to market signals has been an important point of debate in the assessment of indirect land use change.[19] In both GLOBIOM and MIRAGE-BioF assumptions are made on technological changes that allow yields to increase over time independently from other economic assumptions (e.g. breeding, introduction of new varieties, technology diffusion, etc.) In addition both models represent yield responses to prices, although in a different way.

In GLOBIOM, crops and livestock have different management systems with their own productivity and cost. The distribution of crops, animals and their management types across spatial units determines the average yield at the regional level. Developed regions rely for most of their production on high input farming systems whereas developing countries have a significant share of low input systems and even, in the case of smallholders' subsistence farming with no fertilizer at all. Farmers can adjust their management systems and the production locations following changes in prices, which impact the average yields in different ways:

- shifts between rainfed management types (subsistence, low input and high input) and change in rotation practices;[20]
- investment in irrigated systems. This development is controlled through a simplified representation of the regional water supply potential;
- change in allocation across spatial units with different suitability (climate and soil conditions).

In MIRAGE-BioF, yield response to prices is described in a much more simple manner due to the aggregated production function that does not differentiate land suitability or management systems (see Box 1). When the relative price for land increases, yield can increase too by adding additional fertilizer, capital and labour. Hence, additional demand can be met while keeping land requirement constant. As explained in section 3.1, the production function has been modified to avoid unrealistic responses of yield in case of strong fertilizer input increase. The yield response however remains based on a simplified representation without explicit link to the real biophysical potentials.

Box 1. Production functions in MIRAGE-BioF and in GLOBIOM

Production in GLOBIOM and MIRAGE-BioF follow two different settings, due to differing theoretical approaches.

GLOBIOM, as a bottom-up mathematical programming model, relies on a detailed representation of technology for each sector with different management systems and production locations. Each management option has its own input requirements, production cost, and production efficiency. For instance, in the case of crops, the level of fertilizer and water requirements is precisely known depending on the level of intensity of the management (low, high input, irrigated). The model computes for a given demand, what the most cost-efficient systems are under a constraint of land availability and cost of resources. At the level of a region, the production pattern is then obtained by the sum of all production systems and locations used. This representation provides non-linear supply functions, whose slope patterns directly depend on the distribution of cost-efficiency across management systems and locations. The advantage of this approach is the explicit link

[19] See for instance Keeney and Hertel (2009) or CARB (2011).

[20] Change in tillage practice can also intervene. However, the impact on yield is second order, this management most significant impact on the level of carbon stocked in the soil.

between technological options and the production potentials. The shape of the supply function, however, cannot be simply inferred ex-ante and requires simulation experiments to be calculated.

MIRAGE-BioF, as a top-down computable general equilibrium model (CGE), relies on a more aggregated representation of production, directly calculated at the regional level. Input and production factor requirements (land, capital, labour) are set for the base year at regional level, as observed in statistics. When prices of these inputs or factors change, their level of consumption and level of output changes as well, following a simplified formula designed to capture the aggregated effect directly. For this function, MIRAGE-BioF, like many applied CGEs, relies extensively on the Constant Elasticity of Substitution form (CES) that defines the easiness of substitution between all factors (labour, capital, land) from a specific parameter, the elasticity of substitution (see Box 3 for more details on the CES). MIRAGE-BioF uses this design at the regional level for all its sectors, but relies for several levels on CES nesting, with different elasticity values that depend on inputs and factors.[21] Such stylized representations are very convenient for macro-economic approaches (trade policies, budgetary policies, etc.) when estimation of the different level of substitution around an equilibrium point is the main interest. They however lose the link to underlying technological relations, and generally display a smooth supply profile and lower sensitivity to biophysical constraints due to input substitution possibilities.

4. Representation of woody biofuel feedstocks and forestry

In addition to crop feedstocks, the GLOBIOM model also provides potential for woody biomass feedstock extraction that can be used for bioelectricity and second generation biofuels. This is based on a detailed representation of plantation deployment potentials, as well as a refined description of the forestry sector. This combination of a detailed agriculture and forestry sector in one modelling framework is a strong asset of GLOBIOM. The description of forestry in MIRAGE-BioF is limited to a single sector, without biofuel feedstocks, whereas GLOBIOM explicitly models extraction of five primary wood products and distinguishes between short rotation plantations and managed forests.

4.1. Short rotation plantations

Besides energy crop, woody biomass can be supplied in GLOBIOM through short-rotation plantations, a sector that covers very short rotation periods (short rotation coppice i. e. 2 to 5 years) but also longer rotation periods (short rotation forestry, closer to 10 years).[22] Suitable areas for this sector are determined by using a geographic information system (GIS) that analyses temperature, precipitation (rain), altitude, and population density. The productivity of plantations is based on estimates from the Potsdam Net Primary Productivity[23] Model Inter-comparison, and production costs are calculated based on literature sources.[24] Several deployment potentials can be considered depending on the assumption used for plantation type (cropland, grassland, other natural vegetation). These data are also used to update the model with the amount of carbon that is sequestered.

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[21] See Bouet et al. (2010) for a description of most CES nesting in the different production functions.
[22] Weih (2004)
[23] Net primary productivity is the measure of the net carbon flow from the atmosphere to the terrestrial biomass, ie the amount of biomass that is growing in a given period of time, a year in our approach. See Cramer et al., 1999.
[24] See Havlik et al (2011) for full details.

4.2. Woody biomass from managed forests

GLOBIOM relies on information from the global forestry model G4M[25] for its representation of forestry productivity. Locations of forests are supplied to GLOBIOM at a half degree resolution (see Figure 2). Harvest potentials of stemwood are determined based on net primary productivity (NPP) maps and combined with maps of forest biomass stock such as the Global Forest Resources Assessment provided by FAO.

The information on forestry harvest potential from G4M allows four main primary woody resources to be represented in GLOBIOM: industrial roundwood, non-commercial roundwood, harvest losses and branches and stumps. Harvesting costs include logging and timber extraction and depend on harvesting equipment, labour costs and terrain conditions. Primary resources, once extracted, are separated into five primary woody products: sawn wood biomass, pulp wood biomass, energy wood biomass (biofuels, heat and electricity), traditional use biomass (fuel, cooking) directly collected in the forest (no processing chain) and other non-energetic use biomass. Primary forest residues are included (branches and stumps) and can be used for second generation biofuels, electricity and heating. All harvested primary woody products are sent to processing activities which can lead to other types of bioenergy feedstocks (secondary residues such as saw dust and cutter shavings, black liquor, bark), see section 5.

This detailed representation of the forestry sector will allow for an in-depth analysis of potential impacts of woody biomass use, an analysis that is not possible with MIRAGE-BioF that only contains one aggregated forestry sector (see Box 1) which does not supply feedstock for biofuels and contains no specific information on forest biomass productivity.

5. Overview of feedstock processing and biofuel production

GLOBIOM expands the number of feedstocks and processing pathways that have been explored so far with MIRAGE-BioF. It includes second generation technologies and offers a flexible framework that can be further developed to describe additional biofuel pathways, present or future, with their expected production costs and conversion coefficients.

5.1. Sector coverage and role of supply chain

At the level of primary sectors, GLOBIOM represents, in total, 27 crops, 7 animal products and 5 primary wood products (see details in Appendix B). These products can then be directly sent to markets to satisfy the demand of households and various industries and services (food industry, seeds, cosmetic industry, etc. – not explicitly represented in the model[26]). Part of the commodities can also be used as animal feed in the livestock sector, which is the case for a significant share of many crops. Some other products are transformed explicitly in the model into intermediate or final products, before being sent to the market. This is the case for oilseeds, wood primary products and products used as bioenergy feedstocks. For these products, all processing industries are explicitly

[25] See Kindermann et al. (2008).
[26] Industrial uses are captured in the FAOSTAT database in the category "Other uses" of the Supply Utilisation Accounts.

represented in the model, with their transformation coefficients, their co-products and processing costs. The role of processing industries in the supply chain is illustrated in Figure 3.

The representation of market flows in GLOBIOM is based on information from FAOSTAT that provides details on the quantities of biomass which is processed, directly purchased by final consumers, used as animal feed, or allocated to seeds or other industrial users. The accounting of this distribution across potential users is important to assess the competition between food, energy and other uses.

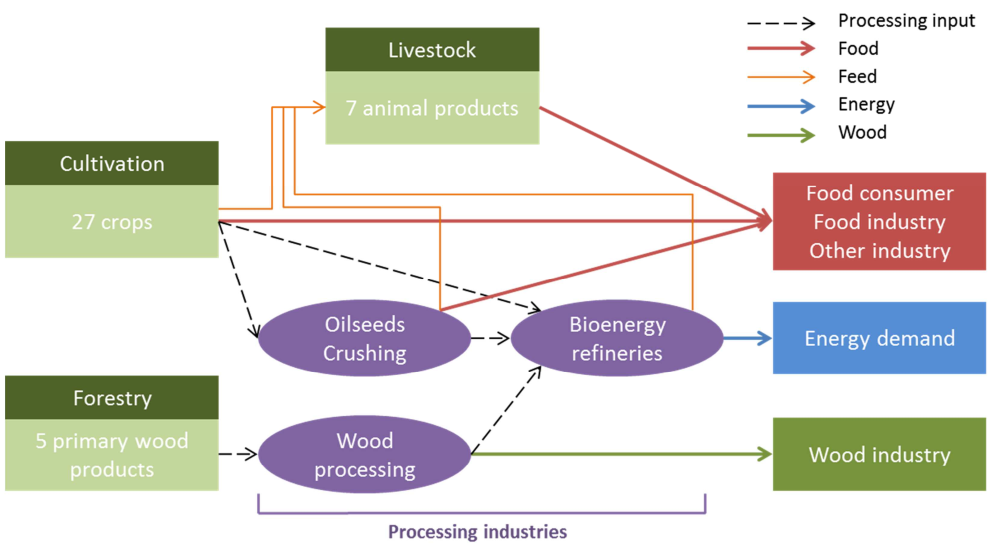

Figure 3. Supply chain in GLOBIOM and role of processing industries

In comparison, MIRAGE-BioF relies on a more comprehensive representation of economic flows, because it contains a complete mapping of all economic sectors with their demand for raw products. For instance, the food industry is represented explicitly in the model, as well as the chemical industry. However, the number of primary sectors is more limited, with only 11 crops, two animal products, and one forestry product. The volume of input in each sectors relies on aggregated regional accounts in monetary units, less precise than in the FAOSTAT utilization accounts expressed in quantities. For crops of interest for biofuels however, some bottom-up data reconstructions were performed in MIRAGE-BioF to refine the initial data and make them more consistent with FAO statistics. Because the supply chain is long and complex and commodities are aggregated according to their economic value, it is often difficult to trace the flow of the raw commodities 'from field to plate'. For instance, the raw output of an aggregated sector such as fruit and vegetables can be purchased by sectors as diverse as (in decreasing order) food processing (other), vegetable and fruits[27], beverage and tobacco, trade margins, textile, other general services, vegetable oil, chemical rubber plastic, etc.[28] The outputs of these sectors can in turn be purchased by many other sectors.

[27] Auto-consumption in the GTAP database is frequent and is simply the result of aggregation across sectors having input-output flows.
[28] Based on the GTAP8 database for the year 2007 at world level. All sectors listed purchase more than 2% of the output consumed as intermediate consumption (40% of the total production).

5.2. Processing activities and bioenergy pathways

The main processing industries currently represented in GLOBIOM are the oilseed crushing industry, forestry industry, and a certain number of bioenergy industries. Table 2 provides a detailed overview of processing activities and indicates if they are represented in MIRAGE-BioF. This list reflects the GLOBIOM model at the beginning of the project. The list of technologies can be extended to take into account additional transformation pathways. Conversion coefficients from input to final products, quantities of co-products generated and processing costs of pathways are currently sourced from literature. They can be updated if better information would become available.

Table 2. List of current processing activities in GLOBIOM and availability in MIRAGE

Processing activity	**Input product**	**Output product**	**GLOBIOM***	**IFPRI-MIRAGE***
Oilseed crushing				
Rapeseed crushing	Rapeseed	Rape oil Rape meal	✓	✓
Sunflower crushing	Sunflower	Sunflower oil Sunflower meal	✓	✓
Soybean crushing	Soybeans	Soybean oil Soybean meal	✓	✓
Palm fruit processing	Palm fruit	Palm oil Palm fruit fiber	✓**	✓
Wood processing				
Sawmill	Sawn wood biomass	Sawn wood Saw dust Saw chips Bark	✓	
Mechanical pulping	Pulp wood biomass Saw chips	Mechanical pulp Bark	✓	
Chemical pulping	Pulp wood biomass Saw chips	Chemical pulp Black Liquor Bark	✓	
Plywood production	Sawn wood biomass	Plywood Sawdust Saw chips Bark	✓	
Fiberboard production	Pulp wood biomass Saw chips Sawdust	Fiberboards	✓	
Bioenergy				
Combustion	Energy biomass Sawdust Saw chips Black Liquor Bark	Electricity Heat	✓	
Cooking	Traditional biomass	Stove energy	✓	
Biofuel corn based	Corn	Ethanol DDGS	✓	✓
Biofuel wheat based	Wheat	Ethanol DDGS	✓	✓
Biofuel sugar based	Sugar cane	Ethanol	✓	✓
	Sugar beet	Ethanol	✓	✓

Biofuel FAME	Vegetable oil	Biodiesel (FAME)	✓	✓
Biofuel via fermentation	Energy biomass Sawdust Saw chips Black Liquor Bark	Ethanol Electricity Gas Heat	✓	
Biofuel via gasification	Energy biomass Sawdust Saw chips Black Liquor Bark	Methanol Heat	✓	

* GLOBIOM version with disaggregated EU as at the start of this project. MIRAGE-BioF as in Laborde (2011).
** Palm fruit fibers are not represented in the current version of GLOBIOM.

The flexibility of GLOBIOM with respect to modelling supply chains can be used to improve the processing description at the level of detail deemed relevant for an accurate assessment. It is possible for instance to:

- Disaggregate the pathway to represent more precisely the underlying technologies currently used;
- Refine the type of inputs and co-products associated to a processing pathway (e.g. the use of ethanol or methanol during the transesterification for biodiesel production and production of glycerol);
- Account for the quality of co-products generated depending on the supply chain, for example the protein content of dried distiller grain solubles (DDGS).

In Laborde (2011), the number of bioenergy sectors in MIRAGE-BioF is limited to conventional (first generation) biofuels (see Table 2). Main crushing sectors and bioenergy production sectors have been carved out in the GTAP database and their processing costs and conversion coefficients are derived from literature. However, this process is time-consuming because any change made to the model database requires a full rebalancing of all economic flows in the model. In a top-down model like MIRAGE-BioF, the total country income, households and industry purchases, must remain consistent with the national accounts, also after addition of new sectors. For this reason, the number of sectors that can be added is more limited.

Another issue in MIRAGE-BioF is related to the unit of substitution. A product can only have one rate of substitution with other products within the same nest. By default, the unit of substitution is the economic value in the base year, when the model is calibrated. For instance, one dollar of vegetable and fruit imported in the base year from one region can be replaced by one dollar of vegetable and fruit from a different region. In the case of MIRAGE-BioF, the most important flows of homogenous products (wheat, corn, sugar, ethanol, vegetable oil, biodiesel) were reconstructed with the same prices per tonne to make the substitution equally consistent on a quantity basis. But this remains an imperfect adjustment because some products are substituted differently in reality, depending on their final use (for instance, calories or proteins).

GLOBIOM allows for taking into account quality aspects relevant per type of use (food, feed, bioenergy feedstock). For instance, it is possible to substitute bioenergy feedstock on the basis of their biofuel yield when used in a bio refinery and at the same time express the quantity in kilocalories (or other nutrition metric) for the final consumer. Similarly, in the case of feed, the

protein and energy content are both important for the calculation of livestock rations, i.e. the bundle of feed given to the animals, as we will see in the next section.

Another interesting feature of GLOBIOM is its capability to model discontinuities in substitution patterns. For instance, it is possible to represent substitutions between several types of biodiesel sourced from different vegetable oils, but to restrict this substitution to some maximum incorporation constraint (for instance the amount of soybean oil or palm oil, following quality standards). In that case, a competitive price plays a role only when substitution is possible. Once the maximum incorporation level is reached, the more expensive feedstocks have to be used to satisfy the extra demand.

5.3. Dealing with co-products

The role of co-products of biofuel feedstocks has been discussed intensively in the ILUC debate. There is consensus about the fact that the cogeneration of products can limit the land footprint of bioenergy production but evaluations find varying estimates for this effect. The assessment of this effect is in particular related to the representation of feed intake by the livestock sector.

The feed representation of GLOBIOM provides detailed information on animal requirements. Rations of animal feed are calculated based on a digestibility model, which ensures consistency between what animals eat and what they produce, and rations are specific to each management system. When the price of a crop changes, the price of the feed ration changes as well, causing a change in profitability of each livestock management system. Switching between management systems allows for representing changes in the feed composition of the livestock sector.

Oilseed meals are explicitly modelled in GLOBIOM as a part of the rations represented in the livestock sector. If availability of one type of meal increase (e.g. rape), it can replace another type of oilseed meal (soybean) or increase the number of animals relying on a higher share of protein complement in their diet. The substitution of feed types can be handled under a single constraint of minimum protein requirement, or even under a double constraint of minimum protein *and* minimum energy requirement. For instance, it is possible to represent the fact that DDGS can be incorporated in high quantities to substitute some oilseed meals on a protein content basis, but that beyond a certain level of incorporation, this generates a deficit in energy needs that requires other feed items to be added in the ration.

Other co-products such as corn and wheat DDGS are modelled in a simpler way and are just considered to replace some crop groups with a substitution ratio that is determined exogenously. The substitution ratios currently used are the coefficients provided by the Gallagher (2008) review.

Substitution ratios are flexible in GLOBIOM and can be adjusted if better information becomes available during the project. It is also possible to introduce constraints on the maximum level of incorporation of co-products in the livestock sector, in case evidence of a saturation effect is found.

Contrary to GLOBIOM, the representation of feed in MIRAGE-BioF is based on a top-down decomposition of inputs based on economic statistics and FAOSTAT information and not established on the basis of a biophysical model. For that reason, feed quantity and composition are not explicitly linked to production levels for the livestock sectors (and based on aggregated statistics). Grazing input is not determined on the basis of animal feed needs but on the amount of land classified as

grassland in the model. Therefore, increasing production requires increasing grassland, independently from the cattle density on land. This can overestimate the response of grassland area to change in livestock production level.

Co-products are well represented in MIRAGE-BioF and they also substitute in the livestock production functions associated to feed. Feed substitution is managed at two levels: the first level deals with substitution of different types of grains and the protein complement aggregate; the second level disaggregates the protein complement category to represent an easier substitution between oilseed meals and DDGS. However, the substitution ratio remains determined by the economic value associated to the different meals, which are highly correlated with protein contents in the case of protein meals. Although these substitution patterns have been compared and found consistent with literature, the flexibility to fit a specific substitution patterns is limited by the model design. In particular, it is not possible to exactly match a substitution ratio to multiple crops, for instance, one tonne of wheat DDGS replacing 0.5 tonne of soybean and 0.66 tonne of wheat.[29]

6. Capturing the world markets and the global economy

Both GLOBIOM and MIRAGE-BioF have a full representation of world markets but GLOBIOM trades all single goods as perfect substitute[30] in tonnes, whereas MIRAGE-BioF represents imperfect substitution between trade flows measured in monetary terms. GLOBIOM is therefore more suitable to account for replacements between specific goods on international markets, between the sectors covered. In GLOBIOM the description of the economy is however limited to main land based sectors (it is a partial equilibrium *model whereas MIRAGE-BioF is a* general equilibrium *model). MIRAGE-BioF has a greater understanding of interactions between all sectors of the economy but is coarser for sectors highly relevant to the ILUC debate such as agriculture and forestry. The GLOBIOM model might miss certain interactions (fuel market feedback, income impact), a caveat that can be addressed by calculating separately the magnitude of these effects.*

6.1. International markets and trade

Both GLOBIOM and MIRAGE-BioF represent international markets for the various products that are traded between regions. They both rely on international trade statistics for trade flows and tariffs.[31] Their trade specifications however differ, as explained in the section below.

Trade in GLOBIOM follows a representation where products are all expressed in tonnes across the 53 economic regions and are considered as identical goods. Products are always sourced from the region with the least expensive production costs, adjusted by international transportation costs and tariffs. An increasing cost of trade prevents that all exports are provided by the same region. The

[29] Estimate from CE Delft in the Ghallager review (2008).

[30] A perfect substitution means that an importing country will always decide to import from the country which hasthe lowest cost. This is different from an imperfect substitution representation where some stickiness in trade flows is assumed, meaning that trade patterns are not immediately impacted by small changes in price because it takes some effort to switch to a different supplier. Note that in GLOBIOM, as explained in this section, transportation costs increase with the size of trade flows, which also introduce some stickiness.

[31] GLOBIOM relies for its trade on FAOSTAT net export and reallocates trade bilaterally using COMTRADE. MIRAGE-BioF use data from the GTAP database that is built on COMTRADE statistics. Both models use the tariffs information from the MAcMap-HS6 database (Bouët et al., 2008).

advantage of such an approach is that it allows to trace precisely all substitutions of traded goods on a quantitative basis. Some patterns of trade creation are also possible, i.e. if increase of population requires or if a change in production costs makes it more profitable, two countries can start to trade in the future even if they were not trading partners before. This is not possible in the MIRAGE-BioF model.

In MIRAGE-BioF, all products are traded based on their economic value in the base year and consequently all substitution relations are by default measured in base year US dollars. To allow the substitution of agricultural goods and biofuel feedstocks to be on a 1 to 1 basis in quantitative terms, trade values are adjusted in the MIRAGE-BioF database. But this rate of substitution is difficult to maintain in case of large change in trade flows, due to the function of substitution used (see Box 3 for a detailed discussion). Additionally, trade patterns can only evolve in MIRAGE-BioF around the base year trade flows, and no new trade flow can appear. Products are not necessarily sourced from the cheapest region, because consumers are assumed to differentiate them on other criteria (quality or sanitary measures for instance). This can help in reproducing some trade patterns in high value products (limited change in meat trade) but is sometimes a constraint to replicate rapid changes in the trade balance of bulk commodities (for instance, the change in rapeseed trade direction in Europe in the 2000s).

6.2. Including the economy partly or entirely: PE versus CGE

GLOBIOM is a partial equilibrium (PE) model, this means that the relevant sectors (agriculture, forestry and bioenergy) are represented in detail, which makes it suitable for modelling land use change effects. Other economic sectors however are not included or only included in a very coarse way. GLOBIOM assumes that the economy outside land using sectors evolves independently from the policies assessed in the model, following a *ceteris paribus* approach[32].

In the MIRAGE-BioF model, all sectors of the economy are simultaneously and immediately interconnected, for this reason the model is classified as a computable general equilibrium (CGE) model. It works as a giant water bed – if you press on one side of the economy, it moves everywhere. This is because all relations in the economy are described through equations that take the trickle-down effect to all other sectors already into account. The relation between all sectors is described on the basis of base year economic flows (national accounting perspective).

As stated above, GLOBIOM models only agriculture, forestry and bioenergy and focuses on understanding the land use impact of these activities. The impacts on the rest of the economy are assumed to have a second order effect and are not accounted for the modelling of land use change. Using the GLOBIOM model instead of the MIRAGE-BioF model implies that some sector interactions are missing. These interactions are however predictable in the case of biofuel policies, in which an increase in biofuel demand leads to more demand for biofuel crops. In particular, two interactions with sectors not covered in GLOBIOM can have a feedback effect on the land use 1) the effect biofuel policies have on the fuel market and its feedback on agriculture and forestry via fossil fuel and fertilizer prices and 2) the increased regional income in developing countries associated to the

[32] *Ceteris paribus* is an assumption widely used in economics where the effect of changing a parameter in the economic system is analysed, while considering that all other parameters influencing the economy are kept unchanged.

development of bioenergy production, that lead to higher consumption of land based products. These interactions are described in more detail in Box 2. Where necessary, effects not currently covered by GLOBIOM can be calculated ex-ante (before the event) and added to the simulation of the GLOBIOM model. For example, the change in oil price associated to the biofuel policy can be calculated based on a literature review or a simplified model. If required, it is also possible to introduce a simplified representation of the fuel market in GLOBIOM to represent its relation to the bioenergy market.

Box 2. General equilibrium effect from biofuel policies not captured in GLOBIOM

A certain number of general equilibrium effects are not captured in GLOBIOM, for instance across sectors or economic agents. Depending on additional information coming available during the present study (from literature, from stakeholders), we can decide to improve the description of interaction between the increasing biofuels volume and the feedback effects on other land based sectors.

- *Fuel market leakage*: Biofuels can lead to a decreased demand for fossil fuel and therefore somewhat reduce prices of fossil fuels. In response, cheaper prices can lead to an additional consumption of fossil fuel. This means that the replacement of fossil fuels by biofuels may not be 1 to 1.[33] This leakage is of different nature than the indirect land use change leakage but is important for the final GHG balance of biofuels.
- *Impact on fuel prices and feedback on agriculture*: Al-Riffai et al. (2010) report (using MIRAGE)-BioF that the EU biofuel mandate will lead to a fall in oil price of about 0.8% and a price reduction in the EU of about 0.3% of conventional petroleum based fuel at the pump. This could have a feedback effect on the input side of the agricultural sector and forestry sector. As this impact is usually small, this feedback effect should remain limited.
- *Impact on fertilizer prices*: fertilizer prices can be influenced by the price of fossil energy as well as by the change in production level required by the expansion of the agricultural sector. Furthermore, changing crop prices change the specific intensity of input use, increasing demand for biofuels thus increases the use of fertilizer on the existing cropland. As mentioned in the previous bullet, oil prices are expected to change in response to biofuel policy shocks, which could impact the price of fertilizer. However, as this effect is expected to remain small, the magnitude of this impact will remain limited, as long as quantities of extra fertilizer are low compared to overall agricultural needs.
- *Change in consumer income.* Impact on food prices is captured by a model like GLOBIOM. But in some developing regions, the development of a biofuel sector can have a significant impact on national income. Additionally, a change in fuel price can also lead to an increase or decrease of purchasing power and consequently a higher or lower consumption of other products.
- *Change in exchange rates, wages, cost of capital, service input prices, etc.*: many other interlinkages are described in a general equilibrium framework such as impacts on the labour market, capital market and currency market. However, as the biofuel sector remains of limited size compared to the rest of the economy, its macroeconomic impact usually remain limited. Bouet et al., 2010 find that the welfare impact of the EU biofuel mandate is close to zero (-0.01%) for the EU and regions in the world that are more notably affected are the least advanced countries, due to change in commodity prices, captured in GLOBIOM.

[33] Rajagopal et al., 2011; 2013; de Gorter et al., 2011

7. Modelling land use change and associated GHG emissions

The modelling of land use change is a strength of GLOBIOM, as land is the starting unit to all production processes. GLOBIOM uses a flexible framework that represents all major land use substitution possibilities and takes into account the heterogeneity of production across locations. This offers a solution to the limitations observed with the simplified representation of land substitution in MIRAGE-BioF. The link between land use change and GHG emissions is more precise in GLOBIOM because it relies on a more refined approach than MIRAGE-BioF, which uses the default IPCC coefficients, and an updated estimate for peatlands. Additionally, GLOBIOM contains sources of non-CO_2 emissions from agriculture that can complement the understanding of the full GHG effect of bioenergy policies. MIRAGE-BioF however can inform policy on the emissions from the rest of the economy (industry and services).

7.1. Land allocation for crops

Trade in GLOBIOM is handled at the level of its 53 economic regions (EU28 + 25 world regions). The supply side of the model optimises the location of crop cultivation at a much finer resolution in so-called Supply Units: geographical areas of similar topographic, climatic and soil conditions of which more than 10,000 are distinguished in GLOBIOM. Depending on the potential yield and cost in each Supply Unit the model determines which crops will be allocated in that unit and in what quantity.[34] Each supply unit contains information (derived from the biophysical model EPIC) on the productivity of each crop. Therefore the quality of land is not an absolute characteristic of a Supply Unit, but is crop specific. Additionally for the EU region, more precise data could be fed into the model to represent crop rotations in GLOBIOM and substitutions occurs between these rotations (defined as group of crops including rotations) instead of between single crops.

This representation is more detailed than in MIRAGE-BioF, which relies on an aggregated approach at the level of the region and agro-ecological zone. Land substitution in MIRAGE-BioF is managed through a Constant Elasticity of Substitution (CES) nested structure that allows different levels of substitutability between crop productions to be distinguished (see Box 3). Two elasticities of substitution determine which crops are grown (see Figure 4). For instance, corn and wheat are highly substitutable. If the price of wheat increases, a significant share of corn harvested area is reallocated to wheat. Rice is placed at a lower level of substitution. Therefore, for the same wheat price increase, the increase of rice acreage will be much smaller. This simplified approach has the advantage of representing all the relevant substitution mechanism at the aggregated level. However, it does not use the full biophysical information useful to know the relative crop profitability in each location and may neglect non-linearities in the system. For instance, in the previous example, it is possible that corn remains very profitable in many suitable regions, initially limiting substitutions. When the wheat price hits a record, making it more profitable everywhere, substitutions will occur more massively.

[34] This process of allocation of land between crops can be assimilated as a perfect substitution. In practice, to avoid the model to reallocate too abruptly across production systems, a flexibility constraint is implemented, often a lower or upper limit to the share of harvested area that the crop can use in the given location. In the EU, crop rotations also play this role of flexibility contraint.

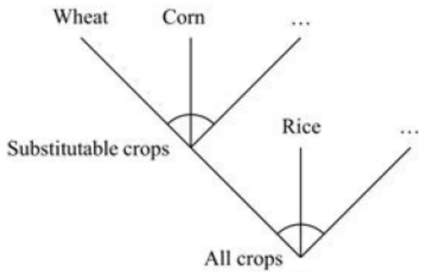

Figure 4. Land substitution nesting structure for crops in MIRAGE-BioF

Box 3. CES and CET functional forms, the bricks of MIRAGE-BioF

The Constant Elasticity of Substitution (CES) function is a production function widely used in applied economics to define how the level of output of one sector depends on a certain number of inputs or production factors (labour, capital, land, etc.). In a CES, when a quantity Q of output is obtained using two inputs in quantity q_1 and q_2, a mathematical relation defines how q_1 and q_2 can substitute each when their relative prices change. The central parameter of the CES is the elasticity of substitution σ that defines the easiness of substitution. For instance, an elasticity of substitution of 0.1 between labour q_1 and capital q_2 means that if price of labour increases by 10% relative to capital, more capital will be used such as capital purchase over labour purchase (q_2/q_1) increases by 1% (10% x 0.1).

The Constant Elasticity of Transformation (CET) function is used to define allocation of production factors (typically land or labour) where the returns are the highest. It works exactly as a CES but in the other direction: quantity is increased for the good that gets a higher relative price. For instance, a land owner puts more land in production in the sector that has higher market prices. Mathematically, the two functional forms are the same but the sign of the elasticity of substitution becomes negative for the CET.

CES and CET are used as elementary bricks in many top-down models and are extensively used in MIRAGE-BioF. One level of substitution (one elasticity only and all products at the same level) is usually too coarse to represent the complex substitution patterns observed at the aggregated level., In an attempt to approach reality and model capacities, modellers usually increase the number of levels (nested CES or CET) to differentiate different levels of substitution.

Although this approach allows for controlling the ease of substitution with different elasticity values for the different nests, three limitations are however to be noted. First the number of degrees of freedom for the calibration is only one per nest. So for instance, using one CET level for land means that forest, crop land and pasture is the same.[35] Moreover, the substitution patterns are by construction symmetrical, i.e. it is possible to reverse the land conversion with the same easiness. In other words, if prices come back to their initial values, land use comes back to its initial distribution.[36] In a conversion cost approach as in GLOBIOM, costs can be different for changing from land type A to B and for the reverse relation.

A second issue is that the substitution around the equilibrium is performed on the basis of input values (one USD versus one USD) To obtain a substitution in a different metric (for instance, one tonne for one tonne), it is necessary to reconstruct all the input values, using a same price per unit of substitution (in our example, same

[35] This specification is for instance used in GTAP-BIO (Golub and Hertel, 2012). See discussion in CARB (2011) and Laborde and Valin (2012).

[36] In MIRAGE-BioF, this symetry is also observed. However, if natural forest disappears, and is later replaced again by forest, it is assumed that the level of carbon is lower, equivalent to a managed forest.

price per tonne). In MIRAGE-BioF, this was indeed required for a large number of agricultural goods, to ensure consistent substitution patterns.

A last drawback for the CES and CET is that the sum of volumes is not conserved by the substitution. This is a critical issue in the case of land use substitution and in the case of MIRAGE-BioF, it has been corrected for land by applying a correction factor.[37] However, it remains a limitation for the many other CES functional forms in the model, when moving away far from the initial equilibrium point.

7.2. Cropland, grassland and agricultural land expansion

Another important difference between GLOBIOM and MIRAGE-BioF is the way in which land use is represented between land cover types.

In MIRAGE-BioF, several representations have been tested. The design used for Laborde (2011) is as represented in Figure 5. Land expansion is managed at two levels:

- First level: Land expansion within agricultural and managed forest area (i.e. economic use area). For these cases, the substitution between cropland, grassland and forest is managed through a CET functional form (see Box 3).
- Second level: Land expansion in other natural area is managed through a separated elasticity of total managed land expansion.

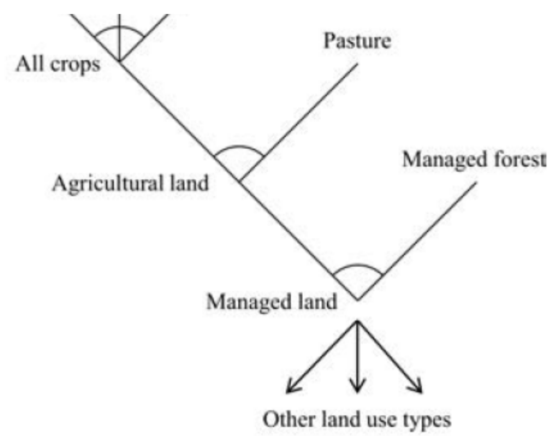

Figure 5. Land use type substitution nesting and expansion in MIRAGE-BioF

The limitation of this approach is the proper evaluation of land rents associated to grassland and managed forest (see Box 4). The aggregated representation of MIRAGE-BioF does not allow for capturing the value of land in the different locations adequately. Moreover, the quality of land is often related to the type of cultivation, livestock activity, or forest plantation that land owners can choose, depending on output and inputs prices. A very suitable land for wheat is not necessarily as

[37] See Golub and Hertel (2012) for an illustration of how this correction is made. Elasticities of transformation are however no longer constant in that case, which imposes some recalibration when far from the initial point.

suitable for corn, or for cotton, as illustrated by the regional specialization observed all over the world.

In GLOBIOM, the productivity of land for each type of crop is specific to the grid cell, also for land not currently used as cropland. Therefore, it is possible to consider conversion of other land to cropland on the basis of the expected profitability associated to productivity of new locations. A similar approach is used for grassland and grass productivity. This allows for direct calculation of the value of the marginal productivity of land in the model (a parameter often discussed in the ILUC debate). This value is estimated on the basis of real land use productivity estimates from EPIC (see section 3.1) instead of using an ad-hoc coefficient like in MIRAGE-BioF. By default, a yield value equivalent to 75% of average yield in the region was applied in MIRAGE-BioF in case of land expansion (with an interval for sensitivity analysis of 50%-100%).

Land expansion in GLOBIOM is described at the level of each spatial unit. Instead of substituting use with an aggregated function at a regional level, as for crop substitution in MIRAGE-BioF, land conversion is performed at the local level, on a one to one hectare basis, to allocate the new production to the spatial unit. A matrix of land use conversion between land use types defines which land use conversions are possible and what the associated costs are (Figure 6).

The land transition matrix has the great advantage of offering a flexible representation of land conversion patterns that has close resemblance with the real world. Conversion costs are not the same and vary between land types. For instance, it can be less costly to expand into natural vegetation than into forest (although less economically rewarding if the timber can be valued). This conversion cost approach in particular allows for a more flexible representation of the main drivers of land use change and deforestation observed in the different regions of the world.[38]

Peatland is one of the land covers that are under scrutiny in the biofuel debate. No spatially explicit information on peatland is currently available in GLOBIOM. Therefore, as in MIRAGE-BioF, drainage of peatlands drainage is currently accounted ex-post (with hindsight) in the model and based on other indicators, in particular cropland expansion in areas already containing drained peatlands. This representation can be improved if more information becomes available in the course of the project.

Box 4. Land rent and land areas

One of the main challenges of the top-down approach used by MIRAGE-BioF is the mapping between the value of land represented in the production function, and the effective land area observed in the statistics. In the GTAP database, land use is represented as *land rent*, because production functions account for purchases of the different production factors (labour, capital, land). High value products (e.g. vegetables, fruits, cash crops) are therefore allocated a higher land rent, but only for a limited cultivated area. This can become a problem when starting to reallocate land input from one sector to another. For example, in GTAP, cereals have generally lower value added and therefore lower land rent per hectare. Transferring all land rents from vegetable and fruits to the cereal sector provides a lot of *virtual land* because, even though the value of land rent is very high (providing great expansion possibilities for cereals), the real biophysical area transferred is in reality small.

[38] All land use changes in GLOBIOM are driven by expansion of agriculture and forestry. Hosonuma et al. (2012) estimate that 80% of deforestation is driven by agriculture.

In MIRAGE-BioF, this anomaly has been fixed in the crop sector by reconstructing all land rents and assuming the same rent per hectare for all crops in a given region. However, the issue remains in the mapping of other land use. In particular, it is not possible to assume the same land rent per hectare for grassland, managed forest and cropland, as the areas considered are too vast. Consequently, representation of cropland expansion remains delicate when managed through a CET function (see Box 3). Several modelling options are proposed in Al Riffai et al. (2010) and Laborde and Valin (2012).

The methodological difficulties above are avoided in the bottom-up approach taken with GLOBIOM by relying on an explicit gridded representation of land, based on detailed information from remote sensing and data downscaling. This approach however does not remove the need for specification and calibration efforts when defining land conversion costs associated to the different transitions allowed.

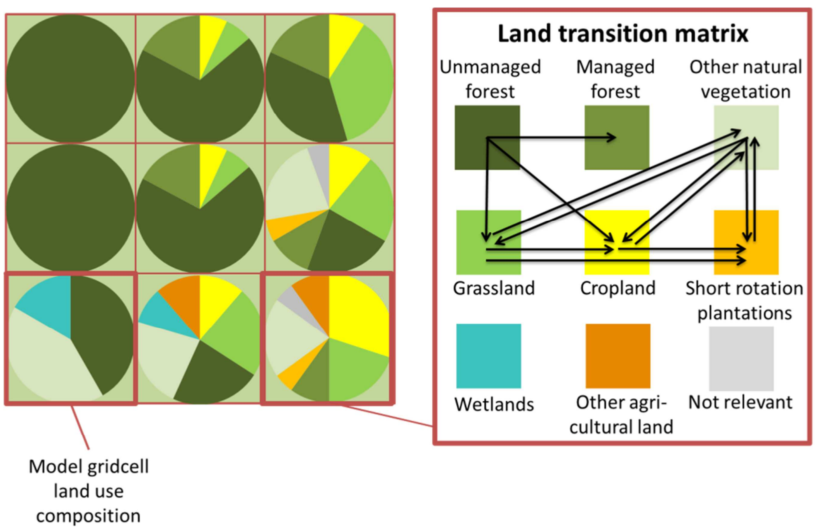

Figure 6. Land cover representation in GLOBIOM with land use distribution in each model gridcell (left hand-side) and land transition matrix defining in each gridcell the conversion allowed (arrows, right hand-side)

7.3. GHG emissions of agriculture and land use change

A dozen different GHG emissions sources related to agriculture and land use change are represented in GLOBIOM. Agricultural emission sources covered represent 94% of total agricultural emissions according to FAOSTAT, and land use change emissions are consistent with recent reporting, although slightly lower[39](Valin et al., 2013). All GHG emission calculations in GLOBIOM are based on IPCC guidelines for GHG accounting (IPCC, 2006). These guidelines specify different levels of detail for the calculations. Tier 1 is the standard calculation method with default coefficients, whereas Tier 2 requires local statistics and Tier 3 onsite estimations. Seven out of eleven GHG sources in GLOBIOM are estimated through Tier 2 or Tier 3 approaches.

[39] This is due to the fact that the model only represents land use change emissions from agricultural activities and not from other activities such as illegal logging, mining, etc. Current observations however show decreasing patterns of deforestation in some regions with significant deforestation in the past, in particular Brazil.

Table 3. GHG emission sources in GLOBIOM

Sector	Source	GHG	Reference	Tier
Crops	Rice methane	CH_4	Average value per ha from FAO	1
Crops	Synthetic fertilizers	N_2O	EPIC runs output/IFA + IPCC EF	1
Crops	Organic fertilizers	N_2O	RUMINANT model + Livestock systems	2
Crops	Carbon from cultivated organic soil (peatlands)	CO_2	FAOSTAT	1
Livestock	Enteric fermentation	CH_4	RUMINANT model	3
Livestock	Manure management	CH_4	RUMINANT model + Literature review	2
Livestock	Manure management	N_2O	RUMINANT model + Literature review	2
Livestock	Manure grassland	N_2O	RUMINANT model + Literature review	2
Land use change	Deforestation	CO_2	IIASA G4M Model emission factors	2
Land use change	Other natural land conversion	CO_2	Ruesch and Gibbs (2008)	1
Land use change	Soil organic carbon	CO_2	JRC / EPIC	3

For specific cases of land use change emissions, four different sources are particularly relevant:

- Deforestation: only changes in above and below ground living biomass are accounted for. G4M provides estimates that are consistent with Forest Resource Assessment (FAO, 2010). When forest is converted to a non-forest land cover, forest C stock is lost and replaced by the carbon stock from the new land cover (see next bullet).
- Natural land conversion: for other land cover than forest, above and below living biomass is accounted for based on the Ruesch and Gibbs (2008) database. This applies to grassland, other natural land and short rotation plantations.
- Soil organic carbon: soil organic carbon (SOC) is accounted for in Europe only, using data from JRC. SOC is influenced by crop management practices, in particular tillage. For regions outside Europe currently no data is present in the model.
- Organic soil cultivation: this concerns peatlands that are taken into cultivation and emit GHG emissions over multiple years. We estimate these flows using data from FAOSTAT, in line with IPCC emission factors.

In comparison to GLOBIOM, MIRAGE-BioF land use change GHG accounts are based on more generic calculations as they often rely on Tier 1 approach from IPCC. Non-CO_2 emissions from agriculture were not used to avoid some double counting with the direct emissions coefficients from biofuel life cycle analyses.

From the four types of emission sources listed above, only three sources are represented in MIRAGE-BioF, natural land carbon stocks in living biomass are not represented. MIRAGE-BioF models the other three as follows:

- Carbon stock in forests is based on IPCC Tier 1 emission factors applied to the different AEZ in the 15 regions (Laborde and Valin, 2012). Forest coefficients correspond to above and below

ground living biomass and a distinction is made between primary forest, managed forest, and in the case of EU, afforested areas. However, the carbon stocks are not spatially allocated like in G4M.

- Soil organic carbon is estimated for all regions in the world using IPCC Tier 1 emission factors
- IPCC coefficients are not applied for peatland, but instead a higher value of 55 tCO_2 ha^{-1} yr^{-1} is used, sourced from more recent literature estimates. Based on historical observations, a share of 33% of oil plantations is assumed to expand into peatland (based on Edwards et al., 2010).

8. Modelling changes in food consumption

Both GLOBIOM and MIRAGE-BioF represent a response of food demand that increases the price of agricultural products. MIRAGE-BioF features the most sophisticated approach to modelling food demand having a full representation of household substitution patterns. Consumers in GLOBIOM do not substitute across products, but the impact of their change in food intake can be estimated in a more tangible way, using statistics on kcal per capita per day provided by FAO.

Food demand is endogenous in GLOBIOM and depends on population size, gross domestic product (GDP) and product prices. When population and GDP increase over time, food demand also increases, putting pressure on the agricultural system. Change in income per capita in the baseline drives a change in the food diet, associated to changing preferences. Current trends in China for example show that per capita rice consumption decreases, whereas pig consumption increases and milk consumption grows even faster.

Food prices are another driver for a change in food consumption patterns. When the price of a product increases in GLOBIOM, the level of consumption of this product decreases by a value determined by the price elasticity associated to this product in the region considered. The price elasticity indicates by how much the relative change in consumption is affected with respect to relative change in price. For instance, an elasticity of -0.1 means that if the price of the product increases by 10%, the consumption of this product decreases by 1% (10x-0.1). The values of these elasticities in GLOBIOM are sourced from the USDA demand elasticity database[40]. In this database, price elasticities of demand are lower for developing countries than for developed countries and lower for cereals than for meat products. This is consistent with observations.

The representation of demand in MIRAGE-BioF is more comprehensive because the model incorporates a full representation of the consumer budget covering consumption responses to changes in household income and to the different product prices at the same time. In particular MIRAGE-BioF allows for representation of cross-price effects. This means that when the price of wheat increases the consumption of wheat decreases (own-price effect) whereas the consumption of corn increases to compensate for wheat loss (cross-price effect). GLOBIOM models the own-price effect but does not account for the cross-price effect. Therefore its assessment of food demand

[40] This database provides demand elasticities for 144 regions and eight food product groups. See Muhammad et al. (2011).

change cannot account for substitution, which may underestimate the transmission of effects across agricultural markets.[41]

An additional feature of GLOBIOM compared to MIRAGE-BioF is that it accounts for kcal per capita supplied per day by using FAOSTAT data. The impact of food prices on food demand can therefore be assessed as a change in kcal per capita per day for each of the products.

[41] Market interactions however also occur through the supply side with land use competition.

References

Al-Riffai, P., Dimaranan, B. & Laborde, D. (2010). *Global Trade and Environmental Impact Study of the EU Biofuels Mandate* (Report to the European Commission). International Food Policy Research Institute.

Balkovic, J., van der Velde, M., Schmid, E., Skalský, R., Khabarov, N., Obersteiner, M., Stürmer, B. & Xiong, W. (2013). Pan-European crop modelling with EPIC: Implementation, up-scaling and regional crop yield validation . *Agricultural Systems* 120 (0), 61 - 75.
Retrieved from http://www.sciencedirect.com/science/article/pii/S0308521X1300070X.

Bchir, H., Decreux, Y., Guerin, J.-L. & Jean, S. (2002). *MIRAGE, a Computable General Equilibrium Model for Trade Policy Analysis* (Working Paper 2002-17). CEPII. Retrieved from http://www.cepii.fr/anglaisgraph/workpap/summaries/2002/wp02-17.htm.

Bouët, A., Decreux, Y., Fontagné, L., Jean, S. & Laborde, D. (2008). Assessing Applied Protection across the World. *Review of International Economics* **16** (5), 850--863.

Bouët, A., Dimaranan, B. V. & Valin, H. (2010). *Modeling the global trade and environmental impacts of biofuel policies* (IFPRI Discussion Paper 01018). International Food Policy Research Institute (IFPRI).

Britz, W. & Hertel, T. W. (2011). Impacts of EU biofuels directives on global markets and EU environmental quality: An integrated PE, global CGE analysis. *Agriculture, Ecosystems & Environment* **142** (1-2), 102 - 109. (Doi: 10.1016/j.agee.2009.11.003.) Retrieved from http://www.sciencedirect.com/science/article/pii/S016788090900334X.

CARB (2011). *Final Recommendations From The Elasticity Values Subgroup* (ARB LCFS Expert Workgroup). California Air Resource Board.

Chen, X., Huang, H. & Khanna, M. (2012). Land-use and Greenhouse Gas Implications of Biofuels: Role of Technology and Policy. *Climate Change Economics* **03** (03), 1250013. (Doi: 10.1142/S2010007812500133.) Retrieved from http://www.worldscientific.com/doi/abs/10.1142/S2010007812500133.

Cramer, W., Kicklighter, D. W., Bondeau, A., Iii, B. M., Churkina, G., Nemry, B., Ruimy, A., Schloss, A. L. & Intercomparison, T. P. O. T. P. N. M. (1999). Comparing global models of terrestrial net primary productivity (NPP): overview and key results. *Global Change Biology* **5** (S1), 1--15. (Doi: 10.1046/j.1365-2486.1999.00009.x.) Retrieved from http://dx.doi.org/10.1046/j.1365-2486.1999.00009.x.

Day, R. H. (1963). On Aggregating Linear Programming Models of Production. *Journal of Farm Economics* **45**, 797-813.

Decreux, Y. & Valin, H. (2007). *MIRAGE, Updated Version of the Model for Trade Policy Analysis Focus on Agriculture and Dynamics* (Working Papers 2007-15). CEPII research center. Retrieved from http://www.cepii.fr/anglaisgraph/workpap/summaries/2007/wp07-15.htm.

EC (2012). *Impact Assessment accompanying the document Proposal for a Directive of the European Parliament and of the Council amending Directive 98/70/CE relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources.* (Commission Staff Working Document). European Commission.

Edwards, R., Mulligan, D. & Marelli, L. (2010). *Indirect Land Use Change from Increased Biofuels Demand: Comparison of Models and Results for Marginal Biofuels Production from Different Feedstocks*. Joint Research Center - European Commission.

EPA (2010). *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis* (EPA-420-R-10-006). U.S. Environmental Protection Agency, Office of Transportation and Air Quality, Assessment and Standards Division.. Retrieved from http://www.epa.gov/otaq/fuels/renewablefuels/regulations.htm.

FAO (2010). *Global Forest Resources Assessment* ( ). Food and Agriculture Organization of the United Nations. Retrieved from http://www.fao.org/forestry/fra/fra2010/en/.

Gallagher, E. (2008). *The Gallagher review of the indirect effects of biofuels production* ( ). Renewable Fuel Agency. (http://www.renewablefuelsagency.org/-db/-documents/Report-of-the-Gallagher-review. pdf)

de Gorter, H. & Drabik, D. (2011). Components of carbon leakage in the fuel market due to biofuel policies. *Biofuels* **2** (2), 119--121.

Havlík, P., Schneider, U. A., Schmid, E., Böttcher, H., Fritz, S., Skalský, R., Aoki, K., Cara, S. D., Kindermann, G., Kraxner, F., Leduc, S., McCallum, I., Mosnier, A., Sauer, T. & Obersteiner, M. (2011). Global land-use implications of first and second generation biofuel targets. *Energy Policy* **39** (10), 5690 - 5702. (Doi: 10.1016/j.enpol.2010.03.030.) Retrieved from http://www.sciencedirect.com/science/article/pii/S030142151000193X.

Herrero, M., Havlik, P., Valin, H., Rufino, M., Notenbaert, A., Thornton, P., Blummel, M., Weiss, F. & Obertsteiner, M. (2013). High resolution livestock productivity, biomass use, non-CO2 greenhouse gas emissions and excretion maps for global change and sustainability research.. *PNAS (forthcoming)*.

Hertel, T., Hummels, D., Ivanic, M. & Keeney, R. (2007). How confident can we be of CGE-based assessments of free trade agreements?. *Economic Modelling* **24** (4), 611--635.

Hosonuma, N., Herold, M., Sy, V. D., Fries, R. S. D., Brockhaus, M., Verchot, L., Angelsen, A. & Romijn, E. (2012). An assessment of deforestation and forest degradation drivers in developing countries. *Environmental Research Letters* **7** (4), 044009. Retrieved from http://stacks.iop.org/1748-9326/7/i=4/a=044009.

IPCC (2006). IPCC guidelines for national greenhouse gas inventories. In S. Eggleston, L. Buendia, K. Miwa, T. Ngara & K. Tanabe (ed.),. Institute for Global Environmental Strategies, Hayama, Japan.

Keeney, R. & Hertel, T. (2009). The Indirect Land Use Impacts of United States Biofuel Policies: The Importance of Acreage, Yield, and Bilateral Trade Responses. *American Journal of Agricultural Economics* **91** (4), 895--909.

Kindermann, G., Obersteiner, M., Sohngen, B., Sathaye, J., Andrasko, K., Rametsteiner, E., Schlamadinger, B., Wunder, S. & Beach, R. (2008). Global cost estimates of reducing carbon emissions through avoided deforestation. *Proceedings of the National Academy of Sciences* **105** (30), 10302.

Laborde, D. (2011). *Assessing the Land Use Change Consequences of European Biofuel Policies* (ATLASS Consortium, Final report). IFPRI. Retrieved from http://www.ifpri.org/publication/assessing-land-use-change-consequences-european-biofuel-policies.

Laborde, D. & Valin, H. (2012). Modeling land-use changes in a global CGE: Assessing the EU biofuel mandates with the Mirage-BioF Model. *Climate Change Economics* **03** (03), 1250017. (Doi: 10.1142/S2010007812500170.) Retrieved from http://www.worldscientific.com/doi/abs/10.1142/S2010007812500170.

McCarl, B. A. & Spreen, T. H. (1980). Price Endogenous Mathematical Programming as a Tool for Sector Analysis. *American Journal of Agricultural Economics* **62** (1), 87--102. Retrieved from http://www.jstor.org/stable/1239475.

Muhammad, A., Seale, J., Meade, B. & Regmi, A. (2011). *International Evidence on Food Consumption Patterns: An Update Using 2005 International Comparison Program Data* (Technical Bulletin 1929). USDA-ERS.

Narayanan, B. G., Aguiar, A. & McDougall, R. (2012). *Global Trade, Assistance, and Production: The GTAP 8 Data Base.* Center for Global Trade Analysis, Purdue University..

Rajagopal, D. (2013). The fuel market effects of biofuel policies and implications for regulations based on lifecycle emissions. *Environmental Research Letters* **8** (2), 024013. Retrieved from http://stacks.iop.org/1748-9326/8/i=2/a=024013.

Rajagopal, D., Hochman, G. & Zilberman, D. (2011). Indirect fuel use change (IFUC) and the lifecycle environmental impact of biofuel policies. *Energy Policy* **39** (1), 228 - 233. (Doi: 10.1016/j.enpol.2010.09.035.) Retrieved from http://www.sciencedirect.com/science/article/pii/S0301421510007214.

Ramankutty, N., Evan, A., Monfreda, C. & Foley, J. (2008). Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. *Global Biogeochemical Cycles* **22** (1), 1--19.

Ruesch, Aaron & Gibbs, H. K. (2008). *New IPCC Tier-1 Global Biomass Carbon Map For the Year 2000.* (Available online from the Carbon Dioxide Information Analysis Center [http://cdiac.ornl.gov]). Oak Ridge National Laboratory. Retrieved from http://cdiac.ornl.gov/epubs/ndp/global_carbon/carbon_documentation.html.

Schneider, U. A., McCarl, B. A. & Schmid, E. (2007). Agricultural sector analysis on greenhouse gas mitigation in US agriculture and forestry. *Agricultural Systems* **94** (2), 128 - 140. (Doi: DOI: 10.1016/j.agsy.2006.08.001.) Retrieved from http://www.sciencedirect.com/science/article/pii/S0308521X06001028.

Seré, C. & Steinfeld, H. (1996). *World livestock production systems: current status, issues and trends* (Animal and Health Paper 127). Food and Agriculture Organisation. Retrieved from http://www.fao.org/WAIRDOCS/LEAD/X6101E/X6101E00.HTM.

Shoven, J. B. & Whalley, J. (1984). Applied General-Equilibrium Models of Taxation and International Trade: An Introduction and Survey. *Journal of Economic Literature* **22** (3), 1007--1051. Retrieved from http://links.jstor.org/sici?sici=0022-0515%28198409%2922%3A3%3C1007%3AAGMOTA%3E2.0.CO%3B2-Y.

Takayama, T. & Judge, G. (1971). *Spatial and temporal price and allocation models.* North-Holland Amsterdam.

Takayama, T. & Judge, G. G. (1964). An Interregional Activity Analysis Model for the Agricultural Sector. *Journal of Farm Economics* **46** (2), pp. 349-365. Retrieved from http://www.jstor.org/stable/1236540.

Valin, H., Havlík, P., Mosnier, A., Herrero, M., Schmid, E. & Obersteiner, M. (2013). Agricultural productivity and greenhouse gas emissions: trade-offs or synergies between mitigation and food security?. *Environmental Research Letters* **8** (3), 035019. Retrieved from http://stacks.iop.org/1748-9326/8/i=3/a=035019.

Weih, M. (2004). Intensive short rotation forestry in boreal climates: present and future perspectives. *Canadian Journal of Forest Research* **34** (7), 1369-1378. (Doi: 10.1139/x04-090.) Retrieved from http://www.nrcresearchpress.com/doi/abs/10.1139/x04-090.

Wint, W. & Robinson, T. (2007). *Gridded livestock of the world 2007.* FAO.

Appendix A General characteristics of GLOBIOM and MIRAGE-BioF

GLOBIOM and MIRAGE-BioF are two very different types of economic models: GLOBIOM is a detailed multi-sector multi-region mathematical programming model focused on agriculture and forest activities, and therefore follows a partial equilibrium approach; MIRAGE-BioF is a multi-sector multi-region computable general equilibrium model (CGE), based primarily on the Global Trade Analysis Project database (GTAP). Although these approaches differ in several important points, they are both grounded in microeconomic traditions and based on the same assumptions of optimizing behaviors of the agents they focus on, producers for GLOBIOM, and producers and consumers for MIRAGE-BioF. Prices play a central role in these models to shape decisions of agents.

A.1 GLOBIOM, a partial equilibrium mathematical programming model

GLOBIOM is a multi-sectoral model developed at the International Institute for Applied Systems Analysis (IIASA) since 2007. The model is grounded in the mathematical programming tradition (McCarl and Spreen, 1980). This type of model is derived from aggregation of more simplified linear programming models of production used in microeconomics (Day, 1963). This type of approach has been long used in economics for many sectoral problems, in particular in agricultural economics (Takayama and Judge, 1964; 1971). Development of recent computation capacities allowed application of this framework to large scale problems with a high level of details, for example to US policies affecting agriculture and forestry sectors (Schneider et al., 2007; US EPA, 2010).

Sectors covered by GLOBIOM are currently agriculture, forestry and bioenergy, with their supply side production functions, their markets and the demand side. The model is therefore a partial equilibrium model, because not all goods, factors or agents are represented in this approach. It is therefore designed to address issues affecting land use based sectors, and consider that situation in the rest of the economy is unchanged (ceteris paribus).

The economic formulation problem in GLOBIOM is expressed as follows: the model optimizes an objective function defined as the sum of producer and consumer surplus associated to the sector represented, under a certain number of constraints. Producer surplus is determined by the difference between market prices and the cost of the different production factors (labour, land, capital) and purchased inputs. International transportation costs are also taken into account in the producer costs. On the consumer side, surplus is determined by the level of consumption on each market: the lower a price is, and the higher this consumption level can be, as well as the consumer surplus. Technically, this is achieved by integrating the difference between the demand function of the good on its market and the market price level. Constraints in the model are related to various dimensions: technologies available, biophysical resources availability (land, water), capacity constraints, etc.

In this type of approach, the supply side can be very detailed, in particular benefiting from the possibility of linearizing the non-linear elements of the objective function, the model can be solved as a linear programming (LP) model, allowing a large quantity of data to be used for production characteristics. The GLOBIOM model for instance can optimize the production for each sector on a large number of geographic units (maximum resolution is 212,000 units but typically the model is run at a more aggregated level of around 10,000 units). Additionally, many technologies and transformation pathways can be defined for the different sectors. This detailed representation on

the production side however induces a trade-off on the demand side. Because of the linear optimization structure, demand is represented through separated demand functions, without a representation of total households budget and the associated substitution effects (McCarl and Spreen, 1980).

A.2 MIRAGE-BioF, a computable general equilibrium based on the GTAP framework

MIRAGE-BioF is a computable general equilibrium model (CGE) dedicated to biofuel impact analysis, derived from the trade policy analysis model MIRAGE developed at CEPII (Bchir et al, 2002; Decreux and Valin, 2007) and based on the GTAP database (Narayanan et al., 2012).

CGE models have their basis grounded in microeconomic theory, but operate in a macroeconomic framework, with a complete coverage of economic flows circulating in the economy for purchase of goods, remuneration of production factors. The father of the general equilibrium theory is Leon Walras who defined this framework in 1871, emphasizing the importance of interactions across the different component of the economy, ie sectors and regions, but also factor market, government expenditure, households savings and investment, current accounts disbalances, etc. Kennet Arrow and Gérard Debreu implemented these principles in the 1950s in a more systematic formalized framework. To the difference of partial equilibrium models, all prices in CGEs are endogenous determined through equations to other economic trade flows, including real wages, return on capital, or exchanges rates (only one single price needs to be fixed to serve as a reference, called *numeraire*). These models are calibrated to a preexistent state of the economy, considered in equilibrium. Prices all vary around this initial equilibrium in response to a shock (change in tax level, tariff, level of quota). Data on the preexisting state is supplied by extensive datasets, called Social Accounting Matrices (SAM), usually produced by national statistical agencies.

The big advantage of CGEs is their full theoretical consistency as no ceteris paribus assumption is necessary with all sectors of the economy simultaneously interconnected. This however comes at the expense of details because SAMs are often more limited in their sectoral representations, due to their macroeconomic perspective and they only provide economic flows in monetary terms. Even if some countries produce precise datasets tracking all economic interdependencies, with high level of representation of sectors, households and factor markets, many others rely on coarser information, and must rely on construction assumption and allocation rules to build up a complete and consistent SAM. These models were used until the end of the 80s mainly to assess the effect of taxation policies and trade policies (Shoven and Whaley, 1984), but they have been progressively extended to other applications such a climate change impact, carbon trading policies or bioenergy policies.

In the case of global CGEs, the GTAP database is very often used as the source of data, as it represents a unique effort of reconciling information from the SAMs of the different countries around the world. The process is however delicate as SAMs from various countries are usually not consistent with each another, due to differences in accounting method but also to the year in which the SAM has been constructed (SAMs are rarely available for every year). The GTAP consortium performs this reconciliation process and succeeded to put together an increasing number of SAMs over the years (96 for GTAP6 with base year 2001, 112 for GTAP7 with base year 2004, 134 for GTAP8 with base year 2007).

The GTAP database currently uses a nomenclature of 57 sectors, including 12 for raw agricultural products, and 1 for forestry. This often makes the data too coarse for a precise assessment of bioenergy. For instance, ethanol and biodiesel are missing but also fossil fuel. Oilseeds are aggregated and vegetable oil and their co-products are in the same sectors. For that reason, IFPRI has developed an extended database used with the MIRAGE-BioF model (82 sectors) for the different biofuels assessments, in which the most important missing sectors have been singled out.

Appendix B Comparison table of main data characteristics in GLOBIOM and MIRAGE-BioF

<table>
<tr><th>GLOBIOM</th><th>MIRAGE-BioF</th></tr>
<tr><td>Land use resolution</td><td></td></tr>
<tr><td>Simulation units (SimU) architecture (Skalsky et al., 2008)

• Global-SimU
= Countries boundaries
x HRU* at 5' resolution
x Grid layer with 30' resolution

Total number of Global-SimU (incl. EU): 212,707
Usual aggregation for global runs (2°x2°): 10,893

Max number of Global-SimU for Brazil: 11,003
Usual aggregation for global runs, Brazil: 443

• EU-SimU
= NUTS2 spatial unit
x HRU at 1 km resolution

Max number of EU SimU: 379,220
Usual aggregation: 648
(NUTS2 x AEZ regions)

*HRU = Region of same altitude, soil type, slope and other characteristics (Balkovic et al., 2010)</td><td>GTAP Land database (GTAP-AEZ)

1 spatial unit = 18 agro-ecological zones
x GTAP7 countries (112)

Typical aggregation, world:
155 units but of unequal importance (Laborde and Valin, 2012)

Typical aggregation, EU27:
10 units (87% of rent in 2 AEZ)
Typical aggregation, Brazil:
9 units (98% of rent in 4 AEZ)</td></tr>
<tr><td>Land cover types</td><td></td></tr>
<tr><td>World: Global Land Cover 2000 (JRC, 5’x5’)
EU: CORINE Land Cover 2000 (EEA, 1 x 1 km)

Land cover types imported into GLOBIOM:
• Cropland
• Other agricultural land
• Grassland
• Forest
• Wetlands
• Other natural land
• Not relevant

Improvements performed in the model
• Split managed/unmanaged forest (G4M data)
• Grassland match to grazing requirements
• Short rotation plantation land cover</td><td>FAOSTAT database

Land cover types imported into MIRAGE:
• Arable land
• Meadows and permanent pasture
• Permanent crops
• Forest
• Other

Land available for expansion:
GAEZ (IIASA and FAO, 2002)

Improvements performed in the model:
• Split managed/unmanaged forest (GTAP-AEZ data)</td></tr>
</table>

Crop production	
World: 18 crops: • cereals: barley, corn, millet, rice, sorghum, wheat, • oilseeds: groundnut, rapeseed, soybeans, sunflower, palm • sugar cane • roots/tubers/vegetables: cassava, chick peas, dry beans, potatoes, sweet potatoes, • cotton EU: 9 additional crops: • cereals: soft wheat, durum wheat, rye, oat • sugar beet • peas • green fodder: corn silage, other green fodder • fallow	World: 11 crops aggregates from an extended GTAP database: (Laborde and Valin, 2012) • Wheat • Maize (built by IFPRI) • Sugar crops • Soybeans (built by IFPRI) • Sunflower (built by IFPRI) • Rapeseed (built by IFPRI) • PalmFruit (built by IFPRI) • Rice • OthCrop (aggregates of GTAP other crops, plant fibers and other coarse grains) • Other oil seeds • Vegetable and fruits
Harvested area: World: FAOSTAT with spatial allocation from Spatial Production Allocation Model (IFPRI) EU28: EUROSTAT NUTS2 statistics	**Harvested area:** FAOSTAT distributed by AEZ according to the M3 database (Ramankutty et al., 2008)
Yield: World: EPIC model on SimU grid for the 18 crops. Yield values adjusted to fit FAOSTAT country level Spatial and management system differentiation. EU28: EPIC run for combination of different rotation systems for all NUTS2 regions.	**Yield:** FAOSTAT, only at regional level.
Production: At SimU level. Consistent with FAOSTAT & EUROSTAT aggregates.	**Production:** FAOSTAT, only at the regional level.
Production costs: FAOSTAT producer prices.	**Production cost:** GTAP database
Technology: Substitution between Leontieff technologies World : 4 technologies estimated by EPIC - Subsistence - Low input, rainfed - High input, rainfed - High input, irritaged EU28: large set of technologies - 2 different levels of fertilizer x 2 different levels of irrigation x 3 different level of tillage	**Technology:** 1 aggregated nested CES function

Livestock sector	
Eight Animal types (and seven associated products): • Bovine dairy (bovine milk and meat) • Bovine other (bovine meat) • Sheep and goat dairy (small ruminant milk and meat) • Sheep and goat other (small ruminant meat) • Pigs (pig meat) • Poultry hens (eggs) • Poultry broilers (poultry meat) • Poultry mixed (poultry meat and eggs)	Two livestock sectors: • cattle • other animals (three sectors in GTAP: cattle dairy, cattle other, other animals)
Animal number: ILRI/FAO Gridded Livestock of the World (GLW) animal number and distribution at the 3’x3’ resolution.	**Animal number:** Not available in GTAP or MIRAGE-BioF. (Assimilated to capital)
Yield: Estimated using RUMINANT, a digestibility model. Ensures perfect consistency between feed input (grass, grains, stover…) and output. For monogastric, based on a literature review.	**Yield:** Input/Output coefficient from the SAM
Production: Seven products: • Bovine meat (from bovine dairy and bovine other) • Bovine milk • Sheep and goat meat (from sheep and goat dairy and sheep and goat other) • Sheep and goat milk • Pig meat • Poultry meat (from broiler and poultry mixed) • Poultry eggs (from hens and poultry mixed)	**Production:** GTAP production value. Can be matched ex post with FAO quantities.
Production cost: FAOSTAT producer prices and grains input.	**Production cost:** GTAP database
Technology: Substitution between Leontieff technologies Ten systems (Seré and Steifeld classifications) 8 systems for ruminant: • Grassfed arid • Mixed arid • Grassfed humid • Mixed humid • Grassfed temperate • Mixed temp. • Urban • Other 2 systems for monogastrics • Industrial • Smallholders	**Technology:** 1 aggregated nested CES function

Forestry sector	
Forest area: based on G4M model (0.5°x0.5°) **Harvest yield:** Stemwood harvest potential determined from net primary productivity (NPP) maps, combined with maps on forest biomass stock (Global Forest Resources Assessment, FAO) **Forest primary products:** 4 forest resources. • Industrial roundwood • Non-commercial roundwood • Harvest losses • Branches and stumps Separated into 5 primary woody products: • Sawn wood biomass • Pulp wood biomass • Energy wood biomass (biofuels, heat and electricity) • Traditional use biomass (fuel, cooking) • Other use biomass **Forest secondary products:** Secondary forestry residues from forest industries and milling activities: • Saw chips • Sawdust • Bark • Black liquor	Forestry as one single sector.
Production costs: Harvesting costs including logging and timber extraction account for: • Unit cost of harvesting equipment and labour • A slope factor accounting for terrain conditions • A regional adjustment of labour cost by the ratio of mean PPP (purchasing power parity over GDP).	**Production cost:** GTAP database
Technology: Substitution between Leontieff technologies Technologies with yield estimated for: • Sawmills • Mechanical pulp mills • Chemical pulp mills • Fiberboard production • Plywood production	**Technology:** 1 aggregated nested CES function

Conversion technologies in agriculture, forestry and bioenergy	
List of sectors/processes: • Agriculture o Rapeseed crushing o Sunflower crushing o Soybean crushing • Forestry o Sawmill o Mechanical pulping o Chemical pulping o Plywood production o Fiberboard production • Bioenergy o Combustion o Cooking o 1st gen biofuel corn o 1st gen biofuel wheat o 1st gen biofuel sugar o 1st gen biofuel FAME o 2nd gen biofuel fermentation o 2nd gen biofuel gasification **Conversion coefficients and costs:** Based on FAOSTAT and literature reviews. Can be expanded or updated more easily as a CGE.	List of sectors/processes: • Agriculture o Rapeseed crushing o Sunflower crushing o Soybean crushing o Palm fruit processing • Bioenergy o 1st gen biofuel corn o 1st gen biofuel wheat o 1st gen biofuel sugar cane o 1st gen biofuel sugar beet o 1st gen biofuel FAME **Conversion coefficients and costs:** Based on the GTAP modified database. Changing in technology representation technical due to modification to report in the SAMs
GHG Emission sources	
Eleven emission sources from agriculture and land use change: • Rice methane CH_4 • Synthetic fertilizers N_2O • Organic fertilizers N_2O • Enteric fermentation CH_4 • Manure management CH_4 • Manure management N_2O • Manure grassland N_2O • Deforestation CO_2 • Other natural land conversion CO_2 • Soil organic carbon CO_2 • Cultivated organic soil CO_2	CO_2 Industrial and service emissions + Three emission sources from land use change • Deforestation CO_2 • Soil organic carbon CO_2 • Cultivated organic soil CO_2