GLOBIOM documentation

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1. Introduction

This document provides a detailed description of main features of the GLOBIOM model, in the standard global version. Main features of the model are presented.

2. GLOBIOM features overview

GLOBIOM is an economic 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). It belongs to the family of partial equilibrium models, as it focuses on a few economic sectors to represent them with a fine level of details. The main characteristics of GLOBIOM are summarized in Table 1. More extensive presentation of such differences as well as technical descriptions can be found in Appendix A.

Table 1. Main structural characteristics of GLOBIOM.

	GLOBIOM-EU [2015]
Model framework	Partial equilibrium, bottom-up, starts from land and technology
Sector coverage	Detailed focus on agriculture (including livestock), forestry and bioenergy
Regional coverage	Global (37 regions)
Resolution on production side	Detailed grid-cell level (>10,000 units worldwide)
Time frame*	2000-2030/2050/2100 (ten year time step)
Market data source	FAOSTAT
Factor of production explicitly modelled	Detailed on natural resources (land, water)
Land use change mechanisms	Grid-based. Land conversion possibilities allocated to grid-cells taking into account suitability, protected areas.
Representation of technology	Detailed biophysical model estimates for agriculture and forestry with several management systems Literature reviews for biofuel processing.
Demand side representation	One representative consumer per region and per good, reacting to the price of this good.
GHG accounting*	12 sources of GHG emissions covering crop cultivation, livestock, above and below ground living biomass, soil organic carbon based. Peatland IPCC emissions factors revised upward based on exhaustive literature review (see Appendix).

As a model specialized in land use based activities, GLOBIOM benefits from a detailed sectoral coverage, with an explicit representation of production technologies, a geographically explicit allocation of land cover and land use and their related carbon stocks and greenhouse gas emission flows (see Figure 1). GLOBIOM is a partial equilibrium, meaning that the only economic sectors represented in details are agriculture (including livestock), forestry and bioenergy. In computable general equilibrium models, all sectors of the economy are represented but with a more limited level of detail on the supply side.

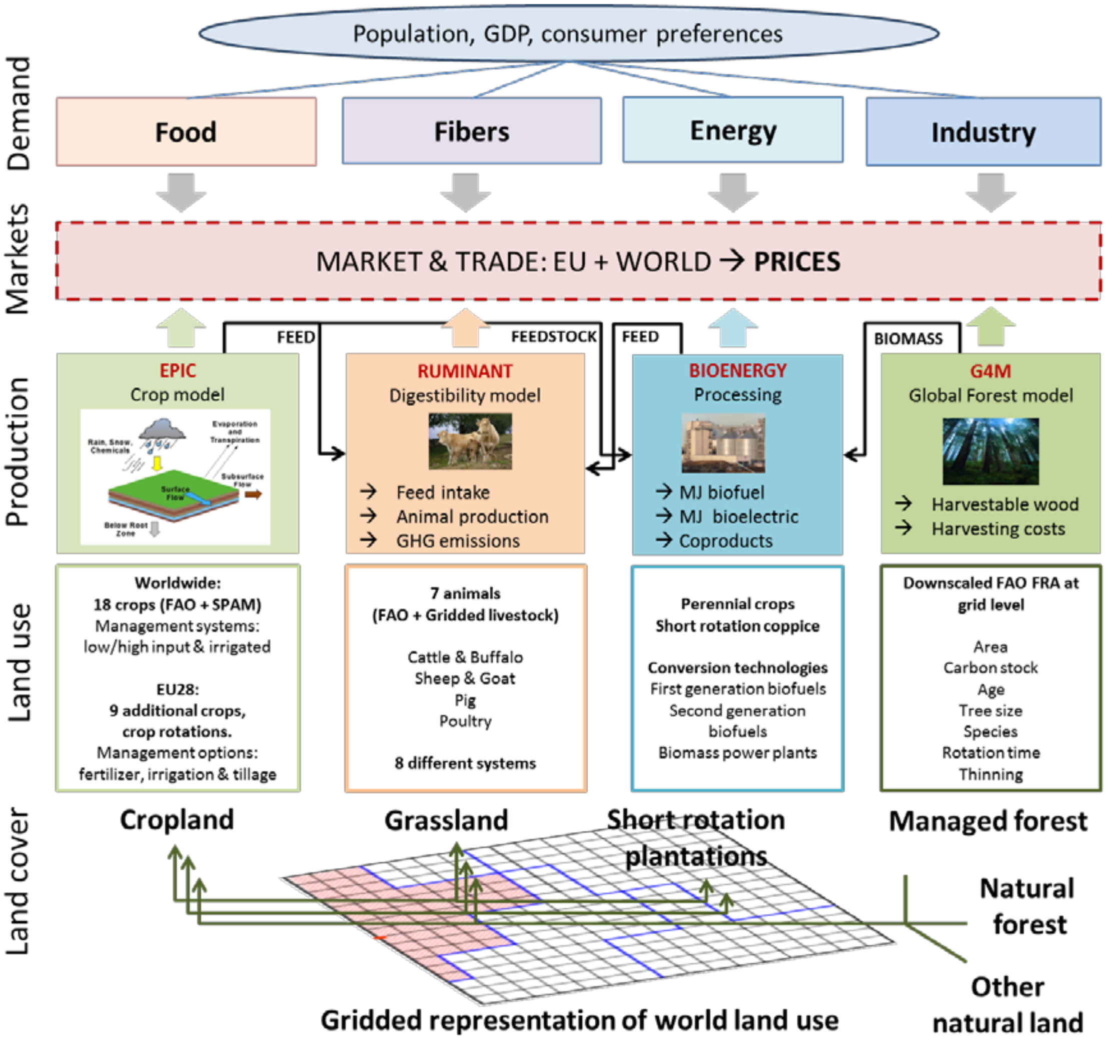


Figure 1. Overview of the GLOBIOM model structure.

3. Economic principals

Market-equilibrium model: Endogenous adjustments in market prices lead to the equality between supply and demand for each product and region.

Partial equilibrium model: GLOBIOM focuses on only few sectors of the economy, crops, livestock, forestry and bioenergy. The agricultural and forestry sectors are linked in a single model and compete for a portion of the land. To the contrary, a general equilibrium model encompasses the whole economy and the equilibrium on all markets must hold simultaneously: on the factor market, the goods and services market, the capital account, the government account and the current account (Arrow and Debreu 1954; Walras 1874). It allows taking into account that the impacts on one sector can affect other sectors through input and factor prices. The implications of a PE are that in GLOBIOM, i) there is no feedback from the sectors represented in the model to the rest of the economy, ii) there is no currency constraint on imports, iii) there is no constraint on government spending, and iv) markets for labor and capital are not represented. However, a partial equilibrium model allows a more detailed representation of the selected sectors – higher spatial and commodity resolution. PE models also usually operate with quantities while CGE models use values allowing a better representation of environmental and biophysical impacts.

Partial equilibrium and the rest of the economy

GLOBIOM is a partial equilibrium (PE) model, which means that the relevant sectors (agriculture, forestry and bioenergy) are represented in details, an important matter for representing land use change impacts of biofuel policies. Other economic sectors however are not included, or only represented through an external variable (e.g. price of fertilizer, price of fossil fuel). GLOBIOM assumes that the economy outside land using sectors evolves independently from the policies assessed in the model, following a ceteris paribus approach. The missing effects from the general equilibrium approach, when expected driving first order impacts, can be added to the simulation of the GLOBIOM model through the linkage with other models. For example, GLOBIOM has been successfully linked to the MESSAGE model representing the energy markets for the integrated assessment framework of IIASA, and to various computable general equilibrium frameworks.

Optimization model: The market equilibrium is found as a result of maximization of the sum of the consumers and of the producers' surplus under a set of constraints including the market balance constraint. These are discrete constraints which encompass equalities and inequalities. In linear programming, the feasible region is a closed convex set which means that to select the optimal solution we just need to find the set of all extreme points instead of finding the entire feasible region. Another important feature of linear programming is that any solution obtained gives not only a local optimum but also a global optimum. GLOBIOM also contains some non-linear functions but they have been linearized using stepwise approximation (McCarl and Spreen 1980). The model is solved using the linear programming solver Cplex in GAMS. In this set-up, prices are not explicit but are given by the dual of the market balance equations.

Spatial price equilibrium model: It is a specific category of partial equilibrium and linear programming model where the equilibrium solution is found by the maximization of total area under the excess demand curve in each region minus the total transportation costs of all the shipments (P.A. Samuelson 1952; Takayama and Judge 1971). They have been largely applied since the 60s to forestry and agriculture (Koo and Thompson 1982). It relies on the homogeneous good assumption where the price difference between two regions is only explained by transportation costs. If the regional prices differ by more than the interregional cost of transporting goods, then trade will occur and the price difference will be driven down to the transport cost. This allows representation of bilateral trade flows between regions but only in one direction i.e. a region cannot import from and export to the same region (see also section 2.2.). The most common alternative to represent bilateral trade flows endogenously is the Armington assumption where each industry produces only one product per country and this product is distinct from the product of the same industry from any other country (Armington 1969). It was introduced mainly in CGE models to be able to represent cross-hauling and avoid the specialization of countries in few goods when there are more goods than factors. In other PEs, the world pool market is quite common. It means that each region exports to and imports from a global market which makes it impossible to trace bilateral trade flows.

Recursive-dynamic: GLOBIOM is run for several periods of 10 years each following some recursive dynamics. Contrary to fully dynamic models, the agents of the economy do not make strategic decision taking into account future value of some parameters over several periods of time. However, the optimal decision in period t depends on some decisions that the agents have taken in the previous period t-1. For instance in GLOBIOM, at the beginning of the next period, the starting conditions for land use are updated using the solutions of the simulations from the previous period. Moreover, the reference situation is updated for each time step using exogenous drivers. For crops, livestock products and timber products, projections of population and GDP growth per region (Nakicenovic and Swart 2000) are used to set-up the initial demand level before market adjustments. Demand for bioenergy is set-up exogenously using outputs of energy models or policy targets.

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 surpluses associated to the sector represented, under a certain number of constraints. Producer surplus is determined by the difference between market prices, at regional level, and the supply curve integrating the cost of the different production factors (labor, 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, the model can be solved as a linear programming (LP) model, allowing a large quantity of data to be used for production characteristics. New technologies and transformation pathways can coexist for the different sectors or be latent technologies. 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).

Table X: List of GLOBIOM regions

	Model regions	**Countries**
Europe (EUR)	**EU Baltic**	*Estonia, Latvia, Lithuania*
	EU Central East	*Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia, Slovenia*
	EU Mid West	*Austria, Belgium, Germany, France, Luxembourg, Netherlands*
	EU North	*Denmark, Finland, Ireland, Sweden, United Kingdom*
	EU South	*Cyprus, Greece, Italy, Malta, Portugal, Spain*
	RCEU	*Albania, Bosnia and Herzegovina, Croatia, Macedonia, Serbia-Montenegro*
	ROWE	*Gibraltar, Iceland, Norway, Switzerland*
Former USSR (CIS)	**Russia**	*Russian Federation*
	Ukraine	*Ukraine*
	Former USSR	*Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Tajikistan, Turkmenistan, Uzbekistan*
Oceania (OCE)	**Australia**	*Australia*
	New Zealand	*New Zealand*
	Pacific Islands	*Fiji Islands, Kiribati, Papua New Guinea, Samoa, Solomon Islands, Tonga, Vanuatu*
	Canada	*Canada*

North America (NAM)	**United States of America**	*United States of America*
Latin America (LAM)	**Argentina**	*Argentina*
	Brazil	*Brazil*
	Mexico	*Mexico*
	RCAM	*Bahamas, Barbados, Belize, Bermuda, Costa Rica, Cuba, Dominica, Dominican Republic, El Salvador, Grenada, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, Netherland Antilles, Panama, St Lucia, St Vincent, Trinidad and Tobago*
	RSAM	*Bolivia, Chile, Colombia, Ecuador, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela*
Eastern Asia (EAS)	**China**	*China*
	Japan	*Japan*
	South Korea	*South Korea*
South-East Asia (SEA)	**Indonesia**	*Indonesia*
	Malaysia	*Malaysia*
	RSEA OPA	*Brunei Daressalaam, Singapore, Myanmar, Philippines, Thailand*
	RSEA PAC	*Cambodia, Korea DPR, Laos, Mongolia, Viet Nam*
South Asia (SAS)	**India**	*India*
	RSAS	*Afghanistan, Bangladesh, Bhutan, Maldives, Nepal, Pakistan, Sri Lanka*
Middle-East North Africa (MNA)	**Middle East**	*Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates, Yemen*
	Northern Africa	*Algeria, Egypt, Libya, Morocco, Tunisia, West Sahara*
	Turkey	*Turkey*
Sub-Saharan Africa (SSA)	**Congo Basin**	*Cameroon, Central African Republic, Congo Republic, Democratic Republic of Congo, Equatorial Guinea, Gabon*
	Eastern Africa	*Burundi, Ethiopia, Kenya, Rwanda, Tanzania, Uganda*
	South Africa	*South Africa*
	Southern Africa (Rest of)	*Angola, Botswana, Comoros, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Swaziland, Zambia, Zimbabwe*

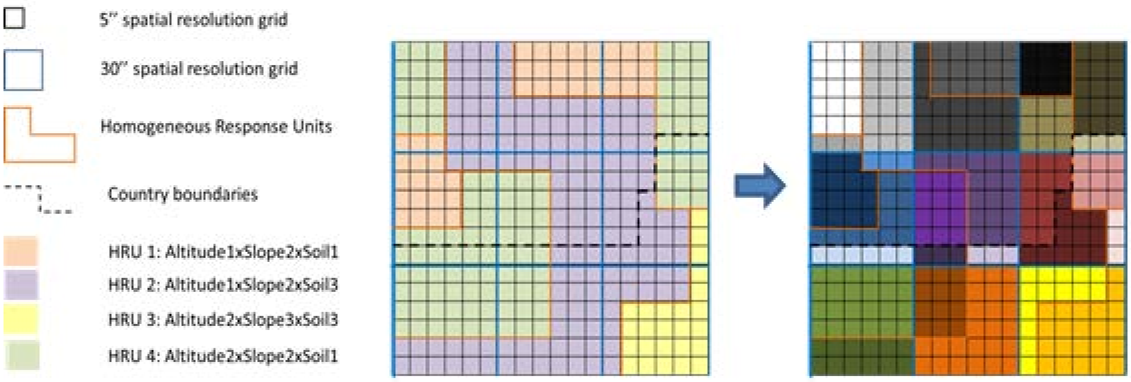
	West and Central Africa	*Benin, Burkina Faso, Cape Verde, Chad, Cote d'Ivoire, Djibouti, Eritrea, Gambia, Ghana, Guinea, Guinea Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Somalia, Sudan, Togo*

4. Land resource

4.1 Spatial resolution

The first step was to build a global database on land characteristics. Available global observation data and data coming from other sources addressing climate, topography, soil, and crop management were gathered (Skalský et al. 2008). The global scale 5'' spatial resolution grid (corresponds to ~10x10km at the equator), covering land surface was created as primary spatial reference for geographical reference of all other spatial objects. Totally, the global grid comprises 2,186,775 pixels. Then, country delineation, 30'' spatial resolution grid, and classification for homogeneity in topographical and soil attributes are used to create the simulation unit which is the ultimate spatial geographical representation that serves as basis both for biophysical model EPIC and economic model GLOBIOM (Figure 2). The 30'' spatial resolution grid (corresponds to ~50x50km at the equator) is the minimum resolution level of global climate data. Homogeneous Response Units (HRU) are defined by characteristics of the landscape which are stable over time and hardly adjustable by farmers in order to simplify the biophysical computations. In particular, 5 altitude classes, 7 slope classes and 5 soil classes have been retained to represent these stable landscape characteristics. This results in 150 unique combinations of altitude, slope and soil classes, globally. There are 212 707 simulation units globally which are polygons with a size varying between 5'' and 30''spatial resolution grid.

Figure X. Spatial elements used for the delineation of homogeneous land characteristics and definition of Simulation Units



Land cover and land use are crucial input data in the modeling framework. The land cover corresponds to the vegetation type while the land use corresponds to a specific kind of production. The land cover map is taken from GLC2000 which attributes to each 1x1km resolution pixel a certain land cover by using remote-sensing technique. The primary source of data for specific land uses comes from national census. Crop distribution maps computed at IFPRI are used for crops and crop shares (You and Wood 2006).

Inconsistencies are observed between the land cover map and the agricultural census data which can be due to measurement errors, different treatment of idle land, double-cropping, etc. It has been decided that the crop distribution maps determine the final cropland area and other land cover classes were adjusted if necessary (Skalský et al. 2008). Grassland is even more problematic since it is hard to differentiate between grazing and natural herbaceous land. It has been decided to merge grassland and other natural land and extract grassland as the area which is required to feed ruminants based on the livestock distribution map (Kruska et al. 2003; Sere and Steinfeld 1996). There is currently no global map of managed forest area and short rotation tree plantations area. Their initial allocation is thus taken respectively from the forest land cover and the other natural land class through the optimization process.

5. Crop production

GLOBIOM represents 18 crops globally and 27 crops for the European Union. The full list of crops covered is detailed in Appendix A. Harvested areas are based on FAOSTAT statistics but spatially allocated using data from the Spatial Production Allocation Model (SPAM).[2] In the case of the EU, crops are allocated across NUTS2 regions using data from EUROSTAT.

Cultivated area currently represent in GLOBIOM around 84% of the total harvested area in the world. A small share of products cultivated on arable land are not explicitly covered in the model due to the whole diversity of crops cultivated on the planet. Harvested area for the non-covered crops is kept constant.[3] 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. This means that “not harvested” arable land is also explicitly represented in GLOBIOM. The standard assumption for model projections is to keep this area constant but some alternative assumptions can be considered for particular policy scenario designs (for instance, decrease in fallow land). However, the data on abandoned land in Europe have been reviewed and improved in some cases, and this land use type explicitly represented in the baseline of the model, for newly created abandoned land (see Section C.3.5 in Appendix for more details).

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. They are however rescaled by a same factor to fit FAOSTAT average yield at the regional level, in order to catch the other management parameters not supplied to EPIC, or other causes of yield mismatch. This approach also allows an endogenous modelling of marginal yield for expansion of crops.

Different crop management systems are distinguished. At the world level, four technologies can be used (subsistence, low input rainfed, high input rainfed and high input irrigated). In Europe, EPIC has additionally been run for a large combination of different rotation systems for all NUTS2 regions.[4] This

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

[3] 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.

[4] 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.

therefore allowed a more precise simulation of the yield achieved through optimization 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, producer price for these systems are calibrated on FAOSTAT data.

Additionally to production of grains or fibers, GLOBIOM also represents the production of straw for some of the major crops (barley, wheat) for the European Union. Only a part of the residues produced is considered available because of the role of residues for soil fertilization. The residues removed are used for the livestock sector and the industrial and energy uses. Several rates of residue removal are now considered and the effect of changing this rate on yield and carbon sequestration is estimated using the EPIC model (see Appendix D.1).

Economic market balances in GLOBIOM are solved at the level of 37 economic regions. But the supply side of the model optimizes the localization of crop cultivation at a much finer resolution in the 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.[5] 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.

5.1 Yield responses and intensification

GLOBIOM has an assumption on technological change that reflect the increase of yield over time independently from market mechanisms, due to progress in breeding, introduction of new varieties, technology diffusion, etc. Yield responses to prices come in addition to the technical change trend, following the principles below.

The linear approach of GLOBIOM allows crops and livestock to be represented with different alternative management systems with their own productivity and cost (see Box 1). 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;[6]
- investments in irrigated systems. This development is controlled through a simplified representation of the regional water supply potential;

For more information see http://epp.eurostat.ec.europa.eu/portal/page/portal/nuts_nomenclature/introduction

[5] 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 constraint.

[6] 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.

- change in allocation across spatial units with different suitability (climate and soil conditions).

Box 1. Production functions in GLOBIOM

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 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.

6. Livestock production

6.1 Livestock population

The principal variable characterizing the livestock production in GLOBIOM is the number of animals by species, production system and production type in each Simulation Unit. We differentiate four species aggregates: cattle and buffaloes (bovines), sheep and goats (small ruminants), pigs, and poultry. Eight production systems are specified for ruminants: grazing systems in arid (LGA), humid (LGH) and temperate/highland areas (LGT); mixed systems in arid (MXA), humid (MXH) and temperate/highland areas (MXT); urban systems (URB); and other systems (OTH). Mixed systems are an aggregate of the more detailed original Seré and Steinfeld's classes (11) – mixed rainfed and mixed irrigated. Two production systems are specified for monogastrics: smallholders (SMH) and industrial systems (IND). In terms of production type, dairy and meat herds are modeled separately for ruminants: dairy herd includes adult females and replacement heifers, whose diets are distinguished. Poultry in smallholder systems is considered as mixed producer of meat and eggs, and poultry in industrial systems is split into laying hens and broilers, with differentiated diet regimes. Overall livestock numbers at the country level are, where possible while respecting minimum herd dynamics rules, harmonized with FAOSTAT.

The spatial distribution of ruminants and their allocation between production systems follows an updated version of Wint and Robinson (12). Since we do not have better information, we assume that the share of dairy and meat herds within one region is the same in all production systems. The share is obtained from the FAO country level data about milk producing animals and total herd size. Monogastrics are not treated in a spatially explicit way since no reliable maps are currently available, and because monogastrics are not linked in the model to specific spatial features, like grasslands. The split between smallholder and industrial systems follows Herrero et al. (13).

6.2 Livestock products

Each livestock category is characterized by product yield, feed requirements, and a set of direct GHG emission coefficients. On the output side, seven products are defined: bovine meat and milk, small ruminant meat and milk, pig meat, poultry meat, and eggs. For each region, production type and production system, individual productivities are determined.

Bovine and small ruminant productivities are estimated through the RUMINANT model (13, 14), in a three steps process which consists of first, specifying a plausible feed ration; second, calculating in RUMINANT the corresponding yield; and finally confronting at the region level with FAOSTAT (Supply Utilization Accounts) data on production. These three steps were repeated in a loop until a match with the statistical data was obtained. Monogastrics productivities were disaggregated from FAOSTAT based on assumptions about potential productivities and the relative differences in productivities between smallholder and industrial systems. The full detail of this procedure is provided in Herrero et al. (13).

Final livestock products are expressed in primary commodity equivalents. Each product is considered as a differentiated good with a specific market except for bovine and small ruminant milk that are merged in a single milk market. The two milk types are therefore treated as perfect substitutes.

6.3 Livestock feed

As mentioned above feed requirements for ruminants are computed simultaneously with the yields (13). Specific diets are defined for the adult dairy females, and for the other animals. The feed requirements are first calculated at the level of four aggregates – grains (concentrates), stover, grass, and other. When estimating the feed-yield couples, the RUMINANT model takes into account different qualities of these aggregates across regions and systems. Feed requirements for monogastrics are at this level determined through literature review presented in Herrero et al. (13). In general, it is assumed that in industrial systems pigs and poultry consume 10 and 12 kg dry matter of concentrates per TLU and day, respectively, and concentrates are the only feed sources. Smallholder animals get only one quarter of the amount of grains fed in industrial systems, the rest is supposed to come from other sources, like household waste, not explicitly represented in GLOBIOM.

The aggregate GRAINS input group is harmonized with feed quantities as reported at the country level in Commodity Balances of FAOSTAT. The harmonization proceeds in two steps, where first, GRAINS in the feed rations are adjusted so that total feed requirements at the country level match with total feed quantity in Commodity Balances, and second, “Grains” is disaggregated into 11 feed groups: Barley, Corn, Pulses, Rice, Sorghum & Millet, Soybeans, Wheat, Cereal Other, Oilseed Other, Crops Other, Animal Products. The adjustment of total GRAINS quantities is first done through shifts between the GRAINS and OTHER categories in ruminant systems. Hence, if total GRAINS are lower than the statistics, a part or total feed from the OTHER category is moved to GRAINS. If this is not enough, all GRAINS requirements of ruminants are shifted up in the same proportions. If total GRAINS are higher than the statistics, first we reallocate a part of them to the OTHER category. If this is not enough, we keep our values, which then results in higher GRAINS demand than reported in FAOSTAT. This inconsistency is overcome in GLOBIOM, by creating a “reserve” of the missing GRAINS. This reserve is in simulations kept constant, thus it enables to reproduce the base year activity levels mostly consistent with FAOSTAT, but requires that all additional GRAINS demand arising over the simulation horizon is satisfied from real production. The decomposition of GRAINS into the 11 subcategories has to follow predefined minima and maxima of the shares of feedstuffs in a ration differentiated by species and region. At the same time, the shares of the feedstuffs corresponding to country level statistics need to be respected. This problem is solved as minimization of the square deviations from the prescribed minimum and maximum limits. In GLOBIOM, the balance between demand and supply of the crop products entering the GRAINS subcategories needs to be satisfied at regional level. Substitution ratios are defined for the byproducts of biofuel industry so that they can also enter the feed supply.

STOVER is supposed less mobile than GRAINS, therefore we force stover demand in GLOBIOM to match supply at grid level. The demand is mostly far below the stover availability. In the cells where this is not the case, the same system of reserve is implemented as for the grains. No adjustments are done to the feed rations as such.

There are unfortunately no worldwide statistics available on either consumption or production of grass. Hence we had to rely for grass requirements entirely on the values calculated with RUMINANT, and use them to estimate the grassland extent and productivity. This procedure is described in the next section.

Finally, the feed aggregate OTHER is represented in a simplified way, where it is assumed that it is satisfied entirely from a reserve in the base year, and all additional demand needs to be satisfied by forage production on grasslands.

6.4 Grazing forage availability

The demand and supply of grass need to match at the level of Simulation Unit in GLOBIOM. But reliable information about grass forage supply is not available even at the country level. The forage supply is a product of the utilized grassland area and of forage productivity. However, at global scale, Ramankutty et al. (15) estimated that the extent of pastures spans in the 90% confidence interval between 2.36 and 3.00 billion hectares. The FAOSTAT estimate of 3.44 billion hectares itself falls outside of this interval which illustrates the level of uncertainty in the grassland extent. Similarly, with respect to forage productivity, different grassland production models perform better for different forage production systems and all are confronted with considerable uncertainty due to limited information about vegetation types, management practices, etc. (16). These limitations preclude us from relying on any single source of information or output from a single model. Therefore we considered three different grass productivity sources: CENTURY on native grasslands, CENTURY on native and managed grasslands, and EPIC on managed grasslands.

We developed a systematic process for selecting the suitable productivity source for each of GLOBIOM's 30 regions. This process allowed us to rely on sound productivity estimates that are consistent with other GLOBIOM datasets like spatial livestock distribution and feed requirements. Within this selection process, the area of utilized grasslands corresponding to the base year 2000 was determined simultaneously with the suitable forage productivity layer. We used two selection criteria: livestock requirements for forage and area of permanent meadows and pastures from FAOSTAT. The selection process was based on simultaneous minimization of *i*) the difference between livestock demand for forage and the model-estimates of forage supply and *ii*) the difference between the utilized grassland area and FAOSTAT statistics on permanent meadows and pastures. Regional differentiation in grassland management intensity – ranging from dry grasslands with minimal inputs to mesic, planted pastures that are intensively managed with large external inputs – further informed our model selection by enabling us to constrain the number of models for dry grasslands.

To calculate the utilized grassland area, we have first defined the potential grassland area as the area belonging to one of the following GLC2000 land cover classes: 13 (Herbaceous Cover, closed-open), 16-18 (Cultivated and managed areas, Mosaic: Cropland / Tree Cover / Other natural vegetation, Mosaic: Cropland / Shrub and/or grass cover), excluding area identified as cropland according to the IFPRI crop distribution map (17), and 11, 12, 14 (Shrub Cover, closed-open, evergreen, Shrub Cover, closed-open, deciduous, Sparse herbaceous or sparse shrub cover). In each Simulation Unit the utilized area was calculated by dividing total forage requirements by forage productivity. In Simulation Units where utilized area was smaller than the potential grassland area, the difference would be allocated to either “Other Natural Land” or “Other Agricultural Land” depending on the underlying GLC2000 class. In Simulation Units where the grassland area necessary to produce the forage required in the base year was larger than the potential grassland area, a “reserve” was created to ensure base year feasibility, but all the additional grass demand arising through future livestock production increases needed to be satisfied from grasslands.

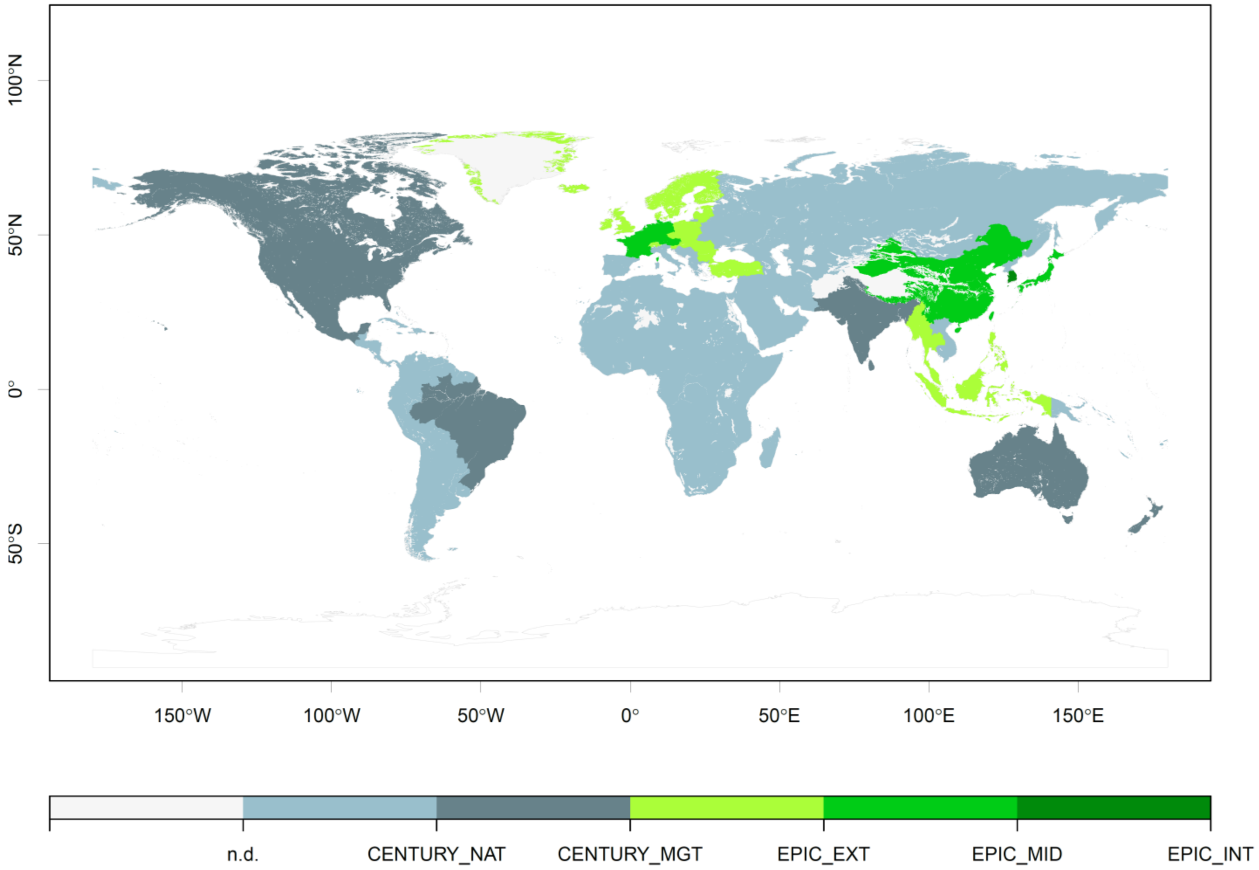

Fig. 2. Data sources used to parameterize forage availability in different world regions. CENTURY_NAT – CENTURY model for native grasslands; CENTURY_MGT – CENTURY model for productive grasslands; EPIC_EXT – EPIC model for grasslands under extensive management; EPIC_MID – EPIC model for grasslands under semi-intensive management; EPIC_INT – EPIC model for grasslands under intensive management.

Forage productivity was estimated using the CENTURY (18, 19) and EPIC (6) models. The CENTURY model was run globally at the 0.5 degree resolution to estimate native forage and browse and planted pastures productivity. It was initiated with 2000 year spin-ups using mean monthly climate from the Climate Research Unit (CRU) of the University of East Anglia with native vegetation for each grid cell, except cells dominated by rock, ice, and water, which were excluded. Information about native vegetation was derived from the Potsdam intermodal comparison study (20). Plant community and land management (grazing) was based on growing-season grazing and 50 per cent forage removal. Areas under native vegetation that were grazed were identified using the map of native biomes subject to grazing and subtracting estimated crop area within those biomes in 2006 (15). We assumed 50 per cent grazing efficiency for grass, and 25 per cent for browse for native grasslands. These CENTURY-based estimates of native grassland forage production (CENTURY_NAT) were used for most regions with low-productivity grasslands (Fig. 2).

Both the CENTURY and EPIC models were used to estimate forage production in mesic, more productive regions. For the CENTURY model, forage yield was simulated using a highly-productive, warm-season grass parameterization. Production was modeled in all cells and applied to areas of planted pasture, which were estimated based on biomes that were not native rangelands, but were under pasture in 2006 according to Ramankutty (15). Pastures were replanted in the late winter every ten years, with grazing starting in the second year. Observed monthly precipitation and minimum and maximum temperatures between 1901 and 2006 were from the CRU Time Series data, CRU TS30 (21) Soils data were derived from the FAO Soil Map of the World, as modified by (22). CENTURY model output for productive pastures (CENTURY_MGT) were the best-match for area/forage demand in much of the world with a mixture of mesic and drier pastures.

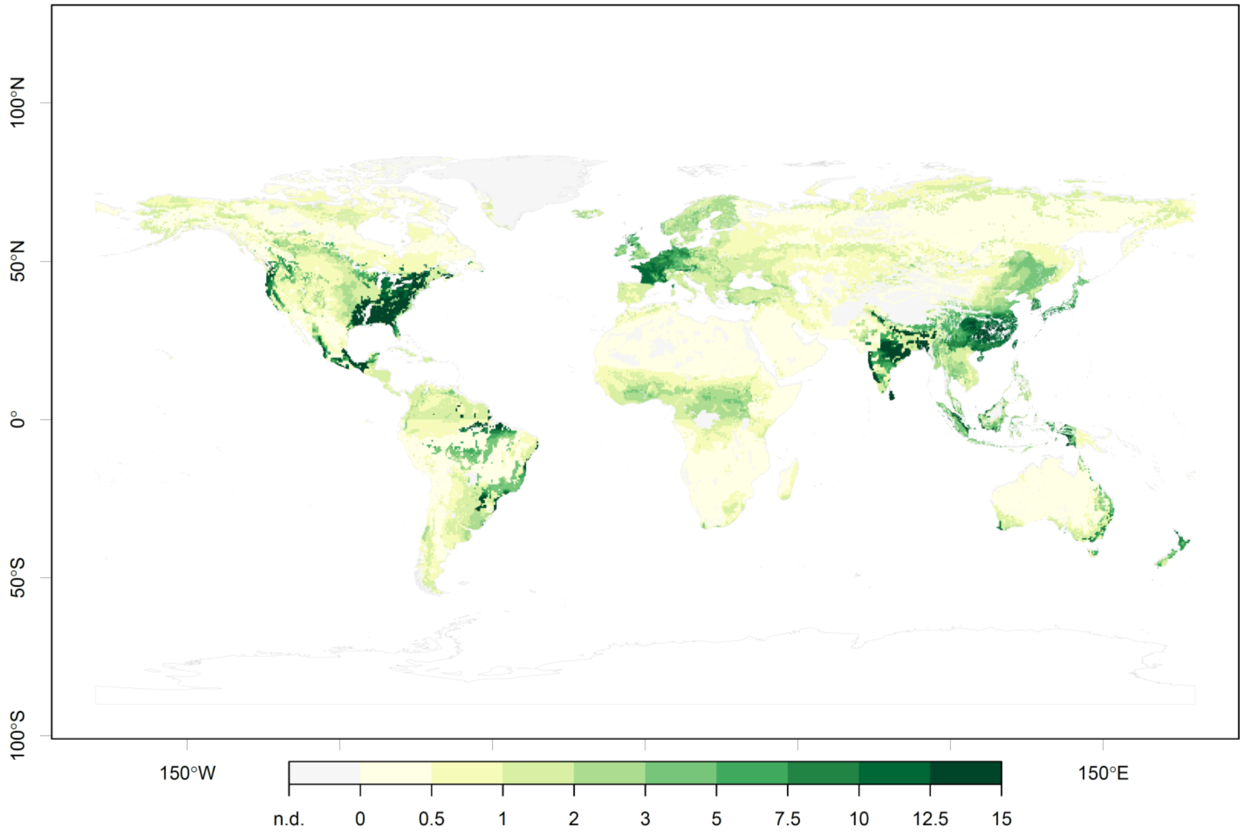

Fig 3. Forage available for livestock in tonnes of dry matter per hectare as the result of combination of outputs from the CENTURY and EPIC models.

The EPIC model was the best fit for much of Europe and Eastern Asia, where most of the forage production is in intensively-managed grasslands. The EPIC simulations used the same soil and climatic drivers as the CENTURY runs plus topography data (high-resolution global Shuttle Radar Topography Mission digital elevation model (SRTM) and the Global 30 Arc Second Elevation Data (GTOPO30). Warm and cold seasonal grasses were simulated in EPIC, and the simulations included a range of management intensities represented by different levels of nitrogen fertilizer inputs and off-take rates. The most intensive management minimizing nitrogen stress and applying 80% off-take rates (EPIC_INT) was found to be the best match for South Korea. Highly fertilized grasslands but with an off-take rate of 50% only were identified in Western Europe, China and Japan (EPIC_MID), and finally extensive management, only partially satisfying the nitrogen requirements and considering 20% off-take rates corresponded best to Central and Northern Europe and South-East Asia (EPIC_EXT). The resulting hybrid forage availability map is represented in Fig. 3.

6.5 Livestock dynamics

In general, the number of animals of a given species and production type in a particular production system and *Supply Unit* is an endogenous variable. This means that it will decrease or increase in relation to changes in demand and the relative profitability with respect to competing activities.

Herd dynamics constraints need however to be respected. First, dairy herds are constituted of adult females and followers, and expansion therefore occurs in predefined proportions in the two groups. Moreover, for regions where the specialized meat herds are insignificant (no suckler cows), expansion of meat animals (surplus heifers and males) is also assumed proportional in size to the dairy herd. The ruminants in urban systems are not allowed to expand because this category is not well known and because it is fairly constrained by available space in growing cities. Finally, we do not consider decrease of animals per system and production type higher than 15 per cent per 10 years period, and no increase by more than 100 per cent on the same period. At the level of individual systems, the decrease can however be as deep as 50 per cent per system on a single period.

For monogastrics, we make the assumption that all additional supply will come from industrial systems and hence the number of animals in other systems is kept constant (23).

7. Food demand

Food demand is in GLOBIOM endogenous and depends on population, gross domestic product (GDP) and own produt price. Population and GDP are exogenous variables while prices are endogenous. The simple demand system is presented in Eq. 1. First, for each product *i* in region *r* and period *t*, the *prior* demand quantity $\bar{Q}$ is calculated as a function of population POP, GDP per capita GDP^{cap} adjusted by the income elasticity ε^{GDP}, and the base year consumption level as reported in the Food Balance Sheets of FAOSTAT. If the *prior* demand quantity could be satisfied at the base year price $\bar{P}$, this would be also the optimal demand quantity Q. However, usually the optimal quantity will be different from the *prior* quantity, and will depend on the optimal price P and the price elasticity ε^{price}, the latter calculated from USDA (9), updated in (10) for the base year 2000. Because food demand in developed countries is more inelastic than in developing ones, the value of this elasticity is assumed to decrease with the level of GDP per capita. The rule we apply is that the price elasticity of developing countries converges to the price elasticity of the USA in 2000 at the same pace as their GDP per capita reach the USA GDP per capita value of 2000.

This allows us to capture the effect of change in relative prices on food consumption taking into account heterogeneity of responses across regions, products and over time.

$$\frac{Q_{i,r,t}}{\bar{Q}_{i,r,t}} = \left(\frac{P_{i,r,t}}{\bar{P}_{i,r,2000}}\right)^{\varepsilon_{i,r,t}^{price}} \qquad \text{where} \qquad \bar{Q}_{i,r,t} = \frac{POP_{r,t}}{POP_{r,2000}} \times \left(\frac{GDP_{r,t}^{cap}}{GDP_{r,2000}^{cap}}\right)^{\varepsilon_{i,r,t}^{GDP}} \times \bar{Q}_{i,r,2000} \qquad \text{(Eq. 1)}$$

Our demand function has the virtue of being easy to linearize which allows us to solve GLOBIOM as a linear program. This is currently necessary because of the size of the model and the current performance of non-linear solvers. However, this demand function has although some limitations which need to be kept in mind when considering the results obtained with respect to climate change mitigation and food availability. One of them is that we do not consider direct substitution effects on the consumer side which could be captured through cross price demand elasticities. Such a demand representation could lead to increased consumption of some products like legumes or cereals when prices of GHG intensive products like rice or beef would go up as a consequence of a carbon price targeting emissions for the agricultural sector. Neglecting the direct substitution effects may lead to an overestimation of the negative impact of such mitigation policies on total food consumption. However, the effect on emissions would be only of second order, because consumption would increase for commodities the least affected by the carbon price, and hence the least emission intensive. Although we do not represent the direct substitution effects on the demand side, substitution can still occur due to changes in prices on the supply side and can in some cases lead to a partial compensation of the decreased demand for commodities affected the most by a mitigation policy. This phenomenon can be observed in our results for mitigation policies targeting the livestock sector only (Fig. 4. In the main text).

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.

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 implies that if the price of the product increases by 10%, the consumption of this product then decreases by 1% (10x-0.1). The values of these elasticities in GLOBIOM are sourced from the

USDA demand elasticity database.[7] 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. Because GLOBIOM accounts for food commodity through the commodity balance accounts from FAO, the model can then report impact of these price changes as variation in supply of kcal per capita, but also proteins or other macronutrients, as a result of a specific policy.

Although GLOBIOM does not represent cross-price effect for its usual food products, one exception is the case of vegetable oil for which a specific substitution mechanism was introduced. Indeed, vegetable markets are closely connected, as illustrated by the strong correlation between the different oil prices. Introducing some substitution possibilities between vegetable oil on the supply side is therefore important, while keeping in mind the restrictions to such substitution related to the different properties of these oils, the specific needs of industries, as well as the preferences of consumers. This food substitution possibility is even more important as feed does not offer substitution options for the vegetation oils, to the difference of cereals for instance. A vegetable oil food aggregate was therefore introduced, into which the shares of the different oil can change, with some imperfect substitution pattern. For this purpose, the objective function of GLOBIOM was modified to include some non-linear costs associated to the change in composition of the vegetable oil aggregate.[8]

8. Forestry

8.1 Available supply of wood biomass and types of wood

Total forest area in GLOBIOM is calibrated according to FAO Global Forest Resources Assessments (FRA) and divided into used and unused forest utilizing a downscaling routine based on human activity impact on the forest areas (Kindermann et al., 2008a). The available woody biomass resources are provided by the forest model G4M ((Kindermann et al., 2008b) for each forest area unit, and are presented by mean annual increments. Mean annual increments for forests are then in GLOBIOM divided into commercial roundwood, non-commercial roundwood and harvest losses, thereby covering the main sources of woody biomass supply. The amount of harvest losses is based on G4M estimates while the share of non-commercial species is based on FRA (2010) data on commercial and non-commercial growing stocks. In addition to stemwood, available woody biomass resources also include branches and stumps; however, environmental and sustainability considerations constraint their availability and use for energy purposes.

Woody biomass production costs in GLOBIOM cover both harvest and transportation costs. Harvest costs for forests are based on the G4M model by the use of spatially explicit constant unit costs that include planting, logging, and chipping in the case of logging residues. Harvest costs also vary depending on geographical considerations such as the region and the steepness of terrain. Transport costs are on the

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

[8] The patterns of change in the oilseed market are complex as the following points are observed simultaneously: i) food consumption per capita of vegetable oil has been relatively stable in Europe for rapeseed over the past decade; ii) at the same time, significant substitution in the EU has been observed between vegetables oils through imports and within the industrial uses market; iii) decrease in EU food consumption of rapeseed has remained limited compared to total increase in supply; iv) palm oil imports to the EU have expanded over the period 2000-2012, parts of these driven by a direct use by the industrial sector, in particular biofuels, but also for the food sector. For more details on the analysis of vegetable oil substitution patterns in the EU, see Valin et al. (2015).

other hand not spatially explicit but are modeled by using regional level constant elasticity transport cost functions, which approximate the short run availability of woody biomass in each region. These transport costs functions are then shifted over time in response to the changes in the harvested volumes and related investments in infrastructures.

8.2 Woody biomass demand and forest industry technologies

The forest sector is modeled to have seven final products (chemical pulp, mechanical pulp, sawnwood, plywood, fiberboard, other industrial roundwood, and household fuelwood). Demand for the various final products is modeled using regional level constant elasticity demand functions. Forest industrial products (chemical pulp, mechanical pulp, sawnwood, plywood and fiberboard) are produced by Leontief production technologies, which input-output coefficients are based on the engineering literature (e.g. FAO 2010). By-products of these technologies (bark, black liquor, sawdust, and sawchips) can be used for energy production or as raw material for pulp and fiberboard. Production capacities for the base year 2000 of forest industry final products are based on production quantities from FAOSTAT. After the base year the capacities evolve according to investment dynamics, which depend on depreciation rate and investment costs. This implies that further investments can be done to increase production capacities or allow industries to reduce their production capacities or be closed. For further details of the modelling approach of the depreciation rates, capital operating costs, and investment costs as applies, we refer to Lauri et al. (2014).

9. Energy plantations

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).[9]

Suitable areas for this sector relies on a geographic information system (GIS) analysis looking at temperature, precipitation, altitude, and population density. The productivity of plantations is based on estimates from the Potsdam Net Primary Productivity Model Inter-comparison, and production costs are calculated based on literature sources.[10] 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.

10. International trade

GLOBIOM represent international markets and their various products traded between regions, relying on international trade statistics for trade and tariffs.[11]

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[9] See Weih (2004).

[10] See Havlik et al (2011) for full details.

[12] 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.

Trade in GLOBIOM follows a representation where products are all expressed in physical units (tonnes) across localization and are exchanged as homogeneous 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 trade is provided by the same region. In this framework, all substitutions of traded goods are performed on a quantity basis. Some patterns of trade creation are also possible, i.e. two countries can start to trade in the future even if they were not trading partners before.

As a spatial equilibrium model, GLOBIOM endogenously computes bilateral trade flows through the minimization of total trading costs. In this framework, trade patterns are determined by initial trade flows, the evolution of relative costs of production between regions and the trading costs. It relies on the homogeneous good assumption i.e. when two goods within the same industry are perfect substitutes. It leads to one unique price for one good on the market and the absence of intra-industry trade between different regions.

10.1 Data

Net trade - It is computed as the difference between domestic production and consumption based on FAO food commodity balance over 1998-2002. It is computed at the regional level, so it excludes intra-regional trade flows. It is expressed in thousands tons for crops, livestock products, and pulp wood and thousands cubic meters for other wood products. It is based on FAO data but after adjustments to ensure consistency in the model between production, and consumption for different uses i.e. food, livestock feeding and bioenergy.

Bilateral trade flows - COMTRADE provides annual trade flow information covering imports, exports, and re-exports expressed in quantity and in value (thousands USD) for all countries based on international nomenclatures (1962 for SITC and since 1988 for HS). It is developed at the United Nations Commodity Trade Statistics Database Statistics Division. Usually, country A reported imports from country B would match with country B reported exports to country A but this is not the case in practice due to different recording system for imports (CIF) and exports (FOB), data quality, error in classification of the good or in the identification of trading partner i.e. confidentiality issues. The first version of BACI database is used, which provides reconciled trade flows at the HS6 level from 1995 to 2004 (Gaulier and Zignago 2008). Data do not include trade flows lower than 1000 USD and all quantities have been converted to metric tons. It should be noticed that there are important inconsistencies between FAO and BACI data for 2000. For instance, BACI and FAO do not always agree if the region is a net exporter or a net importer in the base year. This raises some challenges for the trade calibration procedure.

Trade policies - Agriculture remains one of the last sectors where policy barriers are still high, both in developed and in developing countries and yet no agreement could have been found to conclude the Doha negotiations Round started in 2001. Trade policy instruments include tariffs and non-tariff barriers (NTBs) and could vary largely across one region's trading partners due to numerous regional and preferential agreements. The focus is put on tariffs. Non-tariff barriers such as standards, sanitary and phyto-sanitary conditions are widely used by developed countries in food and wood products but they are quite challenging to model (Anderson and van Wincoop 2004). Tariffs can be expressed as specific duties which are fixed amounts paid per physical unit, ad valorem duties which are, a percentage of the import price, or specific tariffs which are a mix of specific and ad valorem duties. In order to compare in a consistent way, the levels of protection across countries and industries, the International Trade Center (ITC) and the CEPII created the MacMap database which includes exhaustive information on the level of applied trade barriers and on ad valorem equivalent measures of border protection across the world (Bouët et al. 2008). Moreover, in order to get comparable information on level of protection applied by all the countries, ad valorem equivalents for specific and mixed duties are available in the MacMap database. The 2001 MacMap version is used in the GLOBIOM analyses.

International freight costs - Transportation costs have significant impacts on the structure of economic activities as well as on international trade. It is not uncommon for transport costs to account for 20% of the total cost of a product. But there is still little concrete evidence as to the nature, size, and shape of the barriers especially at product level. Maritime transport remains the backbone of international trade with over 80% of world merchandise trade by volume being carried by sea. Transport costs tend to be higher in bulky agricultural products (Anderson and van Wincoop 2004; Berthelon and Freund 2008). Moreover, imbalances between imports and exports have impacts on transport costs as it implies the repositioning of empty containers. For example, it costs about USD 400 to ship a container to the United States from China, about USD 800 to ship from India, and USD 1,300 to ship from Sierra Leone (World Development Report 2009).

There are three main sources of data for transport costs. The first and the most direct is industry or shipping firm information, but it has not been feasible to collect this kind of data because of the data limitations and the very large size of the resulting datasets. The second possibility is to use national customs data in the case where they provide at least the valuation of imports at FOB and CIF bases. In fact they are only provided in a few countries i.e. U.S., New Zealand, and some Latin American countries (Hummels 2001). In COMTRADE database, exports are reported FOB and imports are reported CIF, so in principle, transportation costs could be computed as the difference between CIF values and FOB values. In reality, it is not recommended because of measurement problems. Aggregate bilateral CIF/FOB ratios are produced by the IMF based on the COMTRADE database and supplemented in some cases with national data sources, but a high proportion of observations are imputed. In GLOBIOM, the results of Hummels' (2001) econometric estimates are used where transport cost expressed as the ad valorem freight cost is a log linear function of distance (DIST), weight to value ratio (WGT/V) and a residual term (ε):

$$(8)\quad \ln f_{i,j,k} = \alpha_i + \beta \ln DIST_{i,j} + \delta \ln \frac{WGT_{i,j,k}}{V_{i,j,k}} + \varepsilon_{i,j,k}$$

The resulting coefficient for log of the distance to exporter in km is 0.26 and the coefficient before the log of the weight over value variable is 0.24. Distance data between each capital is taken from CEPII.

Per unit costs - Even if per unit costs or ad valorem trade costs do not have the same effects on the price transmission from international to domestic market, the most common approach to implement policy barriers in the existing models is to compute ad valorem equivalents tariffs. To implement trade costs in GLOBIOM, the same simplification is used but instead of computing ad valorem equivalents we compute 'specific duties equivalent'.

10.2 Trade calibration method

Despite the long history of transport models, calibration of these models has received little attention (Jansson and Heckelei 2009). Many contributions to the transportation costs minimization problems perform no balancing of the baseline and start at a disequilibrium situation, or if they do, they do not use data on prices and trade flows. We use the calibration method proposed by Jansson and Heckelei based on bi-level programming for estimating parameters of transport model. A bi-level program is an optimization problem – the outer problem - which uses the solution of another optimization problem – the inner problem - as its domain. In this case the outer problem is the minimization of the weighted squared deviations from observed values and the inner problem is the minimization of the transportation costs. In their initial work, their objective is to minimize the deviations between estimated trade costs and prices with the observed ones. This bi-level optimization problem is extended in differentiating tariffs and transportation costs and in using also bilateral trade flows. Moreover, asymmetric transportation costs are considered i.e. the transportation cost from region i to region j is not equivalent to the transportation cost from j to i.

For each product, the first step or inner problem is the minimization of the sum of the trade costs (9) under the market equilibrium constraint (10). This is solved with the linear programming solver cplex.

$$(9) \quad \underset{x}{Min} \sum_{ij} (co_{ij} + t_{ij}).x_{ij}$$

$$(10) \quad e_i + \sum_{j} (x_{ij} - x_{ji}) = 0$$

$$(11) \quad x_{ij} \geq 0$$

Parameters are coij the bilateral transportation costs, tij the specific equivalent tariffs and ei the net trade. The variable xij is the traded quantity between region i and region j. Resulting trade flows and prices (dual on the market equilibrium constraint) are equivalent to those obtained after the maximization of economic surplus in GLOBIOM without the trade calibration.

The objective of the second step is to minimize the sum of the squared deviations of c the transportation costs, p the prices and x the bilateral trade flows to their observed value co, po, and xo (10). It relies on the assumption that transportation costs, prices and bilateral trade flows are measured with error while tariffs and net trade are more reliable. The weights associated with each component wc, wp and wx, are chosen accordingly to the confidence we can have in the data. For instance transportation costs are the less reliable data so a smaller weight has been chosen. The constraints of this minimization problem are the market equilibrium equation (10) and the price chain constraint (13) which ensures that the first order condition of the inner problem is satisfied i.e. when trade is observed the price in the importing region must be equal to the price in the exporting region plus the transportation cost plus the tariff. We use the duals of the market clearing condition from the inner problem solution to set-up starting price values p.

$$(12) \qquad z = w_c \sum_{ij} \left(c_{ij} - co_{ij}\right)^2 + w_p \sum_i \left(p_i - po_i\right)^2 + w_x \sum_{ij} \left(x_{ij} - xo_{ij}\right)^2$$

$$(13) \qquad c_{ij} + t_{ij} - p_j + p_i = 0$$

As it is noticed by Jansson and Heckelei (2009), already with a modest number of regions, the large number of possible bilateral trade flows results in an equally large number of zero arbitrage conditions which render the selection of a basis for fitting the base data a difficult problem. The algorithms based on a smooth approximation (Ferris, Dirkse, and Meeraus 2002) were performing reasonable compared to the other ones and the penalty function method that has been implemented here obtained on average the smallest sum of squared errors. This consists in replacing the zero condition in (13) by a positive variable π as shown in the equation (14). Then, we add a complementary slackness condition (15) where the penalty depends on the value of the parameter µ and the value of the trade flow times the corresponding price chain residual πij computed in (14). If trade occurs (xij > 0) πij has to be null and if trade does not occur it can take any value. The penalty variable is added to the objective function z (16) and the value of µ is progressively increased to force πij to decrease to zero.

$$(14) \quad c_{ij} + t_{ij} - p_j + p_i = \pi_{ij}$$

$$(15) \quad c_{ij} + t_{ij} - p_j + p_i = \pi_{ij}$$

$$(16) \quad c_{ij} + t_{ij} - p_j + p_i = \pi_{ij}$$

$$(17) \quad \pi_{ij} \geq 0$$

In order to get closer estimated trade flows to the observed ones and to avoid large re-exports phenomenon, we also add the constraint to condition estimated trade flows only when there was one trade flow observed (18). However, this constraint has been relaxed when there are no imports recorded in BACI while the region is a net importer according to FAO data or when no exports are recorded in BACI and the region is a net exporter in FAO to avoid infeasibilities. This constraint on null trade flows introduces errors on computed prices p. This is the reason why a second round of simulation is required without (16) but with the set of possible trade flows being restricted to the only estimated trade flows in the first round i.e. equations are not defined for the pairs of regions where no trade flow has been estimated.

$$(18) \quad if\ xo_{ij} = 0\,, x_{ij} = 0$$

Results - Endogenously computed trade flows are compared to the observed levels according to i) no trade calibration and no tariffs, ii) trade calibration with tariffs. The trade calibration and the implementation of tariffs into GLOBIOM allows reducing the gap between computed demand, bilateral shipments and net exports with the observed values for the base year but it increases the gap between FAO prices and computed prices.

10.3 Non-linear trade cost function

The use of an exponential trade cost function when trade flows are observed in the base year or in the previous period and a quadratic trade cost function when there is no trade observed helps reproducing the fact that there is a certain continuity of trade patterns over time and could also be justified by capacity constraints in the transport sector. Maritime transport represents 80% of world merchandise trade by volume. It is costly for a company to open a new shipping route so that it does not occur unless a significant amount of trade volume is expected. In periods of rapidly rising demand, shipping capacities can become scarce since it would need some time to build new boats. Moreover, ports can become congested, leading to some delay in the delivery which translates in extra-cost. Better port infrastructure is in general highly correlated to lower shipping costs (Clark, Dollar, and Micco 2004; Haveman, Ardelean, and Thornberg 2009; Limão and Venables 2001).

The different parameters of the constant elasticity trade cost function are the initial traded quantity between two regions, the trade cost, and the trade cost elasticity to traded quantities (Figure 6). When elasticity is low, trade cost rises quickly with the increase in traded quantities. This means that there are more incentives to increase trade at the extensive margin i.e. to increase the number of trading partners. To the contrary, when elasticity is high, there are more incentives to increase trade with existing partner i.e. to increase trade at the intensive margin.

Figure 6: Illustration of the impact of different elasticity value on the evolution of per unit trade cost with traded quantities for an initial shipment quantity of 1000 and an initial trade cost of USD 50 per unit

11. Land use change

Productivity of land for each type of crop is specific in GLOBIOM to the grid cell level, 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 and input costs in the 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 in the case of GLOBIOM the direct results of productivity estimates from EPIC. In the case of GTAP-BIO, the marginal productivity is derived from an exogenous coefficient derived from the TEM model. This coefficient is applied to land productivity, which means it is the same for the different crops.

Land expansion in GLOBIOM is described at the level of each spatial unit. Land use change is considered at the local level, on a one to one hectare basis, through a conversion ruled by a matrix of land use conversion possibilities between land use types, and associated conversion costs (Figure 3). The land transition matrix offers the possibility to reflect land conversion patterns specific to a region, and to vary conversion costs depending on the land type to convert. 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 allows for a more flexible representation of the main drivers of land use change and deforestation observed in the different regions of the world.[12]

An important attention has been given to peatland among land cover types. However, the information available on patterns of peatland conversion did not allow so far for a spatially explicit modelling in GLOBIOM. Instead, peatlands drainage is currently accounted through an ex-post calculation in the model (with hindsight) and based on other indicators in the model, in particular palm plantation expansion in areas already containing drained peatland (mainly Southeast Asia). Such calculation is grounded on historical observation of patterns of land use change patterns in the regions.

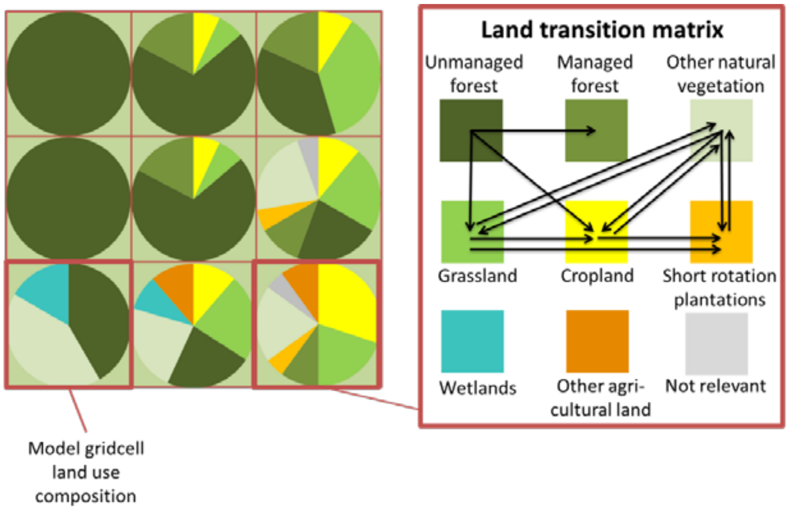

Figure 2. Land cover representation in GLOBIOM and land transition matrix

12. GHG emissions

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[13] (Valin et al., 2013). All GHG emissions calculations in GLOBIOM are based on IPCC guidelines on GHG accounting (IPCC, 2006). These guidelines specify different levels of details 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 ten GHG sources in GLOBIOM are estimated through Tier 2 or Tier 3 approaches.

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[12] 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.

[13] 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 2. 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	Herrero et al. 2013	2
Livestock	Enteric fermentation	CH_4	Herrero et al. 2013	3
Livestock	Manure management	CH_4	Herrero et al. 2013	2
Livestock	Manure management	N_2O	Herrero et al. 2013	2
Livestock	Manure grassland	N_2O	Herrero et al. 2013	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	Agricultural biomass	CO_2	EPIC data and literature review	1/2

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Appendix A: GLOBIOM structure: parameters, variables and equations

A.1 Main exogenous parameters

A.1.1 Costs and technical coefficients

- *TCOST*: costs to ship a good from region in the first index to the region in the second index including tariff and transportation costs (in 1000 USD/ton or in 1000 USD/m3)
- *CROP_DATA*: production costs, yield, fertilizer and water requirement, and harvested area in 2000 for a crop in a certain management system in a simulation unit (per ha)
- *FOREST_DATA*: production costs, sustainable timber harvesting potential, total wood biomass and carbon content of the forested area in a certain simulation unit (per ha)
- *SRP_DATA*: suitable production area, production costs, timber harvesting potential, total wood biomass and carbon content of the forested area in a certain simulation unit (per ha)
- *PROCESSDATA*: processing cost and quantity of output by unit of input by product, processing technology and region (?)
- *LIVE_DATA*: feeding requirements by product, quantity of animal final product and GHG emissions by unit of animal by animal type, management system and country (?)
- *LIVETECH_DATA*: ? by country, animal type and management system
- *GRAS_DATA*: grassland productivity by simulation unit (in ton DM/ha)
- *DHERDRELSIZE_DATA*: herd composition by animal type, management system and region (?)

A.1.2 Parameters for nonlinear functions

- *DDATA*: nonlinear demand function parameters including initial demand quantity, price and own-price elasticity by final product and region
- *RESOURCE_DATA*: nonlinear resource use function parameters including maximum resource quantity available, price and price elasticity by region
- *LUCDET_DATA*: nonlinear land use conversion cost function parameters including maximum land use change, land conversion cost and elasticity for land expansion of the land category in the first index into the land category in the second index
- *TRADECOST_DATA*: nonlinear trading costs function parameters including initial traded quantity, trading cost and elasticity for a good shipped from the region in the first index to the region in the second index

A.2 Endogenous variables

A.2.1 Objective

- *CSPS*: sum of global consumer and producer surplus

A.2.2 Resource use

- *RESOURCE_VAR*: total water and land use per region (water in X and land in 1000 ha)

A.2.3 Land use change

- *LANDAVAIL_VAR*: land use by category in a simulation unit at the end of the period (in 1000ha)
- *LUCDET_VAR*: land conversion from land category in first index to land category in second index in a simulation unit (in 1000ha)

A.2.4 Market

- *DQUANTITY*: final demand of a good in a region (in 1000tonnes for crops, animal products and pulp wood, in 1000m3 for other wood products and in 1000 GJ for bioenergy)
- *SHIPMENTS*: amount shipped from region in first index to region in second index (in 1000tonnes for crops, animal products and pulp wood, in 1000m3 for other wood products and in 1000 GJ for bioenergy)

A.2.5 Production

- *CROP_VAR*: harvested area of one crop in a certain management system in a simulation unit (in 1000ha)
- *LIVE_VAR*: number of animals in one animal category in a certain management system in a simulation unit (in 1000 livestock tropical units)
- *LIVETECH_VAR*(COUNTRY,LIVE_SYSTEM,ANIMALS,MITIGTECH) in 1000 lut
- *GRAS_VAR*: total grazed area by simulation unit (in 1000 ha)
- *FEEDQUANTITY*: total demand for animal feeding by product and by region (in 1000 tons)
- *PQUANTITY*: processed quantity of a certain input product in a region and transformed quantity of a certain product in a region (in 1000tonnes for crops, animal products and pulp wood, in 1000m3 for other wood products and in 1000 GJ for bioenergy)
- *SQUANTITY*: aggregated supply of composite goods in a region (in 1000 tons- only used for milk currently)

- *HARVEST_VAR*: area of harvested forest by simulation unit (1000 ha)
- *SQUANTITY_FOREST*: quantity of biomass produced by primary wood product and by simulation unit (1000 m3)
- *SRP_VAR*: area of short rotation tree plantations (1000 ha)

A.2.6 Separable variables used for the linearization of non-linear functions

- *RESOURCE_STEP*: separable resource use by region
- *LUCDET_STEP*: separable land use change from land category in the first index to land category in the second index by region (1000 ha)
- *DEMAND_STEP*: separable demand quantity of final goods by region
- *TRADECOST_STEP*: separable shipped quantity of a good from region in the first index to region in the second index

A.3 Equations

A.3.1 Objective equation

- *OBJECTIVE_EQU*: definition of the global consumer and producer surplus as the sum of the area under the demand functions minus the area under the production functions i.e. the sum of all production, resource and trading costs

A.3.2 Exogenous demand equations

- *BIOEN_DEMAND*: fix processed quantity of feedstock by region (in 1000 tons)
- *BIOEN_SCEN_EQU*: fix final demand of bioenergy product by region (in 1000 GJ)

A.3.3 Product balance equations

- *DS_BALANCE*: market must be balanced for each product and each region i.e. the total supply (including domestic production and imports) must equal the total demand (including demand for food, processing, animal feeding and the exports). Price is the dual of this market balance equation.
- *FEED_BALANCE*: the total feeding demand for a product in a region is equal to the sum over all simulation units of the feeding requirements times the number of animals
- *GRAS_BALANCE*: the total grass production (area grazed times the grassland productivity) must equal the grazing requirements for ruminants feeding in a simulation unit

A.3.4 Land balance equations

- *LUCDET_EQU*: ensures that the total land area in a simulation unit remains constant over time even if some conversion of one land use type to another land use type occurs (in 1000 ha)
- *CROPLAND_EQU, HARVLAND_EQU, SRPLAND_EQU, SRPSUIT_EQU and GRASLAND_EQU*: the total area of a productive land i.e. cropland, managed forest, short rotation tree plantation or grazed grassland, is equal to the total amount of managed area for a specific production i.e. the sum over crop and management system of crop harvested area, etc. (in 1000 ha)

A.3.5 Resource accounts

- *LAND_ACCOUNT*: the total use of land in a region is equal to the sum of land requirements for cropland, grassland and short rotation tree plantations in all the simulation units included in this region (in 1000 ha)
- *WATER_ACCOUNT*: the total use of water in a region is equal to the sum of water requirements for cropland irrigation in all the simulation units included in this region (in km3)

A.3.6 Management equations

- *MAXCROPSYS_EQU, SUBSFARMING_EQU, CROPLANDUSE_EQU*: set specific constraints to the evolution of crop management area by simulation unit or by region (1000 ha)
- *MINCROP_EQU, MAXCROP_EQU*: set specific constraints to the evolution of harvested area by crop in a simulation unit (1000 ha)
- *MAXSAWLOG_EQU, MAXTSWLOG_EQU, MAXTHWLOG_EQU, OBLIG4PRD_EQU*: set specific constraints on the forest management according to the availability of different kinds of biomass (1000m3)
- *DAIRYHERD_EQU*: sets the general herd dynamics (1000 lut)
- *NOSUCKLERHERD_EQU2, MNGASTOTHER_EQU, RUMURBAN_EQU*: set specific livestock constraints (1000 lut)
- *MINLIVESTOCK_EQU, MAXLIVESTOCK_EQU, MINLIVESTOCK_EQU2, MAXLIVESTOCK_EQU2*: set specific expansion constraints on the livestock number in a simulation unit (1000 lut)

A.3.7 Emissions account

- *EMISSION_EQU*: total GHG emissions in a region from agriculture and land use change and savings from fossil fuel replacement by biofuels (in million metric tons CO2 equivalent)

A.3.8 Separable Programming Equations (specific to the linearization of nonlinear functions)

- *DEMAND_IDENTITY, RESOURCE_IDENTITY, LUCDET_IDENTITY, TRADECOST_IDENTITY*
- *DEMAND_CONVEXITY, RESOURCE_CONVEXITY, LUCDET_CONVEXITY, TRADECOST_CONVEXITY*