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GLOBAL BIOSPHERE MANAGEMENT MODEL (GLOBIOM) DOCUMENTATION 2023 - VERSION 1.0

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Contents

List of Abbreviations

AFOLU	Agriculture, Forestry and Other Land Use
AMU	Arab Maghreb Union
BACI	Before-After Control-Impact
BII	Biodiversity Intactness Index
BIOD	Biodiversity
CEPII	Centre d'Etudes Prospectives et d'Informations Internationales
CERDI	Centre d'Études et de Recherches sur le Développement International
CGE	Computable general equilibrium
CH_4	Methane
CIF	Cost-insurance-freight
CO_2	Carbon Dioxide
COMESA	Common Market Eastern and Southern Africa
CUST	Customer Efficiency Index
EAC	East African Community
ECCAS	Economic Community of Central African States
EAS	Eastern Asia
EPA	Environmental Protection Agency
EPIC	Environmental Policy Integrated Climate
FAO	Food and Agriculture Organizations
FC	Fixed cost
FOB	Free on Board
FRA	Forest Resources Assessments
FTA	Free Trade Agreement
G4M	Global Forest Model
GAMS	General Algebraic Modeling Software
GCM	Global climate models
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GIEWS	Global Information and Early Warning System
GIS	Geographical Information Sciences
GLOBIOM	Global Biosphere Management Model
GTAP	Global Trade Analysis Project
GTOPO30	Global 3 Arc Second Elevation Data
GUI	Graphic User Interface
HOS	Hecksher-Ohlin-Samuelson
HRU	Homogeneous Response Unit
HS	Harmonised system
IFPRI	International Food Policy Research Institute
IIT	Intra Industry Trade

ILRI	International Livestock Research Institute
IIASA	International Institute for Applied Systems Analysis
IMF	International Monetary Fund
IND	Industrial systems
IPCC	Intergovernmental Panel on Climate Change
ITC	International Trade Center
IUCN	International Union for Conservation of Nature
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
LGA	Grazing systems in arid areas
LGH	Grazing systems in humid areas
LGT	Grazing systems in temperate/highland areas
LP	Linear Programming
LPJmL	Lund-Potsdam-Jena Managed Land
MDER	Minimum Dietary Energy Requirement
MNA	Middle East and North Africa
MXA	Mixed systems in arid areas
MXH	Mixed systems in humid areas
MXT	Mixed systems in temperate/highland areas
N_2O	Nitrous Oxide
NPP	Net Primary productivity
NPV	Net Present Value
NTB	Non Tariff Barriers
NTM	Non Tariff Measures
NUTS	Nomenclature of Units for Territorial Statistics
OECD	Organisation for Economic Co-operation and Development
OTH	Other systems
PE	Partial Equilibrium
POP	Population
RCEAf	Rest of Central-East Africa
RCEU	Rest of Central Europe
RCP	Representative Concentration Pathways
REC	Regional Economic Communities
RL	Rotation Time
ROWE	Rest of Western Europe
RSEA	Rest of Southeast Asia
RSAM	Rest of South America
SACU	Southern African Customs Union
SADC	Southern African Development Community
SEA	Southeast Asia
SD	Stocking Density
SITC	Standard International Trade Classification
SMH	Smallholder Systems
SPA	Shared Policy Assumption
SPAM	Spatial Production Allocation Model

SPE	Spatial Price Equilibrium
SPS	Sanitary and phytosanitary measures
SRP	Short rotation tree plantation
SRTM	Shuttle Radar Topography Mission
SSP	Shared Socioeconomic Pathways
TBT	Technical barriers to trade
TC	Transportation Cost
tC/t	Total Carbon per ton
tC/ha	Total Carbon per hectare
TFI	Trade Facilitation Indicator
TLU	Total livestock units
TBT	Technical Barriers to Trade
UNEP-WCMC	United Nations Environment Program World Conservation Monitoring Centre
URB	Urban systems
USD	US Dollar
USDA	United Stated Department of Agriculture
VC	Variable cost
WDPA	World Database of Protected Areas
WEF	World Economic Forum
WGT/V	Weight to value ratio
WWF	World Wildlife Fund

SECTION 1

Brief Introduction to GLOBIOM

1.1 GLOBIOM Model - Background

The Global Biosphere Management Model (GLOBIOM) is a partial-equilibrium model representing main land use sectors, including agriculture, forestry and biofuels. The supply side of the model is built from the bottom (spatially explicit land cover, land use, management systems and economic cost information) to the top (regional commodity markets). Demand is determined at the level of aggregate regions. Food demand projections are based on the interaction of three different drivers: population growth, per-capita income growth, and response to prices (based on consumer preferences), and policies.

The spatial resolution of the supply side relies on the concept of Simulation Units that are aggregates of 5 to 30 arcmin pixels belonging to the same altitude, slope, and soil class, and following country borders. For crops, livestock, and forest products, spatially explicit Leontief production functions covering alternative production systems are parameterized using biophysical models like Environmental Policy Integrated Climate Model (EPIC) or Global Forest Model (G4M) as seen below in Figure1.

GLOBIOM covers major greenhouse gas (GHG) emissions from Agriculture, Forestry and Other Land Use (AFOLU) based on IPCC accounting guidelines. These include N_2O from application of synthetic fertilizer and manure to soils, N_2O from manure dropped on pastures, CH_4 from rice cultivation, N_2O and CH_4 from manure management, and CH_4 from enteric fermentation, and CO_2 emissions/removals from above- and below-ground biomass changes for other natural vegetation following conversion. CO_2 emissions/removals from

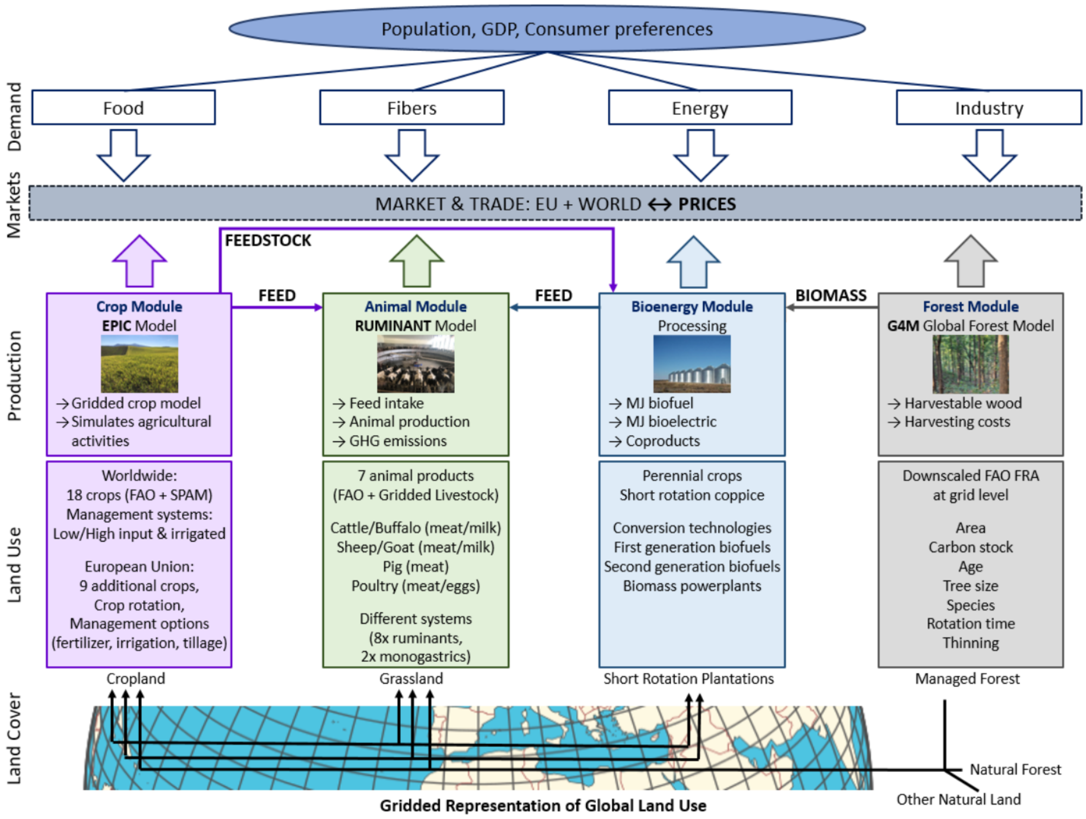

Figure 1: GLOBIOM Model

afforestation, deforestation, wood production in managed forests are estimated by the geographically explicit (0.5x0.5 degree) model G4M that is connected to GLOBIOM based on the parameters derived from G4M (Kindermann et al., 2006). For some select cases, GLOBIOM also provides input into G4M (Gusti et al., 2008) which is used to calculate forest emissions. In addition, GLOBIOM endogenously represents GHG mitigation technologies including technological and structural mitigation options.

Commodity markets and international trade are modelled at the level of aggregate economic regions (the aggregation is flexible and can be adapted to the users needs) where prices are endogenously determined at the regional level to establish market equilibrium. Trade is modelled following the spatial equilibrium approach representing bilateral trade flows bases on cost competitiveness and homogeneous good assumption. Besides primary products for the different sectors, the model has several final and by-products, for which, processing activities are defined. The model computes market equilibrium for agricultural and forest products by allocating land use among production activities to maximize the sum of producer and consumer surplus, subject to resource, technological, demand and policy constraints. GLOBIOM captures the multiple interrelationships between different systems involved in production of agricultural and forestry products. For example, population dynamics, changes in socio-economic and technological conditions, ecosystems and climate that lead to adjustments in the product mix and the use of land and other productive resources. The model is calibrated to an average around the year 2000 and solved recursively dynamic, typically done in 10-year time steps, and depending on the study, going up to 2100.

1.2 Spatial Resolution and Land Use Representation

GLOBIOM represents nine land cover types, of which, six are being modelled dynamically (cropland, managed grassland, short rotation plantations, managed forests, unmanaged forests, and other natural vegetation land) and three are kept constant at their initial level over time (other agricultural land, wetlands, and not relevant including bare areas, water bodies, snow and ice, and artificial surfaces). Managed forests refers to all forest areas where harvesting operations take place, while unmanaged forests refers to undisturbed or primary forests. Economic activities are associated with the first four land cover types (cropland, managed grassland, short rotation plantations, managed forests).

Land use change is endogenously determined for each spatial unit with restrictions on biophysical land suitability and production potentials, and by a matrix of potential land cover transitions along with associated conversion costs. Using the land transition matrix, we can reflect land conversion patterns that are specific to a region, and vary conversion costs that depend on the land type that needs to be converted. Depending on the profitability of production activities from primary, by-, and final products, the model can switch from one land use type to another. This is considering a non-linear conversion cost - increasing with the area of land converted at the regional level - that is taken into account in the producer optimization behaviour. Productivity of land for each crop type, and land currently used as cropland are specified in GLOBIOM at the grid cell level. Therefore, the model considers conversion of other land to cropland on expected profitability associated with productivity (based on the EPIC model) and input costs in the new locations. A similar methodology is used for grassland and grass productivity that allows for direct calculation of the value of the marginal productivity of land in the model.

1.3 Agriculture

1.3.1 Crop Production

GLOBIOM explicitly covers the production of 18 major crops globally (barley, dry beans, cassava, chickpeas, corn, cotton, groundnut, millet, palm oil, potato, rapeseed, rice, soybean, sorghum, sugarcane, sunflower, sweet potato, wheat), representing the majority of total harvested area and crop-derived calorie supply as reported by FAOStat. Each crop can be produced under different production systems that differ in productivity and cost:

1. Subsistence farming
2. Low input rainfed
3. High input rainfed
4. High input irrigated

Using the EPIC model, crop yield data is represented at the grid cell level on the basis of soil, slope, altitude and climate information. Using FAOStat, GLOBIOM harmonizes the regional production. Within each production system, the input structure is fixed, following a Leontief production function. Crop yields are allowed to change endogenously based on external drivers through switching from one production system to another, or reallocation of the production to a gridcell with different productivity. Aside from the endogenous mechanisms, an exogenous component that represents long-term technological change is considered.

1.3.2 Dedicated Energy Crops

GLOBIOM explicitly covers biomass feedstocks from energy plantations and existing forests for energy use (Havlík et al., 2011). Energy plantations are represented through short rotation tree plantations (SRP) of poplar, willow, or eucalyptus with rotation periods of up to 10 years. SRP productivity is based on Net Primary Productivity (NPP) maps (Cramer et al., 1999). The potential for plantation area expansion is determined by land suitability criteria based on aridity, temperature, elevation, population, and land-cover.

1.3.3 Livestock Production

GLOBIOM incorporates a detailed representation of the livestock sector globally (Havlík et al., 2013). For animal species, there is a distinction between dairy and other bovines, dairy and other sheep and goats, laying hens and broilers, and pigs. The livestock sector includes several production systems that have been adapted from Sere et al. (1996): for ruminants, grass-based (arid, humid, temperate/highlands), mixed crop-livestock (arid, humid, temperate/highlands, and other; for monograstics, smallholders and industrial. For each of these species, management systems, and regions, a set of input-output parameters (using the Leontief production functions) is calculated based on the approach developed by Herrero et al. (2013).

The feed rations in GLOBIOM are defined using the RUMINANT digestion model, that consists of grass, stovers, feed crop aggregates, and other feed. The outputs in the model include four meat types, milk and eggs, and environmental factors like manure production, N-excretion and GHG emissions. Transitions between production systems allow for feedstuff substitution, and for the intensification or extensification of livestock production. Additionally, grassland productivity is explicitly represented in the model. Therefore, GLOBIOM can represent a full inter-dependency between grassland and livestock [1].

1.4 Forest

1.4.1 Biomass Supply

Total forest area is calibrated using the FAO Global Forest Resources Assessments (FRA) and divided into managed and unmanaged forest. This is utilizing a

[1] A detailed description of the livestock sector representation is also provided in Havlík et al. (2013)

downscaling technique based on the impact of human activities on forest areas (Kindermann et al., 2008b). The Global Forest Model (G4M) provides the available woody biomass resources for each forest area unit, that is presented by mean annual increments (MAI). Woody biomass production cost covers harvest and transportation costs. Forest harvest costs are based on the G4M model by using spatially explicit constant unit costs that include planting, logging, and chipping in the case of logging residues. Harvest costs vary depending on geographical considerations such as the region and steepness of terrains. Transport costs on the other hand are not spatially explicit but are modeled by using regional level constant elasticity transport cost functions, which approximate short run availability of woody biomass in each region. These transport costs functions are then shifted over time in response to changes in the harvested volumes and related investments in infrastructure.

1.4.2 Forest Industries

The forest sector demand is modeled for the various final products using regional level constant elasticity demand functions (Lauri et al., 2017). Forest industrial products are produced by Leontief production technologies, which input-output coefficients are based on the engineering literature. By-products of these technologies can be used for energy production or as raw material for pulp and fiberboard. Initial production capacities for forest industry final products are based on production quantities from FAOStat. After the base year, the capacities evolve according to investment dynamics, that depend on the rate of depreciation and investment costs. GLOBIOM has detailed representation of the forest sector and its supply chain. The model includes five primary wood products (pulplogs, sawlogs, other industrial roundwood, fuelwood, and logging residues) that can be used as inputs for material or energy production processes. The current version of the model includes eight final products (sawnwood, plywood, fiberboard, chemical pulp, mechanical pulp, other industrial roundwood, fuelwood, and energy wood) and five by-products (sawdust, woodchips, bark, black liquor, and recycled wood). Biomass for bioenergy production can be sourced from pulplogs, fuelwood, logging residues or forest industry by-products. Detailed information on the forest sector representation is provided in Lauri et al. (2017).

1.5 Overview of the Principles of the GLOBIOM Model

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 with a fine level of detail. The main characteristics of GLOBIOM are summarized in Table 1.

Table 1: Main Structural Characteristics of GLOBIOM

Model Framework	Partial equilibrium , bottom-up, starts from land and technology

Sector Coverage	Detailed focus on agriculture bioenergy
Regional Coverage	Global (Can cover all regions and countries)
Resolution on production side	Detailed gridcell level (>10,000 units worldwide)
Time-frame	2000-2100 (ten year time step)
Market data source	FAOStat
Factor of production explicitly modelled	Detailed on natural resources (land, water)
Land use change mechanisms	Gridbased. 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

1.5.1 Economic Principles

Each sector covered by GLOBIOM have their supply side production functions, their markets and demand side functions. The model is a partial equilibrium model, as not all goods, factors or agents are represented. It is therefore designed to address issues affecting land use based sectors, and assumes 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 with 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 the price, the higher the consumption – as well as the consumer surplus. 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 & Spreen, 1980).

SECTION

2 Technical Description of GLOBIOM

2.1 Economic Principles

This section has been adapted from Valin (2014) and Valin et al. (2015)

2.1.1 Market-equilibrium model

Endogenous adjustments in market prices lead to equality between supply and demand for each product and region.

2.1.2 Partial equilibrium model

GLOBIOM focuses on few sectors of the economy, crops, livestock, and forestry. The agricultural and forestry sectors are linked within a single model and compete for limited land available. On the other hand, a general equilibrium model encompasses the entire economy, and equilibrium in all markets must hold simultaneously: on the factor market, the goods and services market, the capital account, the government account and current account (Arrow & Debreu, 1954; Walras, 1874). The impacts on one sector can affect other sectors through input and factor prices. The implications of a Partial Equilibrium (PE) in GLOBIOM are the following: 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 for a more detailed representation of the selected sectors – higher spatial and commodity resolution. PE models also usually operate with quantities while Computable general equilibrium (CGE) models use values allowing for a better representation of environmental and biophysical impacts.

2.1.3 Partial equilibrium and the rest of the economy

As GLOBIOM is a partial equilibrium model, the relevant sectors (agriculture and forestry) are represented in detail, an important factor 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 use 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 to drive first order impacts, can be added to the simulation of the model through linkages 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 CGE frameworks.

2.1.4 Optimization model

The market equilibrium maximizes the sum of consumer and producer surpluses under a set of constraints including the market balance constraint. These are discrete constraints that encompass equalities and inequalities. In linear programming, the feasible region is a closed convex set, i.e. to select the optimal solution we need to find the set of all extreme points instead of finding the entire feasible region. An important feature of linear programming is that any solution obtained provides both, a local and global optimum. GLOBIOM also contains some non-linear functions but they have been linearized using stepwise approximation (McCarl & 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.

2.1.5 Spatial price equilibrium (SPE) model

It is a specific category of partial equilibrium and linear programming model where the equilibrium solution is found by maximizing total area under the excess demand curve in each region minus the total transportation costs of all shipments (Samuelson, 1952; Takayama & Judge, 1971). SPE has been largely applied since the 1960s to forestry and agriculture (Koo & Thompson, 1982). The model relies on homogeneous good assumption, where price differences between the two regions is solely explained by transportation costs. If regional prices differ by more than the inter-regional cost of transporting goods, then trade will occur and the price difference will be driven down to the transport cost. This allows for the 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. 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 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.

2.1.6 Recursive-dynamics

GLOBIOM is run for several periods (at 10 years time steps) 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 time period t depends on some decisions that agents have taken in the previous time period t-1. For instance in GLOBIOM, at the beginning of a time period, the starting conditions for land use are updated using the solutions of the simulations from the previous time period. Moreover, the reference 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 & 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.

The model is grounded in the mathematical programming tradition (McCarl & Spreen, 1980) that 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 & 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; EPA, 2010).

Each sector covered by GLOBIOM have their supply side production functions, their markets and the demand side function. 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 with 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 the price, the higher the consumption – as well as the consumer surplus. 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.

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2.1.7 Region or Country Definitions in GLOBIOM

Regions in GLOBIOM are based on different studies. For different topics, we use regions or specified countries for our study. The explanation of changing the code will be available in further sections. For purposes of research, you can also choose a single country. For example, we study 37 regions as seen in table 2 below also represented in the map (Figure 2) below

Table 2: Definition of 37 regions and countries associated with them

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

	Rest of Central America (RCAM)	Bahamas, Barbados, Belize, Bermuda, Costa Rica, Cuba, Dominica, Dominican Republic, El Salvador, Grenada, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, Netherlands Antilles, Panama, St Lucia, St Vincent, Trinidad and Tobago
	Rest of South America (RSAM)	Bolivia, Chile, Colombia, Ecuador, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela
Eastern Asia (EAS)	China	China
	Japan	Japan
	South Korea	South Korea
Southeast Asia (SEA)	Indonesia	Indonesia
	Malaysia	Malaysia
	RSEA OPA	Brunei Dar es Salaam, Singapore, Myanmar, Philippines, Thailand
	RSEA PAC	Cambodia, Korea DPR, Laos, Mongolia, Vietnam
South Asia	India	India
	Rest of South Asian States (RSAS)	Afghanistan, Bangladesh, Bhutan, Maldives, Nepal, Pakistan, Sri Lanka
Middle-East and 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
Africa (excluding North Africa)	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
	Rest of Southern Africa	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

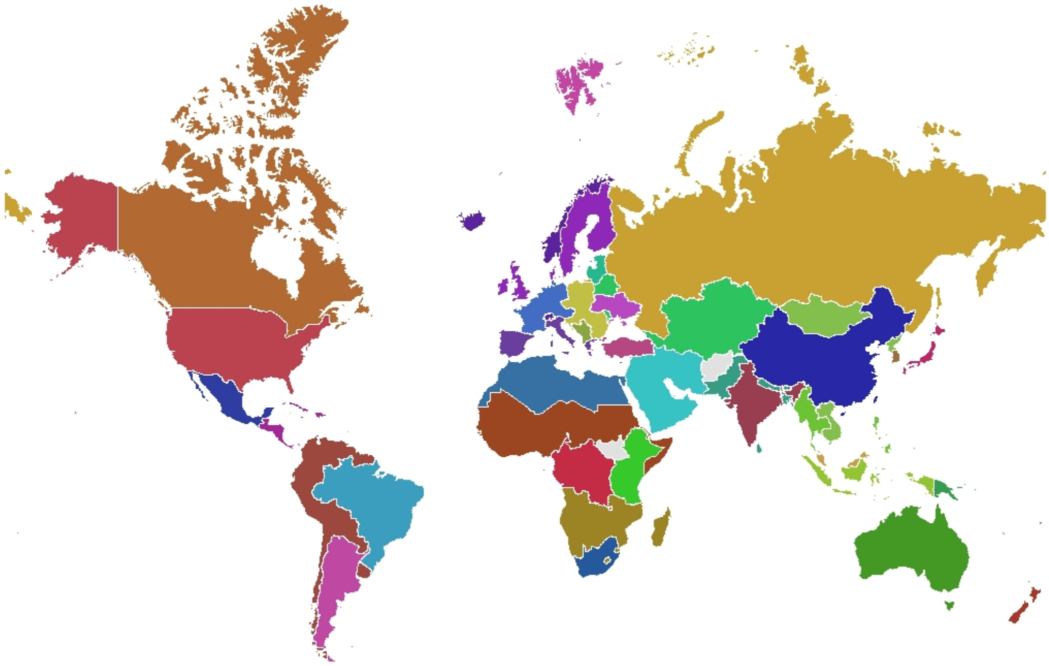

Figure 2: Global map representing 37 regions

2.2 Model

2.2.1 Development of Land Resources and Land Characteristics

Spatial Resolution: The first step for the model development was to build a global database on land characteristics. Available global observation data and data from other sources addressing climate, topography, soil, and crop management were gathered (Skalský et al., 2008). The global scale 5” spatial resolution grid (corresponding to 10x10km at the equator), covering land surface was created as primary spatial reference for geographical reference of all other spatial objects. In total, the global grid comprises 2,186,775 pixels. For 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 a basis for both, the biophysical model (EPIC) and the economic model (GLOBIOM). 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. These HRUs cover 5 altitude classes, 7 slope classes and 5 soil classes to represent these stable landscape characteristics. This results in 150 unique combinations of altitude, slope and soil classes, globally. This gives us more than 200,000 simulation units globally which are polygons with a size varying between 5” and 30” spatial resolution grid (Skalský et al., 2008).

Land cover and land use are critical input data within 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 a certain land cover to each 1x1km resolution pixel by using remote-sensing technique. The primary source of data for specific land uses comes from national census. Crop distribution maps computed at the International Food Policy Research Institute (IFPRI) are used for crops and crop shares (You & Wood, 2006). The crop distribution maps determines the final cropland area and other land cover classes were adjusted when necessary within the model (Skalský et al., 2008). Grassland poses more challenges, as it is hard to differentiate between grazing and natural herbaceous land. Therefore, the model merged grassland and other natural land and extracts grassland, as the area which is required to feed ruminants based on the livestock distribution map (Kruska et al., 2003; Sere et al., 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.

We use the output of biophysical models to get spatially explicit estimates of ***land productivity*** for crops, timber and grassland. The EPIC model is applied at the global scales, and simulates major biophysical processes in agricultural ecosystems (Williams, 1995). In addition to crop production potentials, nitrogen, phosphorous and water requirements are also computed on total cropland area for 17 crops (excluding palm oil) and four input systems - three rainfed systems and one irrigated system - at the Simulation Unit level. For oil palm, which is not yet included in the EPIC model, we use average FAO yields. On the forestry side, we use the output of the forest growth model component of the G4M model Kindermann et al. (2008b) which gives the mean annual increment for each 0.5 degree pixels for the optimal rotation time (sustainable management). Grassland productivity has been estimated from different sources including the University of Natural Resources and Life Sciences (BOKU) in Vienna with EPIC and the International Livestock Research Institute (ILRI) (Havlík et al., 2013). One part of the production intensification is endogenously represented through the transition to a different management system and/or to a more/less productive area of production over time (and one part is exogenous to represent new technologies diffusion. Different assumptions on the exogenous productivity increase have been sit in different versions of the model due to model development.

Other input-output coefficient are defined at a more aggregated level. The livestock feeding requirements, meat and milk production coefficients for each animal type (4 animals) and each system (4 management systems) and agro-climatic zones (3 zones) - are taken from RUMINANT model (Herrero et al., 2013) for ruminants and a literature review for monograstics. They are defined at the regional level. For bioenergy processing, technical coefficients are based on literature (Haas et al., 2006; Hermann & Patel, 2007). Data on the quantity of by-products obtained through biofuels processing and on the rate that by-products are substituted for traditional livestock feeds are taken from the Gallagher review (RFA, 2008).

The final step within the data processing stage is the harmonization between different sources of data to make them consistent with the modelling framework, as seen in equation 1. The spatially explicit data on land area under different uses and associated productivity are adjusted to match FAO statistics at the regional level.

$$Production_{r,s} = \sum_{c \in r,g,o,p,q,m} Area_{c,g,o,p,q,s,m} \times \alpha_{r,a} \times Yield_{c,g,o,p,q,s,m} \tag{1}$$

where r is the region, c is the product, g is the spatial grid, o is the altitude class, p is the slope class, q is the soil class, m is the management system, s is the species, and α is the adjustment factor of the productivity parameters to match the average productivity given by the FAO at the regional level. Main sources of emissions from land use and the agricultural sector are also accounted for in GLOBIOM.

2.2.2 Model

This section is adapted from Havlík et al. (2011)

The model, as seen in equation 2 seeks to maximize the sum of consumer and producer surplus

- ***Variables - WELF:*** the sum of consumers and producers surplus; ***D:*** the final demand; ***W:*** the water use; ***Q:*** the land use/cover change; ***A:*** the land use activities; ***B:*** the livestock number; ***T:*** international shipments; ***P:*** processes quantity; and ***L:*** final endowment of land of given land use/cover class.

- ***Parameters -*** are τ^{land} the management cost per hectare of land use (except for water); τ^{proc}***:*** the processing cost by unit of primary product, and τ^{calib}***:*** the calibrated production cost per hectare of land use activities *or* per livestock unit; α^{land}***:*** crop and tree yields; α^{live}***:*** livestock technical coefficients (positive for final products, negative for crop feed requirements; α^{proc}***:*** conversion coefficients (-1 for primary products); L^{init}***:*** initial endowment of land of given land use/cover class.

- ***Functions -*** φ^{demd}***:*** the constant elasticity demand function; φ^{splw}***:*** the constant elasticity water supply function; φ^{lucc}***:*** the land use/cover change linear cost function; φ^{trad}***:*** the constant elasticity international trade cost function.

- ***Indexes - r:*** the region, ***t:*** the period; ***c:*** the country; ***g:*** the spatial grid identifiers; ***l:*** the land use types; ***s:*** the primary product; ***a:*** the animal type; ***y:*** the final product; and ***m:*** the management system.

The ***objective function*** as seen in the equation 2 below is defined as the sum of global consumer and producer surplus, i.e. the integral under the demand functions minus the sum of all production, resource and trading costs. It is expressed in million US Dollars (USD).

$$
\begin{aligned}
Max\ WELF_t = &\sum_{r,y}[\int \varphi^{demd}_{r,t,y}(D_{r,t,y})d(.)] - \sum_{r}[\int \varphi^{splw}_{r,t}(W_{r,t})d(.)] \\
&- \sum_{r,m}(\tau^{proc}_{r,m}.P_{r,t,m}) - \sum_{r,l,\tilde{l}}[\int \varphi^{lucc}_{r,l,\tilde{l},t}(\sum_{c,g} Q_{r,t,c,g,l,\tilde{l}})d(.)] \\
&- \sum_{r,c,g,l,s,m}(\tau^{land}_{c,g,l,s,m}.A_{r,t,c,g,l,s,m}) \\
&- \sum_{r,c,g,l,s,m}(\tau^{calib}_{c,g,l,s,m}.A_{r,t,c,g,l,s,m}) \\
&- \sum_{r,c,g,l,s,m}(\tau^{calib}_{c,g,l,s,m}.B_{r,t,c,g,l,s,m}) \\
&\sum_{r,\tilde{r},y}[\int \varphi^{trade}_{r,\tilde{r},t,y}(T_{r,\tilde{r},t,y})]
\end{aligned}
\tag{2}
$$

The ***market balance equation*** seen in equation 3 below ensures that for each product and each region, domestic production plus imports must equal demand for food, processing, animal feeding and exports. The dual of the product balance equation gives the equilibrium price. For crops, three kinds of demand have to be satisfied: the food demand (left hand side), the feed demand and the processing demand for bioenergy production (they appear negative in the right hand side of the equation).

$$
\begin{aligned}
D_{r,t,y} \geq &\sum_{c,g,l,s,m}(\alpha^{land}_{t,c,g,l,s,m,y}.A_{r,t,c,g,l,s,m}) \\
&+ \sum_{c,g,l,a,m}(\alpha^{live}_{t,c,a,m,y}.B_{r,t,c,g,a,m}) \\
&+ \sum_{m}(\alpha^{proc}_{r,m,y}.P_{r,t,m} \\
&+ \sum_{\tilde{r}} T_{\tilde{r},r,t,y} - \sum_{\tilde{r}} T_{r,\tilde{r},t,y}
\end{aligned}
\tag{3}
$$

The ***land use balance*** equations connects the productive use of a parcel of land to a certain land cover (equation 4) and ensures that total land area in a simulation unit remains constant over time even if the conversion of one land use type to another land use type occurs (equation 5).

$$
\sum_{s,m} S_{r,t,c,g,l,s,m} \leq L_{r,t,c,g,l} \tag{4}
$$

$$
L_{r,t,c,g,l} \leq L^{init}_{r,t,c,g,l} + \sum_{\tilde{l}} Q_{r,t,c,g,\tilde{l},l} - \sum_{\tilde{l}} Q_{r,t,c,g,l,\tilde{l}} \tag{5}
$$

Other equations are defined:

- to linearize non-linear functions,
- to represent technical constraints of production,
- to introduce minimum demand requirements,
- to limit the suitable area for a certain use or
- to represent some policy objectives (e.g. cap on GHG emissions).

2.3 Crop Production

GLOBIOM represents 18[2] crops globally and 27 crops in the European Union. Globally, the harvested area is based on FAO statistics which are then spatially allocated using data from the Spatial Production Allocation Model (SPAM)[3]. In the case of the EU, crops are allocated across NUTS2 regions using data from EUROSTAT.

Cultivated area currently represent in GLOBIOM around majority 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 rich diversity of crops cultivated globally. Harvested area for the crops not covered in GLOBIOM is kept constant[4]. Global harvested area amounts to majority 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 is explicitly represented in the baseline of the model, for newly created abandoned land.

Yields for all locations and crops are determined in a geographically explicit framework by the EPIC model. The yields are distinguished by crop management system and land characteristics by spatial unit. They are however re-scaled 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 global 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 [5]. This allows for 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 with FAOStat data.

Along with the production of grains or fibers, GLOBIOM also represents the production of straw for some 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

[2]These crops include barley, dry beans, cassava, chickpeas, corn, cotton, groundnut, millet, oil palm, potatoes, rapeseed, rice, soybean, sorghum, sugarcane, sunflower, sweet potato, and wheat.

[3]See You & Wood (2006) and http://mapspam.info/

[4]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

[5]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 242 regions in Europe based on the NUTS 2021 classification.

considered and the effect of changing this rate on yield and carbon sequestration is estimated using the EPIC model.

Economic market balances in GLOBIOM are solved at the level of 37 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 its quantity[6]. 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.

2.3.1 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;[7]
- investments 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).

2.3.2 Agricultural Sector: Local Trade Costs

Adapted from Janssens (2022)

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

[7]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.

Building on the work by Mosnier et al. (2014a), local trade costs are added from farm-gate to market and eventually to the supply side in GLOBIOM. Agricultural markets in GLOBIOM are perfectly competitive, so for each time step t, product i and supply unit su the producer price plus local trade cost equals the regional market price in region r (equation 6). Producer prices within the crop sector are determined by grid-level input costs, structural costs and crop yields, and regional level resource costs (land, water) (equation 7). Input requirements and crop yields are provided by the EPIC crop model, while the structural and resource costs are endogenously determined by GLOBIOM.

$$p_{t,r,i}^{market} = p_{t,se,i}^{producer} + \tau_{t,su,i}^{local\ trade\ cost} \tag{6}$$

$$p_{t,su,i}^{producer} = \frac{cost_{t,su,i}^{production} + cost_{t,su,i}^{structural} + cost_{t,r}^{land}}{yield_{t,su,i}} + \frac{cost_{t,r}^{water} \times input_{t,su,i}^{water}}{yield_{t,su,i}} \tag{7}$$

Local trade costs are defined as the transport and marketing costs from farm-gate to market, represented by the closest city of 50,000 inhabitants [8]. These trade costs (also referred to as market access costs in literature) cover the gap between the (rural) farm-gate producer price and the wholesale (urban) market price. The local trade costs are incorporated in the model only for commercial agricultural production systems, i.e. all crop and livestock production systems except for subsistence crop production and other pig and poultry production in Africa which are not marketed but used for self-consumption. Local trade costs are calculated for the base-year at product (i) and supply unit (su) level (equation 8).

$$\tau_{su,i}^{local\ trade\ cost} = t_{su,i}^{local\ transport} + \left(p_{c,i}^{producer} + t_{su,i}^{local\ transport}\right) \times m_{c}^{marketing} \tag{8}$$

The local transport cost are similarly calculated based on the spatially explicit map of travel time to closest city of 50,000 inhabitants from Weiss et al. (2018), which is converted to distance (d_{su}) assuming an average speed between 30 and 50 km/hour for African countries based on an African trucker survey (Teravaninthorn & Raballand, 2009) and 60 km/hour for countries in the rest of the world. For African countries, the local transport cost is calculated for each supply unit su as the sum of variable (VC, per km, e.g. fuel, tires, maintenance) and fixed costs (FC, e.g. salary and equipment) of transport, adjusted for profit margin of trucker companies (equation 9), which are in turn calculated for each country c based on data and assumptions from survey evidence. The impact of varying road quality along the route from farm-gate to the city is incorporated through the use of different transport modes with different loading capacity for different sections along the route. Based on literature, we assume that the first 5 km is transported with a small vehicle with low load capacity (50 kg e.g. motorcycle)

[8]Note that in the literature transport costs are often regarded as a component of marketing costs. In this study, we split transport costs from other components of marketing costs as transport costs are the largest component of local trade costs in Sub-Saharan Africa (Fafchamps et al., 2005; Gollin & Rogerson, 2010) and poor rural road infrastructure is particularly identified as one of the critical barriers to agricultural development in the region (Berg et al., 2017, 2018).

(Vandercasteelen et al., 2018). The rest is transported with a higher capacity vehicle, where for countries in Sub-Saharan Africa a distinction is made between the first 50 km (vehicle with medium load capacity, 1.2 ton) and the remaining distance (a truck of high load capacity, 12.5 ton) (Crossley et al., 2009; Fafchamps et al., 2005; Vandercasteelen et al., 2018). For South Africa, Egypt and countries in the Arab Maghreb Union (AMU) a large load capacity truck is assumed for the full distance.

$$t_{su,i}^{local\ transport} = \frac{FC_{c,i} + VC_{c,i} \times d_{su}}{load\ capacity_c} \times \left(1 + m_c^{profit\ transporter}\right) \tag{9}$$

For the rest of the world, we assume that per ton-km transport costs fall between 3.5 US cents/ton-km and 10 US cents/ton-km, a conservative range of values reported in literature (Kopicki, 2009). To capture the impact of efficiency of the transport industry, we differentiate costs according to the Infrastructure Score in the World Bank Logistic Performance Indicator (LPI): 3.5 US cents/ton-km for LPI > 3 (e.g. USA), 5 US cents/ton-km for 3 > LPI > 2.5 (e.g. Brazil), 7.5 US cents/ton-km if 2.5 > LPI > 2 (e.g. Colombia) and 10 US cents/ton-km if 2 > LPI (e.g. Kazakhstan). Empirical studies show that the transport along poor quality roads in the first miles from the farm-gate to market leads to a doubling of total transport costs (Aggarwal et al., 2018; Minten et al., 2013; Vandercasteelen et al., 2018). We use the World Bank Rural Access Index, which indicates the percentage of rural population without access to paved roads, to determine the share of transport costs affected by the costly transport in the first miles beyond the farm-gate in rest of the world countries. For all countries, local transport costs are set two (milk) or four times (meat, eggs) the size for animal products compared to crops as these usually require greater care or refrigeration during transport.

Marketing costs include costs of storage and distribution services (e.g. wholesaler fees and profits) and are calculated as fixed mark-up on the purchase price (producer price + local transport cost, Eq. 3). For countries in Sub-Saharan Africa (except for those in Southern African Customs Union (SACU)), we assume a marketing margin of 30% ($m_c^{marketing}$=0.3) based on the ratio between marketing and transport costs reported in the literature (Fafchamps et al., 2005; Minten & Kyle, 1999; World Bank, 2008). For other African countries and the rest of the world, we assume a marketing margin between 10% and 30% based on the quality of warehouse and distribution services as documented in the World Bank Domestic Logistic Performance Index. Though the available data and literature for the compilation of spatially explicit local trade costs is limited, there is a good match between our average producer-to-consumer price ratio's at region level with FAO prices (producer price from FAOStat versus wholesale price from FAO GIEWS - Global Information and Early Warning System) or producer-to-consumer price ratios reported in the literature.

Agricultural sector: land allocation mechanisms.

The allocation of land across agricultural (cropland, grassland) and non-agricultural (short rotation plantations, managed forests, unmanaged forests, other natural land) land cover within a supply unit, and across specific crops, animals and management systems within agricultural land use is endogenously determined in the model optimization. For each time step and scenario, the most cost-efficient production pattern for a given demand is computed. Besides the local production and trade costs, also land availability, cropland expansion constraints and land conversion costs influence the cost-efficiency. This set-up results in non-linear supply functions at the regional level where the slope is determined by the distribution of cost-efficiency across supply units and management systems.

2.3.3 Representation of Irrigation

Crop production system

The representation of irrigated cropland production systems considers both the biophysical suitability and irrigation water requirements of crops at a monthly level, that are simulated by EPIC and harmonized with the country-level FAO AQUASTAT statistics for water withdrawn for irrigation (Palazzo et al., 2019). GLOBIOM represents the spatial and temporal nature of water demand and supply by building on the work from Sauer et al. (2010) to consider the suitability of irrigation systems and crops by considering the biophysical conditions as well as the physical and economic suitability of crops for irrigation (Palazzo et al., 2019; Pastor et al., 2019).

Four irrigation systems are modeled at a high spatial resolution for irrigated cropland – basin, furrow irrigation, localized drip, and sprinkler. Table 3 briefly presents the biophysical and economic suitability and efficiency of each system that is taken into account in determining the crop/system compatibility for each land unit (Sauer et al., 2010). The share of irrigated area by systems according to Sauer et al. (2010) have been harmonized with shares of irrigated area by systems defined by Jägermeyr et al. (2015). The final irrigation water demand for crops for a given land unit depends on the application efficiency of each system.

Table 3: Biophysical, technical, and economic factors considered for irrigation system/crop choice

Biophysical	**Technical**	**Economic**
Crop characteristics	Water application efficiency	Crop market prices
- Water tolerance - Rain-fed and irrigated yields - Irrigation requirement - Length of growing period	Operation time per irrigation event	Investment capital cost
Soil infiltration rate	level of pressurization (energy and labor requirement)	Energy prices
Slope inclination	Coverage per irrigation system unit	Labor cost
Water resource availability	Water application efficiency	Land and water prices
- Surface water - Groundwater - Non-renewable sources		

Representation of Water balance

Water balance for irrigation was made spatially explicit for both the irrigation water demand and water supply available for use by irrigation with an explicit source of water used for irrigation. The seasonality of streamflows are reflected as well as the the impacts of socioeconomic change on water demand from other sectors and the impacts of climate change. Figure 3 provides an overview of the conceptual framework representing the biophysical water availability and irrigation water demand within GLOBIOM. IIASA's Community Water model (CWatM) (Burek et al., 2020). provides GLOBIOM with water withdrawals for domestic and industrial uses for historical water demand up to 2015 (from ISIMIP) and future water withdrawals for different sectors using the per capita and per sector demand methodology from Wada et al. (2011, 2014, 2016) and the local socioeconomic development from the shared socioeconomic pathways (SSPs) (e.g. GDP and population growth and technological progress in the water sector) (Hanasaki et al., 2013; O'Neill et al., 2014). The aggregated runoff is calculated daily 1970-2100 for at a 0.5 deg (around 50 x 50 km). Both aggregated runoff and water demand from municipal and industrial uses is aggregated to GLOBIOM land units and to monthly levels to use in within the GLOBIOM modeling framework (Palazzo et. al. forthcoming, Arbelaez-Gaviria et al. forthcoming).

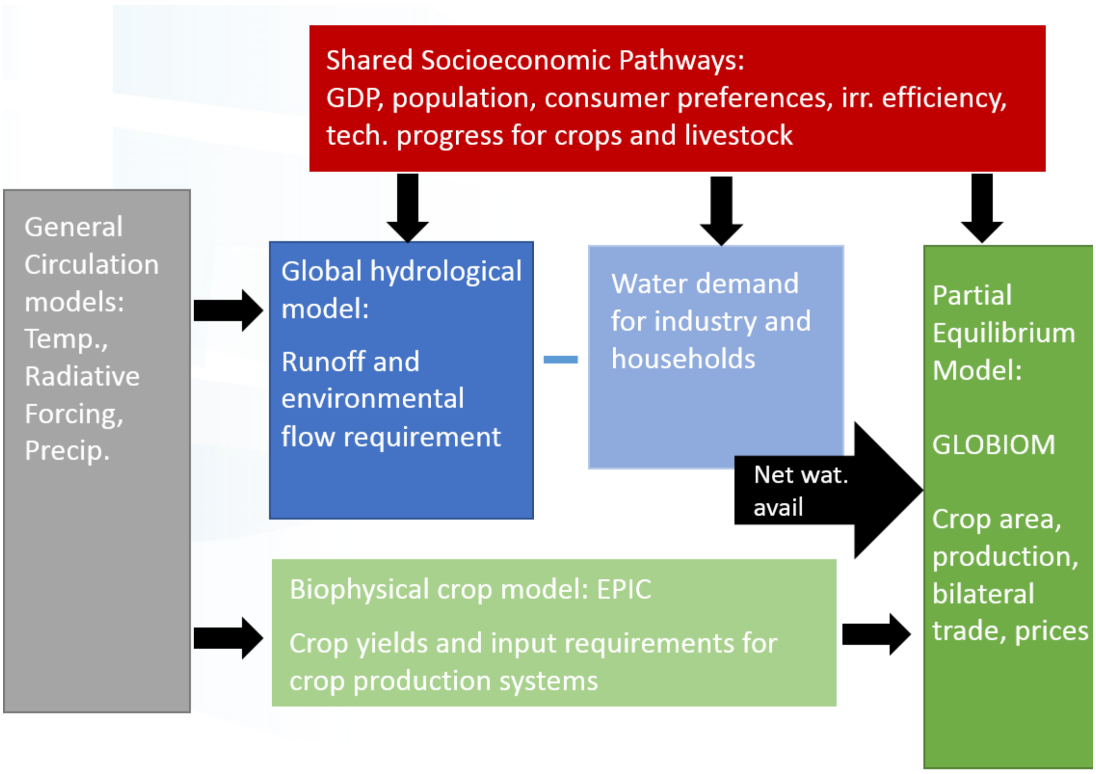

Figure 3: Conceptual framework for representing biophysical water availability and irrigation demand within a global land use model

Irrigation water requirement by crop

Irrigation water requirements at the monthly level were calculated using the globally gridded crop model EPIC. The model simulates the biophysical processes of crop growth under climatic, environmental and management conditions. These irrigation water requirements were harmonized for base year to match the water demands from Aquastat (FAO, 2017), using the irrigated cropland area dataset available from SPAM (You & Wood, 2006) to inform the irrigated area by crop.

Water supply by source

The source of water supply for irrigation is split into three categories: irrigation sourced by surface water, irrigation sourced by groundwater, and irrigation sourced by non-renewable sources. Return flows are an important consideration that we do not currently model within GLOBIOM. Stronger coupling between hydrological models and GLOBIOM in future analyses may allow for the feedbacks of return flows to be captured.

Surface water

Monthly surface water availability is simulated from 2000 to 2050 at a 0.5° x 0.5° spatial resolution using the LPJmL global hydrological model (Bondeau et al., 2007; Gerten et al., 2004). To use these data at the appropriate spatial resolution for GLOBIOM, the mean monthly runoff is estimated by aggregating based on the average discharge rates in each river basin. Additionally, runoff is estimated under the conditions of temperature, radiative forcing, and precipitation from different GCMs to consider the impact of climate change with respect to changes in water availability.

Groundwater and non-renewable water

The share of irrigated area is determined at 0.5° spatial resolution sourced by surface water and groundwater using a spatially explicit map of irrigated areas source from groundwater (Siebert et al., 2010). The total volume of water demanded by each source on a yearly basis is estimated using the shares and the total irrigation water requirement for all crop areas. The use of groundwater over the growing period is based on the share of irrigation water requirements that cannot be met by surface water due to limited monthly stream flows. If available groundwater is in excess of the surface water deficit, the model distributes the excess groundwater supply according to the monthly demand for water. Non-renewable withdrawals were calculated as the water deficit that cannot be fulfilled by surface water or groundwater in year 2000. The amount of water withdrawal coming from groundwater and nonrenewable sources is assumed to remain constant over time. The method to determine the share of irrigation water withdrawals sourced by groundwater and surface water follows closely the methods outlined by Wada & Bierkens (2014). These authors estimate that groundwater withdrawals account for 35% of the total irrigation withdrawals and 65% come from surface water or reservoirs.

2.4 Livestock Production

2.4.1 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 (SU). The model differentiates 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 (Sere et al., 1996) – 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 et al. (2007). 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. (2013).

2.4.2 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 (Herrero et al., 2013, 2008), 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 - SUA) 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. (2013).

Final livestock products are expressed in primary commodity equivalents. Each product is considered as a homogeneous 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.

2.4.3 Livestock Feed

As mentioned, feed requirements for ruminants are computed simultaneously with the yields (Herrero et al., 2013). 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. (2013). In general, it is assumed that in industrial systems pigs and poultry consume 10 and 12 kg dry matter of concentrates per TLU per 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 and 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 kept constant during different simulations, thus enabling it to reproduce base year activity levels that are mostly consistent with FAOStat, but requires that all additional GRAINS demand arising over the simulation horizon to be 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 the 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, while no adjustments are done to the feed rations.

At the time of compilation to our best knowledge there were no worldwide statistics available on either consumption or production of grass. Hence the model relies entirely on the values calculated with RUMINANT for grass requirements, and uses them to estimate grassland extent and productivity. 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.

2.4.4 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. (2008) 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 extent of grassland. 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. (Conant & Paustian, 2004). 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 region within GLOBIOM. This process allows 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 utilized grassland area, the model first defines 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 (You & Wood, 2006; Sere et al., 1996; Wint et al., 2007; Herrero et al., 2008) (Shrub Cover, closed-open, evergreen, Shrub Cover, closed-open, deciduous, Sparse herbaceous or sparse shrub cover). In each Simulation Unit the utilized area is calculated by dividing total forage requirements by forage productivity. In Simulation Units where utilized area is smaller than the potential grassland area, the difference would be allocated to either "Other Natural

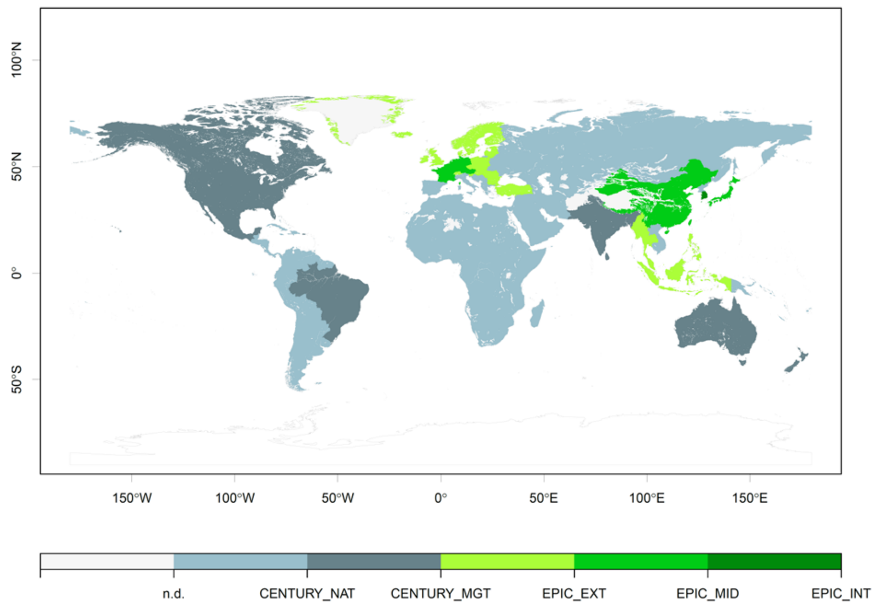

Figure 4: Data sources used to parameterize forage availability in different world regions. CENTURY_NAT – CENTURY model for native grasslands; CENTURY_MGT – CENTURY model for productive grasslands; EPIC_EXT – EPIC model for grasslands under extensive management; EPIC_MID – EPIC model for grasslands under semi-intensive management; EPIC_INT – EPIC model for grasslands under intensive management.

Land" or "Other Agricultural Land" depending on the underlying GLC2000 class. In Simulation Units where grassland area that is 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.

Forage productivity was estimated using the CENTURY (Parton et al., 1987, 1993) and EPIC (Williams, 1995) 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 (Schloss et al., 1999). Plant community and land management (grazing) was based on growing-season grazing and 50% 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 (Ramankutty et al., 2008). We assumed 50% grazing efficiency for grass, and 25% 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 (Figure 4).

Both the CENTURY and EPIC models are used to estimate forage production in mesic pastures, more productive regions. For the CENTURY model, forage yield

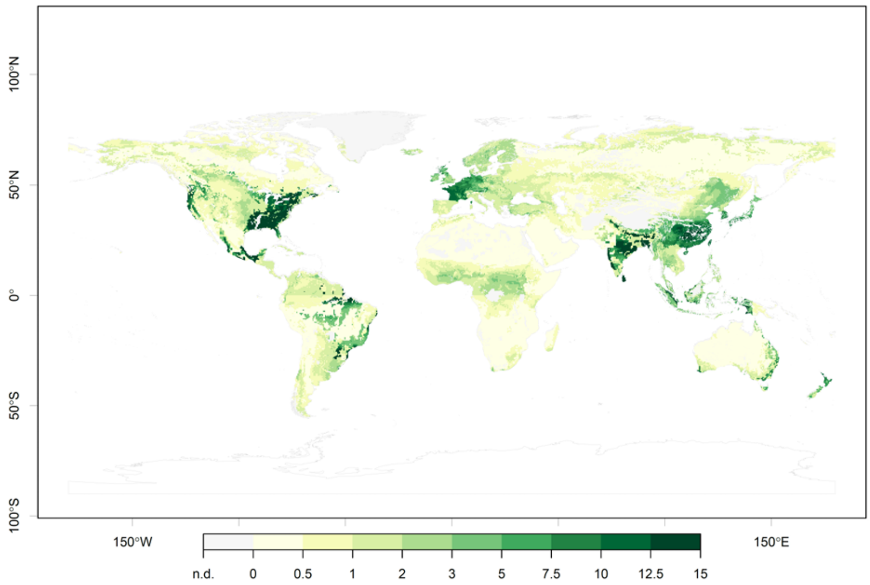

Figure 5: Forage available for livestock in tonnes of dry matter per hectare as the result of combination of outputs from the CENTURY and EPIC models.

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 et al. (2008). 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 (Mitchell & Jones, 2005). Soils data were derived from the FAO Soil Map of the World, as modified by (Reynolds et al., 2000). 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.

The EPIC model is 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 Figure 5.

2.4.5 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, the model does 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 (Keyzer et al., 2005).

2.5 Forestry

2.5.1 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. Woody biomass production costs in GLOBIOM cover 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 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.

2.5.2 Woody Biomass Demand and Forest Industry Technologies

The forest sector is modeled to have eight final products (sawnwood, plywood, fiberboard, chemical pulp, mechanical pulp, other industrial roundwood, fuelwood, and energy wood). 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. (2017).

2.5.3 Description of Global Forest Model (G4M) and its linkage to GLOBIOM

For more detailed representation of forest management systems and carbon dynamics, GLOBIOM can be linked to the Global Forest Model (G4M). G4M estimates the impact of forestry activities (afforestation, deforestation, and forest management) on biomass and carbon stocks. G4M produces afforestation and deforestation decisions by comparing net present values (NPV) of agriculture and forestry land uses. Afforestation occurs where it is more profitable than agriculture, and environmental conditions are suitable for forest growth. Deforestation, in contrast, occurs where agricultural NPV plus profit from single sales of deforested wood exceeds the NPV of forestry. The NPVs are estimated, accounting for agriculture land rents and wood prices, obtained from GLOBIOM along with the price of carbon stored in biomass. The land transitions in G4M are harmonized with GLOBIOM agriculture land demand. G4M simulates forest management aimed at sustainable production of wood that is projected by GLOBIOM on a regional scale, i.e. the harvest of wood does not exceed the forest growth. The main forest management options considered by G4M are variation of thinning, harvest intensity and forest residue collection. The harvest intensity is modelled through defining whether the forest is used for intensive wood production (managed forest) or no wood production (unmanaged forest). For the intensively used forest, harvest is determined by the choice of rotation length. The rotation length can be individually chosen, however, the model can estimate optimal rotation lengths to maximize increment, stocking biomass or harvestable biomass.

As G4M is based on a global 0.5 x 0.5 degree raster, which has a differing coverage and a potentially higher than GLOBIOM (depending on the model version), a downscaling module is used to link GLOBIOM output to G4M (for more details on the downscaling see Subsection 2.17). The downscaling model provides 5 arcminute land-use change projections, which are consistent with GLOBIOM regional totals. For the purpose of linking GLOBIOM and G4M cropland, grassland, short-rotation plantation, forest, and other natural vegetation are downscaled. Cropland, grassland, and short-rotation plantation areas are assumed to be productive land, which is not accessible for the purposes of afforestation. The land areas under forest and other natural vegetation are the base areas where G4M can allocate forest areas.

In every 0.5 x 0.5 deg. grid-cell where forest can grow according to the map of potential vegetation (Ramankutty & Foley, 1999) two virtual forests are created. One virtual forest is parameterised to observed data (forest area, above ground biomass, increment, forest management type, harvest intensity, protection status etc.) and the other virtual forest is created with the same parameters except for the forest area set to zero. The virtual forest area with the zero forest area is used for modelling the future afforestation.

The virtual forest module (Kindermann et al., 2013) simulates forest management on a scale of the forest composed of forest stands. The module describes the forest in terms of the dynamics of the stem wood. It consists of two parts: a submodule of forest growth, where the height of the stem, the diameter of the stem at the height of the breast (1.3 m) and biomass of tree stem for the given age are calculated; and a simulator of age cohorts, where final cut and thinning are simulated, and the dynamics of forest parameters is calculated. The simulator of the age cohorts creates a virtual forest in the form of 4 data arrays: area of age classes, biomass, diameter and height of trees in different age classes. Biomass, height and diameter, as well as total biomass increment with age, are calculated in the sub-module of growth functions in accordance with the forest growth conditions represented by mean annual increment (MAI) of normal forest (forest with uniform age structure), stocking density (SD), tree species and rotation time (RL). The forest is represented by a set of N (N = RL + 1) even age tree stands. The forest, which is created by the simulator of the age cohorts, may have a given age structure, that is determined with a relative area of forest stands of different ages, if such information is known, or have a "normal" age structure, that is all age classes have the same area. At every simulation step (5 years), the age of tree stands increases by the step of simulation; the biomass that is cut during thinning is calculated by comparing the available biomass in a certain age class and the total production in this age class, and taking into account the minimum diameter of the stems to be harvested and amount of wood that can be harvested; the harvesting of wood during the final cut is calculated by clear-cutting 1/RL of the share of forest area and replanting the area that forms normal forest in RL years. The set of forest parameters is initialized iteratively using spatial data and data for countries. The initial value of the relative stocking density of the simulated forest (SD) in the case when the age structure of the forest is known is determined as the ratio of the above-ground biomass of the simulated forest to the observational data. Mean annual increment is determined using a map of net primary production (NPP) (Kindermann et al., 2008a). For European countries, the MAI was modified at the country level to match the data given in the report red(Forest Europe, 2015) or the data provided by country experts. The above and below-ground estimates globally are based on (Kindermann et al., 2008a) and (Gallaun et al., 2010) for EU. The age structure of the forest is known at the country level and only for individual countries (mostly developed countries). The spatial data of MAI and above-ground biomass (stem biomass) are used as additional information to adjust the forest age structure in raster cells. For example, if the above-ground forest biomass, which is modelled with the country average age structure in a raster cell, exceeds the observed biomass considerably, then the age structure of the simulated forest is iteratively shifted by several age classes towards young forests (i.e., the area of young age classes increases and the area of old age classes decreases). If the age structure is not known, then a normal forest is created.

In G4M, protected forests are mapped following the World Database of Protected Areas (WDPA) (WDPA et al., 2010). The protected forests are a part of the UNFCCC managed forests and are subject to indirect human impact. In these forests, land use change and harvest are forbidden, however, the natural disturbances are simulated by adjusting the average tree lifespan to match the country forest management emissions.

In G4M, the forest management decisions in each forested grid cell are adjusted towards satisfying the wood demand in the region. Considered forest management decisions are alteration of rotation time and expansion or shrinking of the forest area used for wood production. A new adopted forest management should bring the regional harvest closer to demand and should not lead to negative net present value (NPV) of forestry or decrease the NPV by more than 5%. The harvest is intensified in the production forest in the first order while if reduction of harvest is required then the least productive forests under risk of deforestation are tuned first. The considered rotation time should be within the range from rotation maximizing MAI (the shortest) to the rotation maximizing standing biomass (the longest) thus assuring sustainable forest harvest.

In the case of non-zero carbon price, the value of carbon accumulated in the forest biomass above the baseline level (i.e., under zero carbon price) is accounted in the NPV calculation. The forest management is adjusted to maximize NPV in a grid cell and still satisfy the wood demand in the region. Usually, the cheapest option is to decrease the harvest intensity (extend rotation time) and expand the harvest area. When this option is exhorted, the wood price in the region increases to make the harvest competitive to carbon sequestration in order to satisfy the regional wood demand. G4M uses information on wood demand, wood and CO_2 prices from GLOBIOM.

The emissions of carbon dioxide from changes in biomass in the forest at the current modelling time step are calculated as a difference of biomass at the current modelling time step per unit area in tC/ha (the share of carbon in dry biomass is about 0.5 tC/t of dry matter) and the biomass at the previous modelling time step divided by the modelling time length and multiplied by the forest area at the current modelling time step. Biomass expansion factors from IPCC Good Practice Guidance (Penman et al., 2003) are used for converting between the stem biomass and total biomass.

The decision on deforestation, afforestation or no land use change in each raster cell at every modelling time step is made by comparison of the net present value of forestry multiplied by the calibration threshold coefficient for each country with the net present value of agriculture plus income from the sale of wood obtained from deforestation, taking into account the tax on carbon loss (if the price of carbon is greater than zero), if the territory is not protected (for example, natural reserve WDPA (2009)). In particular, deforestation occurs when the NPV of agriculture plus the value of deforested wood is greater than the NPV of forestry scaled by the hurdle coefficient. Afforestation occurs when the NPV of forestry scaled by the hurdle coefficient exceeds the NPV of agriculture. The NPVs of agriculture and forestry incorporate the agriculture land rent and wood price information from GLOBIOM. The agriculture NPV is a function of the population density (WDPA et al., 2010;

Grübler et al., 2007), the gross domestic production (GDP) based on World Bank (2005), agriculture suitability (Naidoo & Iwamura, 2007), road density (Center for International Earth Science Information Network - CIESIN - Columbia University & Information Technology Outreach Services - ITOS - University of Georgia, 2023) with an impact of the deforestation in previous modelling time step. Forestry NPV takes into account the price of wood, wood production costs, harvest losses red(UN-ECE/FAO, 2000; (Frank et al., 2020), risk-adjusted discount rate (Benítez et al., 2004), price of carbon and corruption (Kindermann et al. (2006) based on Kaufmann et al. (2005)).

The rate of deforestation is a function of the gross domestic production (GDP), population density, agriculture suitability and a share of the forest in the cell (Kindermann et al., 2008a). The deforestation rate is higher for places with large forest massifs, well suitable for agriculture where GDP is low. The deforestation rate increases when more people move to the place but start decreasing after reaching a certain amount of population density indicating that an urban environment is formed. The rate of afforestation is a function of GDP and agriculture suitability. In this case, GDP represents a capacity of planting or restoring forests and the agriculture suitability indicates the quality of soil and accessibility of land.

Deforestation causes the loss of carbon accumulated in the biomass of trees, which are partially burned, and partly used in industry and construction; carbon of dead trees which are burnt; carbon of forest litter and partly soil. We assume that the biomass emissions are released at the time of deforestation, while the litter and soil follow a decay curve depending on the annual air temperature and precipitation (Copernicus Climate Change Service - Climate Data Store, 2021). Deforestation leads to a loss of up to 40% of soil organic carbon (Czimczik et al., 2005).

In the case of afforestation, G4M considers carbon accumulation in tree biomass, litter, and soil leading to negative CO_2 emissions (or CO_2 sink). Carbon sequestration in stem biomass is estimated using the virtual forest (Kindermann et al., 2013) that applies forest stand growth curve approach with further conversion to total above-ground biomass (similarly as in the case of forest stands established before 2000). The amount of below-ground biomass depends on the amount of above-ground biomass and differs in tropical forests, temperate forests and boreal forests (Penman et al. (2003), Table 3A.1.8). Carbon in litter accumulates with a maximum rate of 0.95 tC/ha per year (Czimczik et al., 2005), the rate of carbon accumulation also depends on the biomass in the age cohorts, the amount of accumulated carbon can reach 5 tC/ha (the biomass dependence function is chosen so that with a biomass of 35 tC/ha, 90% of the maximum value is reached (Gusti et al., 2008). Carbon in the soil accumulates up to 140% of the initial value (almost the maximum value according to (Czimczik et al., 2005), that is achieved with the maximum amount of accumulated litter). The maximum accumulation rate for coniferous forests is 0.04 tC/ha per year, 0.2 tC/ha per year for mixed forests and 0.35 tC/ha per year for deciduous forests (Czimczik et al., 2005).

The rates of afforestation and deforestation in the G4M model were calibrated by minimising the sum of squared differences between the model results and respective data from the national inventory reports to the UNFCCC for the Annex-I countries or the FAO FRA 2020 data for the non-Annex-I countries. The afforestation and deforestation rates were averaged for the periods 1991-2000, 2001-2010, 2011-2015 and 2016-2020 as the data are presented in FAO FRA 2020. During the calibration three coefficients were determined for each country: hurdle – a multiplier of the forestry NPV, afforestation rate multiplier and deforestation rate multiplier. Additionally, the afforestation and deforestation rates for 1990-2020 were fine-tuned to match the respective observed values in each period. The tuning does not impact the afforestation and deforestation rates beyond 2020 but it has an effect on planted forest dynamics, afforestation, and deforestation emissions because of the legacy effect.

The harvest intensity of forests used for wood production is adjusted to match exogenous wood demand for regions (statistical values for the historical period and estimated by GLOBIOM or another model for projections). The intensity of natural disturbances (defined as a reversed value of average lifespan of trees in the forest) for the forests not used for wood production in the initial period is adjusted to match 'observed' forest management biomass emissions averaged for 1991-2020. For the Annex-I countries, we use the biomass CO_2 emissions for the forest land remaining forest land that is derived from the countries' national GHG inventory reports to the UNFCCC. For the non-Annex-I countries, we use the difference in forest biomass in 1991-2020 as presented in the FAO FRA 2020 as non-Annex-I countries do not report their national GHG inventories at the same level of detail as Annex-I countries. First, the disturbance intensity is adjusted for all countries. Then, since the Annex-I countries report the forest management emissions only for the UNFCCC managed area, we adjust the disturbance intensity for the Annex-I countries only for the UNFCCC managed forests that are not used for wood production.

2.6 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. The suitability analysis defines areas according to aridity Zomer et al. (2008), accessibility Nelson (2008), protection WDPA (2009) and altitude. The potential productivity of plantations is based on estimates from the Potsdam Net Primary Productivity Model Inter-comparison calibrated to a global SRP yield database FAO (2006). Potential yields are available in the model for stemwood (tonne dry matter) and whole tree biomass (solid m3), conversion between the two forms is obtained by applying regional expansion factors accounting for tree branches and tops. Production costs per unit of product (including planting, cultivation and harvesting) are calculated by combining econometric and engineering costing based on literature sources[10]. Several deployment potentials can be considered depending on land use available (cropland, grassland, other natural vegetation), natural forests are excluded from energy plantation expansion. The suitability and yield data are also used to update the model with the amount

[9] See Weih (2004)

[10] SeeHavlík et al. (2011) for full details on methods for suitable areas, productivity and costs.

of carbon that is sequestered in energy plantations, according to the biomass accumulated in half period of the rotation cycle. Fertilization rates for Nitrogen and Phosphorus are adjusted to plantation yields according to three yield levels, and fertilizers return rates are calibrated to (Gabrielle, 2013; Gonçalves et al., 2008; Murphy, 2014).

2.7 Food Demand

Food demand in GLOBIOM is endogenous and depends on population, gross domestic product (GDP), and own product price. Population and GDP are exogenous variables, while prices are endogenous. The simple demand system is presented in equation 10. 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 income elasticity ε^{GDP} and the base year consumption level as reported in the Food Balance Sheets of FAOStat. If the *prior* demand 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}.

$$\frac{Q_{i,r,t}}{\bar{Q}_{i,r,t}} = \left(\frac{P_{i,r,t}}{\bar{P}_{i,r,2000}}\right)^{\varepsilon^{price}_{i,r,t}} \text{ where } \bar{Q}_{i,r,t} = \frac{POP_{r,t}}{POP_{r},2000} \times \left(\frac{GDP^{cap}_{r,t}}{GDP^{cap}_{r,2000}}\right)^{\varepsilon^{GDP}_{i,r,t}} \times \bar{Q}_{i,r,2000} \quad (10)$$

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). Initial values of these elasticities in GLOBIOM are sourced from the USDA demand elasticity database[11]. In this database, price elasticities of demand are lower for developed countries than for developing countries and lower for cereals than for meat products. This is consistent with observations. The value of both income and price elasticity are assumed to decrease exogenously with the level of GDP per capita. The rule we apply is that elasticity values converge to the elasticity value 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 and income on food consumption taking into account heterogeneity of responses across regions, products and over time. Because GLOBIOM accounts for food commodity through the commodity balance accounts provided by FAO, the model can report impact of these price changes as variations in supply of kcal per capita, and proteins or other macronutrients, as a result of a specific policy.

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,

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

this demand function has 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.

Although GLOBIOM does not represent cross-price effects 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 [12].

Similarly, food consumption patterns are determined by income (GDP) changes. Income effect in GLOBIOM captures the pure effect of income but also indirectly of some other patterns that reflect structural changes (urbanization, consumer changes with globalization, etc.) and cannot be disentangled for the estimation. Following Engel's law, food demand increases with increasing income - with this increase becoming less proportional with income. When the income of a region changes, any changes in demand are proportional to the income elasticity associated to each region and product. As different food products have different income elasticities, any changes in income will also result in shifting

[12] 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)

dietary patterns. For example, income elasticity values for meat products are typically higher than for cereal products. This means that an increased income will result in a proportionally larger increase in demand for meat products than for cereals. Likewise, any shifts in dietary patterns determined by income changes are considered. Simultaneously, regional differences in the values of income elasticity allow for GLOBIOM to account for heterogeneity in income effects between regions. Income differences within regions are currently not considered.

The initial values of these elasticities are sourced from the same USDA demand elasticity database and the Food Balance Sheets (FBS) from FAO. Indeed, although the USDA database provides a convenient ready-to-use set of elasticities, their values have been criticized, in particular in the case of Europe (see (Abler, 2010)). To complement this dataset with more accurate information, regressions on the FAO FBS versus the change in income per capita on the period 1995-2005 were performed. When a robust trend was observed, the corresponding income elasticity was preferred calibrate the initial year of GLOBIOM. This approach in particular allows for better reflection of recent observed trends (such as decrease of cereals in consumption in several regions such as Europe or China, which are not reflected with the positive elasticity estimates evaluated by USDA).

In order to project food consumption, a last assumption needs to be made on the trend of the income elasticity, to reflect the change in marginal utility associated to food consumption when a country progressively develop. To derive this parameter, we build some scenarios of future diets mainly based on FAO projections (Alexandratos & Bruinsma, 2012). These scenarios are adapted to the different storylines for each modeling exercise. The general rule for developed countries is that consumption do not exceed 3600 kcal/c/d, which is slightly higher than the level of Western Europe. The only exception is the United States that show already consumption over this level and is projected until a level of 4000 kcal/c/d. It is important to note that these levels are much higher than the nutrient prescriptions (usually around 2,800 kcal/c/day for a strong and active adult), because FAO data correspond to food available for final consumer, which therefore includes domestic waste.

The Socio-Economic Pathways (SSPs) developed in the context of climate change scenarios for the next IPCC Assessment Report provide storylines of possible future and quantified population and GDP projections (O'Neill et al., 2012). The storylines were adapted in the food consumption context to derive diet assumption for the different scenarios as follows:

- For SSP2 (Middle of the Road), these future diets follow the projections from FAO at the horizon 2050.

- For SSP1 (Sustainability), future diets are considered to be more sustainable than in the FAO baseline. Therefore some alternative assumptions are made on total consumption per capita and demand for some specific products. First, to reflect the better management of domestic waste in developed countries, consumption per capita in the regions is assumed almost constant, whereas it could increase in SSP2 for some developed regions (North America for example). Second, animal protein demand is reduced in regions where more than 75 grams prot/cap/day are consumed for animal and vegetable products. A minimum consumption of 25 grams prot/cap/day of animal calories is ensured but red meat consumption is reduced to 5 grams prot/cap/day (target remains possible through non ruminant meat, eggs and milk). For developing regions, more nutritious diets are assumed and this materialized through an increase in protein intake at 75 g prot/cap/day and a reduction of root consumption at a level of 100 kcal/cap/day.

- For SSP3 (Fragmented world), as economic growth is much lower in developing region, the income effects alone lead to a significantly lower demand per capita in these regions.

2.8 Biofuel and Bioenergy Representation

2.8.1 Biofuels Representation

Biofuels differentiated by feedstock
First generation biofuel products can be produced from different crop feedstock and include biodiesel (sourced from rapeseed, soya, or oil palm) and bioethanol (sourced from corn, sugar cane or wheat). These feedstocks differ in their conversion efficiencies (Valin et al., 2015). Scenario specific biofuel mandates can be implemented in the model by feedstock and region e.g. that European biodiesel use will continue to rely heavily on rapeseed in the future.

2.8.2 Bioenergy in GLOBIOM

Adapted from paper Wu et al. (2023)
As documented in previous sections, GLOBIOM has a detailed representation of different primary biomass feedstocks and bioenergy production processes (Havlík et al., 2011; Lauri et al., 2017; Frank et al., 2021). Four main categories of bioenergy feedstocks are represented in GLOBIOM:

- Woody biomass feedstocks from forest: these include energy wood from the forest sector, and fuelwood used in the residential sector. Energy wood can be sourced either from forest residues (logging residues) and forest industry by-products (sawdust, bark, woodchips, wood pellets, black liquor, and recycled wood) which are cheaper bioenergy feedstocks that will be first deployed when bioenergy demand increases, or directly from round woods (sawlog or pulp log) whose use for energy is expensive in usual cases and not as cost competitive. Fuelwood is the biomass collected from forest or deforestation, and utilized in traditional forms (for heating and cooking) in the residential sector. The demand for fuelwood is separately estimated by applying income elasticities from empirical study and literature.

- Woody biomass from short rotation tree plantations: these indicate tree plantations including poplar, willow, and eucalyptus with rotation periods of up to 10 years. It is also called industrial plantation biomass, or dedicated energy plantations/crops, since it is planted specially for energy use and therefore distinguishes from other types of biomass feedstocks.

Biofuel products generated from this type of biomass are categorized as second-generation biofuel (also referred to as "cellulosic ethanol" Fargione et al. (2010) or "advanced biofuel" Wu et al. (2019) in literature). Compared with grassy biomass feedstocks, short rotation tree plantations can be more flexible in bioenergy conversion since the energy conversion technologies for tree plantation face fewer limitations Bauer et al. (2020). In deep decarbonization mitigation pathways simulated by integrated assessment models, this type of biomass feedstocks is projected to become increasingly important to achieve higher penetration of bioenergy in the energy system. Demand for bioenergy from woody biomass, including energy wood and short rotation plantations, can be derived from the common application of MESSAGEix-GLOBIOM modeling (Frank et al., 2017; Fricko et al., 2017) or other energy modeling studies.

- Crop feedstocks for first-generation biofuels: these include grain crops (wheat and corn) and sugarcane that can be transformed into bioethanol, and oil crops (oil palm, rapeseed, and soybean) that can be utilized to produce biodiesel. Demand for first-generation biofuel crop feedstocks can be derived from the POLES model Després et al. (2018) or other exogenous estimates.

- Other non-woody biomass: other biomass feedstocks from non-woody materials, including agricultural residues, municipal waste, manure, and other forms of bio-waste. Demand and supply for this part of bioenergy is exogenously considered.

Depending on research need, endogenous representations of bioenergy from crop residues (considering dynamics in crop production and feedstock competition) or more detailed representation of energy wood biomass can be introduced in the GLOBIOM model. Figure 6 illustrates the main biomass feedstocks and the processes related to bioenergy production that are depicted in the GLOBIOM model.

2.9 International Trade

2.9.1 Reasons for Trade and the Homogeneous Good Assumption

Adapted from Mosnier (2014)

Adam Smith (1776) and his theory of absolute advantages stated that trade may occur when one country can produce another good more efficiently than another one. Ricardo (1817) goes further with the theory of comparative advantage by predicting that a country will export products for which it has higher labor productivity relative to its labor productivity in other products. According to the Hecksher-Ohlin-Samuelson (HOS) theory of trade (Ohlin, 1933; Samuelson, 1952), a country should specialize in and export a product that uses more intensively the factor of production with which the country is well endowed. New trade theory emerged in the eighties and relaxed the assumptions of constant returns to scale and perfect competition in the neoclassical framework, and emphasized

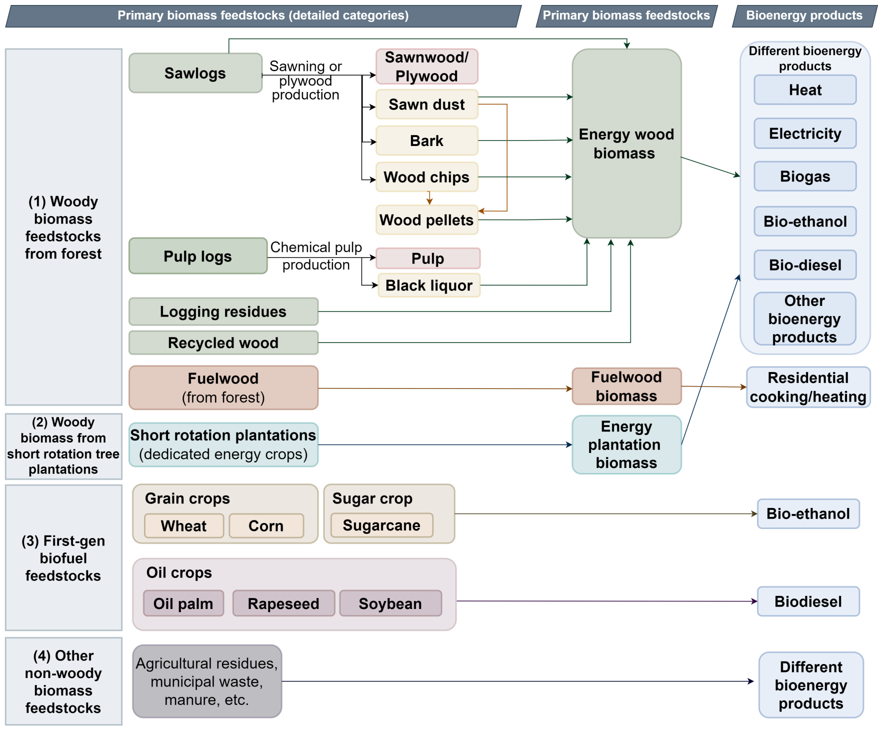

Figure 6: Bioenergy feedstock categories and processes represented in GLOBIOM

economies of scale and product differentiation. Countries may lose from trade when external economies of scale in their specialization pattern are relatively small and/or the income elasticity of the products in which they specialize is low. But when consumers perceive non price differences among the competitors' products, trade increases market size which may expand the scale of production and may enlarge the variety of goods available to consumers. The synthesis advanced in Helpman & Krugman (1987) is that the HOS trade model and the new trade theory are complementary in nature: *inter-industry trade results from factor endowments and specialization while the intra-industry trade can be explained by product differentiation and scale economies.*

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 (IIT) between different regions. It is first explored if this assumption is consistent with observed trade patterns for the products modeled in GLOBIOM. Intra-industry trade can be defined as the value of exports of an industry which can be matched exactly by the value of imports of the same industry (Grubel & Lloyd, 1975). If there are n industries, where $i = 1, \ldots, n$, and X_i is the aggregate value of the i$^{\text{th}}$ industry and M_i is the aggregate value of imports of that industry then intra-trade can be expressed as equation 11 below.

$$R_i = (X_i + M_i) + |X_i - M_i| \tag{11}$$

Where $|X_i - M_i|$ is the measure of inter-industry trade. Thus *IIT* is simply the complement of inter-industry trade. The value of *IIT* can be normalized by dividing R_i by the total industry trade as in equation 12 below.

$$B_i = \frac{R_i}{(X_i + M_i)} = \frac{|X_i - M_i|}{X_i + M_i} \tag{12}$$

It is the proportion of total trade that is intra-industry in nature. This is also known as the Grubel-Lloyd index of IIT. The economy wide measure of IIT is obtained as a weighted average of B_i for all n industries using the relative shares of total trade for each industry as weights. The same is done to compute an average measure of IIT by industry.

For most of the GLOBIOM modeled-products, based on the COMTRADE-BACI trade data, the average share of IIT over 2001-2004 has been lower than 10% (Figure 7). For the largest amounts of traded crops such as wheat, soybeans or maize, IIT is lower than 5% and we observe only one crop – potatoes – with a share of IIT higher than 10%. Rapeseed oil, sunflower oil, sawnwood, pulpwood, and animal products seem to be more differentiated with a share of IIT higher than 10% but still lower than 25%. These results suggest that the homogeneous good assumption is appropriate for the products GLOBIOM represent and that trade in raw agricultural products is mainly explained by factor endowments and specialization. This is consistent with previous studies which have highlighted that even if IIT has considerably increased in the food and animal sector over the previous decades, it was mainly driven by outward processing and remained quite low for primary products (Brülhart, 2009).

GLOBIOM represent international markets and their various products traded between regions, relying on international trade statistics for trade and tariffs[13]. Trade in GLOBIOM represents products 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 trade from the same region. In this framework, all substitutions of traded goods are performed quantitatively. Some patterns of new trade development are 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.

2.9.2 Implementation

Adapted from Janssens (2022)

[13] 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.

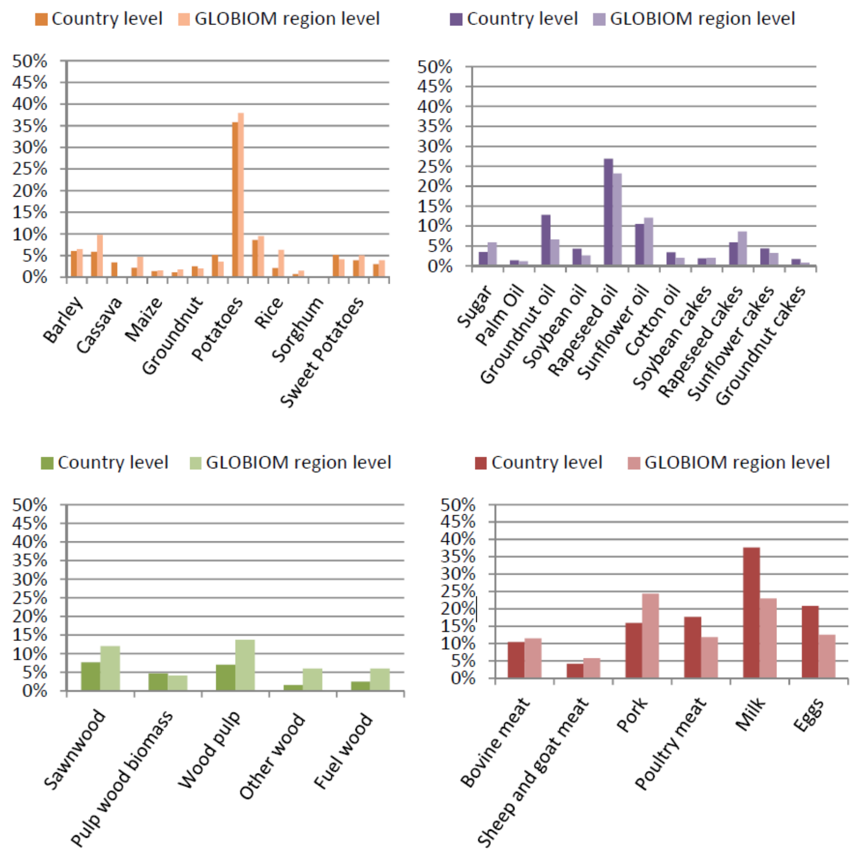

Figure 7: Percentages of intra-industry trade in total traded quantities of GLOBIOM products in 2000

GLOBIOM captures inter-regional trade through Enke-Samuelson-Takayama-Judge spatial equilibrium assuming homogenous goods (Mosnier et al., 2014a; Takayama & Judge, 1971). In each time step, the sum of producer and consumer surplus minus total trade costs is maximized. Total trade costs are defined for existing trade flows (intensive margin, equation 13) and new trade flows (extensive margin, equation 14), respectively

$$\int \varphi^{trad,int}_{r,\check{r},t,i}(T_{r,\check{r},t,i})d(.) = \tau^{policy}_{r,\check{r},t,i} \times T_{r,\check{r},t,i} + \frac{\varepsilon}{1+\varepsilon} \times \tau^{transaction,int}_{r,\check{r},t,i} \left(\frac{T_{r,\check{r},t,i}}{T_{r,\check{r},t-1,i}}\right)^{\frac{1+\varepsilon}{\varepsilon}} \times T_{r,\check{r},t,i} \tag{13}$$

$$\int \varphi^{trad,int}_{r,\check{r},t,i}(T_{r,\check{r},t,i})d(.) = \left(\tau^{policy}_{r,\check{r},t,i} + \tau^{transaction,int}_{r,\check{r},t,i}\right) \times T_{r,\check{r},t,i} + 0.5 \times \sigma \times T^2_{r,\check{r},t,i} \tag{14}$$

where $T_{r,\check{r},t,i}$ is the bilateral trade quantity of product i from exporting region r to importing region ř in period t, $\tau^{transaction,int}_{r,\check{r},t,i}$ the transaction costs, $\tau^{policy}_{r,\check{r},t,i}$ the policy-related costs and parameters ε and σ determine the non-linear trade expansion cost. This non-linear element allows to model persistency in trade flows and reflects the cost of trade expansion in terms of infrastructure and capacity constraints in the transport sector [14]. The maximum factor change allowed per decade for each trade flow is 7.45. Transaction costs (equation 15 abd 16) consist of bilateral transport ($t^{transport}_{r,\check{r},t,i}$) costs and unilateral import ($t^{import}_{\check{r},t,i}$) and export ($t^{export}_{r,t,i}$) costs from inland transport and administrative procedures (documentary and border compliance). In case of new trade flows, an entry cost ($P^{market}_{r,t,i} \times m^{entrycost}_{r,\check{r},t}$) is included to reflect the start-up cost of establishing a new trade relationship. The policy-related costs (equation 17) consist of tariff costs ($t^{tariff}_{r,\check{r},t,i}$) and a calibrated trade cost term ($t^{calib}_{r,\check{r},t,i}$) that fills the importer-exporter price gap in the initial spatial price equilibrium and is kept constant across time steps and scenarios. This term captures any trade cost element that is not explicitly accounted for, but that contributes to the price gap between importer and exporter prices (e.g. import and export taxes).

$$\tau^{transaction,int}_{r,\check{r},t,y} = t^{transport}_{r,\check{r},t,y} + t^{export}_{r,t,y} + t^{import}_{\check{r},t,y} \tag{15}$$

$$\tau^{transaction,ext}_{r,\check{r},t,y} = t^{transport}_{r,\check{r},t,y} + t^{export}_{r,t,y} + t^{import}_{\check{r},t,y} + P^{market}_{r,t,y} \times m^{entry\,cost}_{r,\check{r},t} \tag{16}$$

[14] Other studies that have adopted non-linear (i.e. convex and increasing) trade costs in modelling agricultural trade in order to avoid corner solutions in trade patterns and to derive (closed-form solutions of) smooth specialization patterns are Nolte et al. (2012) and Allen & Atkin (2016). In Nolte et al. (2012) the non-linear trade costs are motivated by diversification of exporters into different destination markets in order to minimize risks. In Allen & Atkin (2016) non-linear trade costs are proposed to originate from heterogeneity in trade productivity across traders that are all equally capacity constrained. In our study, trade costs are increasing in traded quantity to reflect capacity constraints of the transport sector to deal with increasingly larger trade volumes. Port capacity constraints are for example suggested as a constraint for the expansion of short sea shipping in the Southern African Development Community (Konstantinus et al., 2019).

$$\tau^{policy}_{r,\check{r},t,y} = t^{tariff}_{r,\check{r},t,y} + t^{calib}_{r,\check{r},t,y} \tag{17}$$

Enke-Samuelson-Takayama-Judge spatial price equilibrium set-up implies that interregional trade will only occur when the cost of trade between two regions is smaller than the market price difference, and this price difference will become equal to the marginal trade cost in equilibrium (McCarl & Spreen, 1980). The spatial price equilibrium for an intensive (equation 18) and extensive margin (equation 19) trade flow ($T_{r,\check{r},t,i}$) of product i from exporting region r with market price $p^{market}_{r,t,i}$ to importing region $\tilde{r}$ with market price $p^{market}_{\tilde{r},t,i}$ is given below

$$\textit{Intensive Margin: } p^{market}_{r,t,i} + \tau^{policy}_{r,\check{r},t,i} + \tau^{transaction,int}_{r,\check{r},t,i}\left(\frac{T_{r,\check{r},t,i}}{T_{r,\check{r},t-1,i}}\right)^{\frac{1}{\varepsilon}} = p^{market}_{\tilde{r},t,i} \tag{18}$$

$$\textit{extensive Margin: } p^{market}_{r,t,i} + \tau^{policy}_{r,\check{r},t,i} + \tau^{transaction,int}_{r,\check{r},t,i} + \sigma T_{r,\check{r},t,i} = p^{market}_{\tilde{r},t,i} \tag{19}$$

Compared to the trade implementation in earlier versions of GLOBIOM as described in Janssens et al. (2020), additional transaction costs are explicitly incorporated (import export costs) and the parameterization of the trade cost functions is updated to reflect determinants of agricultural trade growth at the extensive margin (next section). Overall, in terms of the size of trade adjustments, our trade implementation lies between the rigid Armington approach of general equilibrium models and the flexible integrated world market approach of many partial equilibrium models.

2.9.3 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.

2.9.4 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 or Standard International Trade Classification and since 1988 for HS or Harmonized system). 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 & 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.

2.9.5 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 & 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 (Guimbard et al., 2012). The 2001 MacMap version is used in the GLOBIOM analyses.

2.9.6 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 & van Wincoop, 2004; Berthelon & 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 from India, and USD 1,300 from Sierra Leone (World Bank, 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, 1999). 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 (1999) 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) as seen in equation 20 below.

$$\ln F_{i,j,k} = \alpha_i + \ln DIST_{i,j} + \delta \ln \frac{WGT_{i,j,k}}{V_{i,j,k}} + \varepsilon_{i,j,k} \tag{20}$$

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.

International transport costs cover road and ocean transport costs and are compiled based on the empirical estimation of (Hummels, 1999) using distance between country pairs and the weight-value ratio of agricultural products. Sea distance is based on CERDI-seadistance database (Bertoli et al., 2016) and road distance is from CEPII's GeoDist database (Mayer & Zignago, 2011). For road transport between African countries, transport costs are directly calculated through the combination of variable (VC) and fixed transport (FC) costs, adjusted for the profit margin of trucking companies (equation 21, 22, 23, 24)[15]. Variable costs cover fuel costs as well as costs of tires, maintenance and bribes. Fixed costs include driver wages and the costs of trucks, taxes and licenses.

$$T_{road,c,\check{c}} = \frac{FC_{c,\check{c}} + VC_{c,\check{c}}}{\mathit{load\ capacity}} \times \left(1 + m_{c,\check{c}}^{\mathit{profit\ transporter}}\right) \tag{21}$$

$$VC_{c,\check{c}} = \mathit{fuel\ consumption}_{c,\check{c}} \times \mathit{fuel\ price}_{c,\check{c}} \times \left(1 + \%\ \mathit{other}\ VC_{c,\check{c}}\right) \times d_{c,\check{c}} \tag{22}$$

$$FC_{c,\check{c}} = \mathit{daily}\ FC_{c,\check{c}} \times \mathit{travel\ time}_{c,\check{c}} \times 2 \tag{23}$$

$$\mathit{travel\ time}_{c,\check{c}} = \frac{d_{c,\check{c}}}{\mathit{speed}_{c,\check{c}}} + \mathit{border\ waiting\ time}_{c,\check{c}} + \mathit{other\ waiting\ time}_{c,\check{c}} \tag{24}$$

The import and export costs cover the costs related to the inland transport (between warehouse and port or border), document preparation and border compliance when importing or exporting a good. The costs related to document

[15] As an illustration of the challenges of cross-border trade in Africa, we refer to the following documentary on formal and informal barriers to cross-border food trade in West-Africa based on a road trip from the port in Tema, Ghana, to Ouagadougou, Burkina Faso: https://univideo.uni-kassel.de/video/Trading-Food-across-West-African-Borders-full-version/9f8eee1ab23e865b6476ce5a4d7eae19

and border compliance are based on the World Bank Doing Business Survey, in specific the "Trading Across Borders" indicators, and reflect the impact of non-tariff measures (NTMs) on African trade costs. NTMs represent a heterogeneous group of policies such as sanitary and phytosanitary measures (SPS), technical barriers to trade (TBT), price- and quantity control, or export restrictions (Bouët et al., 2020). The Tripartite Free Trade Area in Africa, which covers three RECs (COMESA, EAC and SADC) created an online tool to report, monitor and eliminate non-tariff barriers among its member states. Between 2004 and 2019, 40% of the filed complaints dealt with obstacles related to custom procedures and 19% with transport, clearing and forwarding issues. The ITC NTM Business Surveys reveal that the most frequent NTMs faced by African agricultural export firms are conformity assessments (product certification, inspection requirement) and export-related measures (licenses, permits, inspection, taxes) (ITC, 2021). Further, exporters perceive NTMs as burdensome often more because of procedural obstacles associated with technical measures that cause delays or demand high fees, rather than that the technical requirements themselves would be too stringent or complex to comply with (ITC, 2014, 2018a,b). Given that the import and export costs for documentary and border compliance from the World Bank Doing Business Survey reflect the costs of obtaining, preparing and submitting the required documents and the costs of customs clearance and inspections, we consider these as a measure for the impact of NTMs on African trade costs. The inland transportation costs are calculated based on the distance from the capital to the main port (CERDI-seadistance database (Bertoli et al., 2016)) or a country's average internal distance (CEPII GeoDist database (Mayer & Zignago, 2011)) and a per ton-km transport cost based on the compilation of local transport cost (but excluding the first mile cost and low-loading capacity transport).

Data on tariff costs is taken from the MAcMap-HS6 2001 and 2010 releases from CEPII-ITC which provides ad valorem and specific tariffs, and shadow tariff rates of tariff rate quotas (Bouët et al., 2004; Guimbard et al., 2012). Tariffs are converted to specific equivalent to include in GLOBIOM in the 2000 and 2010 time steps as trade is modelled in quantity rather than value.

Trade costs between countries are aggregated to the regional level. The bilateral transport ($t^{transport}_{r,\check{r},t,y}$) and tariff ($t^{tariff}_{r,\check{r},t,y}$) costs between two regions is a weighted average of the transport cost between all country pairs with the production of the exporting countries and consumption of the importing countries as weight. When both road and ocean transport are possible between two countries, the cheapest transport mode is selected. For most African trade links ocean transport is the cheapest, the largest share of road transport occurring between SACU and RSouthAf (37.5% of trade links) and between ECCAS and RCEAf (30% of trade links). Import and export costs are aggregated to regional level ($t^{export}_{r,\check{r},t,y}$, $t^{import}_{r,\check{r},t,y}$) weighted by consumption (import costs) or production (export costs) of the individual countries.

Default values of the trade expansion cost parameters (ε and σ) are calibrated to reflect a stable trade pattern over time. We further adjust the trade expansion parameters by exporting region based on the evolution of a set of key trade growth indicators. Clark et al. (2004) find that an exporter's port efficiency significantly determines maritime transport costs and that improvements in efficiency increase bilateral trade. For the intensive margin function, trade expansion is therefore made more flexible if the port efficiency index of the exporting region improved over time. In specific, the value of ε is increased by factor 4 for medium port efficiency improvement (e.g. Brazil) and by factor 10 for large port efficiency improvement (e.g. Russia, India or Egypt). For the extensive margin function, we estimate a Probit model on the determinants of new trade flows at GLOBIOM region, product and time resolution. Given the 10-year time step in GLOBIOM, we investigate the determinants of trade growth at extensive margin over one decade (2000 – 2010 and 2006 – 2016). We define a sample of importer (i) - exporter (j) pairs that did not trade a certain product (k) in the base time period (t) (2000 or 2006) and estimate the probability to start trading $\rho_{ijk,\triangle t}$ conditional on explanatory variables with the following Probit model below

$$\begin{aligned} \rho_{ijk,\triangle t} &= Pr(Y_{ijk,\triangle t} = 1 | \textit{explanatory variables}) \\ &= \phi\left(\beta_0 + \beta_1 x_{1i} + \beta_2 x_{2ik} + \beta_3 x_{3ij} + \beta_4 x_{4ijk} + \alpha_k + \alpha_j\right) \end{aligned} \tag{25}$$

Recent advances in trade theory highlight that export participation depends on sunk entry costs (Melitz, 2003), consisting of information costs, transaction costs, or market adjustment costs (Kandilov & Zheng, 2011). To the best of our knowledge there is no comprehensive global dataset on entry costs in agricultural trade available. We therefore calculate a proxy for entry costs as a margin on the exporter's market price to reflect that it are only the more productive firms that will enter into export markets (Melitz, 2003). In GLOBIOM, the market price is equal to the sum of the producer price and local trade cost, so regions with more competitive producing areas and lower market access costs will have a larger likelihood to create new exports. Kandilov & Zheng (2011) find that the impact of entry costs on agricultural market participation differs across commodities and bilateral trade patterns. In GLOBIOM, we differentiate the entry cost margin ($m^{entrycost}_{r,\check{r},t}$) across trade partners to reflect the bilateral drivers of the extensive margin of agricultural trade that were identified. In specific, the entry cost margin $m^{entrycost}_{r,\check{r},t}$ is assumed 20% by default, and is reduced to 10% under high bilateral trade intensity (i.e. larger than 6%) or in case that the trade partners participate in a regional free trade agreement.

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'.

Calibration method

Despite the long history of transport models, calibration of these models has received little attention (Jansson & Heckelei, 2009). Many contributions to the transportation costs minimization problems perform no balancing of the baseline and start at a state of disequilibrium, or if they do, they do not use data on prices and trade flows. We use the calibration method proposed by Jansson & Heckelei (2009) 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 (Equation 26) under the market equilibrium constraint (27). This is solved with the linear programming solver cplex.

$$\min_x = \sum_{i,j} (co_{i,j} + t_{i,}) \times X_{i,j} \tag{26}$$

$$e_i + \sum_j (X_{i,j} - X_{j,i}) = 0 \tag{27}$$

$$X_{i,j} \geq 0 \tag{28}$$

Parameters are co_{ij} the bilateral transportation costs, t_{ij} the specific equivalent tariffs and e_i the net trade. The variable x_{ij} 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 (Equation 13). 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 w_c, w_p and w_x, 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 27 and the price chain constraint 31 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.

$$z = w_c \sum_{i,j} (c_{i,j} - co_{i,j})^2 + w_p \sum_i (p_i - po_i)^2 + w_x \sum_{i,j} (x_{i,j} - xo_{i,j})^2 \tag{29}$$

$$c_{i,j} + t_{i,j} - p_j + p_i = 0 \tag{30}$$

As it is highlighted by Jansson & 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 et al., 2005) 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 equation 30 by a positive variable π as shown in the equation 31. Then, we add a complementary slackness condition (equation 32 where the penalty depends on the value of the parameter μ and the value of the trade flow times the corresponding price chain residual π_{ij} computed in equation (15). If trade occurs ($x_{i,j} > 0$), $\pi_{i,j}$ 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 (equation 33) and the value of is progressively increased to force $\pi_{i,j}$ to decrease to zero.

$$c_{i,j} + t_{i,j} - p_j + p_i = \pi_{i,j} \tag{31}$$

$$pen = \mu \times \sum_{i,j} (_{i,j} \times x_{i,j}) \tag{32}$$

$$zz = z + pen \tag{33}$$

$$\pi_{i,j} \geq 0 \tag{34}$$

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 (equation 35). 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 equation 33 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.

$$\text{if } xo_{i,j} = 0 \text{ , } x_{i,j} = 0 \tag{35}$$

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 (Figure 8).

For major traded crops such as wheat, soybeans or barley, the sum of total deviations between computed and observed bilateral trade flows is reduced by more than 10 times with trade calibration and the improvement is even larger for livestock products. The correlation of computed bilateral trade flows with observed ones also increases from 0.27 to 0.68 with trade calibration and it avoids extreme specialization of trade patterns in the model with about 50% of match

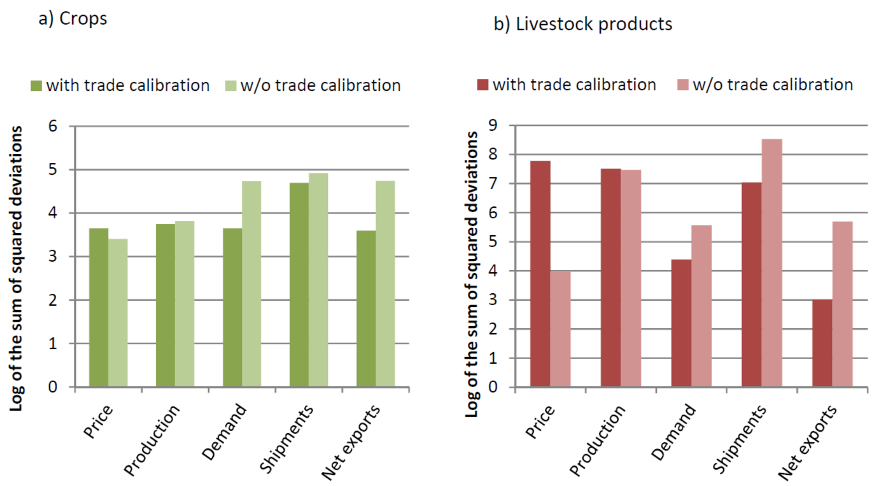

Figure 8: Distance of computed prices, production, demand, bilateral shipments and net exports quantities to observations in 2000 with and without trade calibration for crops (a) and livestock products (b)

between computed and observed bilateral trade flows instead of 10% without trade calibration (Table 4).

Table 4: Comparison of computed bilateral trade flow with observed ones with and without trade calibration in 2000

	With Trade Calibration	Without Trade Calibration
Correlation coefficient		
Total	0.68	0.27
Crops	0.66	0.28
Livestock products	0.98	0.10
Match of computed trade flows with observed trade flows		
Total	49%	10%
Crops	46%	11%
Livestock products	55%	6%

Non-linear trade costs function

There is a certain continuity of trade patterns over time. Helpman & Krugman (1987) found that the rapid growth of world trade between 1970 and 1997 was predominantly due to the growth of the volume of trade between already trading partners rather than due to the expansion of trade among new trade partners. Roberts & Tybout (1997) show that prior export experience increase the probability of export by 60 percentage points. Recent empirical literature also finds that trade is more persistent when it starts with high values (Besedes & Prusa, 2006).

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 this stylized fact 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 et al., 2004; Haveman et al., 2009; Limão & 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. 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. An elasticity of 3 is used in the model.

2.10 GHG Emissions and Mitigation Options

2.10.1 GHG Emissions

A dozen different GHG emissions sources related to agriculture and land use change are represented in GLOBIOM. Agricultural emission sources covered represent nearly all of total agricultural emissions according to FAOStat. Table 5 gives an overview of the CH_4 and N_2O emission sources covered. Currently, N_2O and CH_4 emissions from residue and savannah burning, and soil N_2O emissions from crop residues and cultivation of organic soils are not considered explicitly in the model but kept static over time.

Table 5: Non-CO_2 GHG emission sources covered in GLOBIOM.

Sector	Source	GHG	Reference	Tier
Crops	Methane emissions from flooded rice fields	CH_4	Average value per ha from FAO	1
Crops	Nitrous oxide emissions from the application of synthetic fertilizers on the field	N_2O	EPIC runs output/IFA + IPCC EF	1
Crops	Nitrous oxide emissions from the application of organic fertilizers on the field	N_2O	RUMINANT model + Livestock systems	2
Livestock	Methane emissions from enteric fermentation of ruminants	CH_4	RUMINANT model	3
Livestock	Methane emissions from the management of animal manure (e.g. storage, treatment) on the farm	CH_4	RUMINANT model + Literature review	2

Livestock	Nitrous oxide emissions from the management of animal manure (e.g. storage, treatment) on the farm	N_2O	RUMINANT model + Literature review	2
Livestock	Nitrous oxide emissions from the manure dropped/applied on pastures	N_2O	RUMINANT model + Literature review	2

Land use change emissions as represented in GLOBIOM are consistent with recent reporting, although slightly lower [16] (Valin et al., 2013). All GHG emissions calculations in GLOBIOM are based on IPCC guidelines on GHG accounting. 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.

2.10.2 Greenhouse Gas Mitigation Options

Adapted from Frank et al. (2021)

GLOBIOM models a comprehensive set of GHG mitigation options for the AFOLU sectors (Frank et al., 2018). GLOBIOM considers structural and technical non-CO_2 mitigation options for the agricultural sectors. Structural mitigation options for agriculture are considered in the model through different management systems (four for crop and eight for livestock production systems). This detailed representation of agricultural production systems allows for explicit representation of structural changes in the sector under a climate policy. With this framework, farmers can switch to a more GHG efficient management practices on site, as well as to reallocate production to more productive areas within a region, or through international trade across regions. In addition, a set of technological mitigation options such as anaerobic digesters, animal feed supplements etc. are represented in the model based on the Environment Protection Agency (EPA) mitigation option database. Emission reduction potentials (% emission savings), costs (annual costs i.e. direct costs and labour costs, change in input costs, and investment costs i.e. for anaerobic digesters), and potential impacts on productivity (% increase/decrease) are based on the EPA mitigation options database. Relative emission savings and productivity changes are then applied to different management systems in the model to calculate absolute changes in GHG emissions and product output. Mitigation options (characterized by GHG reduction, productivity changes, and economic costs) are implemented in GLOBIOM as additional management activities which can then can be applied on top of a production system. Mitigation options are adopted if economic benefits (i.e. avoided carbon tax payments or potential productivity changes) exceed the cost of an option. Detailed information on parameterization of the marginal abatement cost curve for agriculture in GLOBIOM is provided in Frank et al. (2018).

[16]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.

For the forest sector, GLOBIOM uses G4M which considers the following mitigation options: reduction of deforestation area, increase of afforestation area, change of rotation length of existing managed forests in different locations, change of the ratio of thinning versus final fellings, change of harvest intensity (amount of biomass extracted in thinning and final felling activity), and change of harvest locations. These activities are not adopted independently by forest owners as the model manages forest land dynamically and activities affect each other. The model calculates economically optimal combination of measures, and the introduction of a GHG price gives an additional value to the forest through the carbon stored and accumulated in it which tends to decrease deforestation and increase afforestation. This may not occur at the same intensity as less deforestation increases land scarcity and could potentially decrease afforestation. The existing forest under a GHG price is managed with longer rotations, and expanding harvest to less productive forest. Where possible, the model increases the area of forests used for wood production, meaning that a relatively larger area is managed with relatively less intensity, which then affects the carbon balance. Forest management activities can also have feedback on emissions from deforestation as they might increase or decrease the average biomass in forests being deforested and influence biomass accumulation in newly planted forests, depending on whether or not they are used for production. Market feedback and effects of these mitigation options — such as prolonging rotation — are explicitly accounted for, as the production of wood to satisfy wood demand has higher priority than the carbon accumulation. In fact, much of the mitigation effects are achieved by structural and geographic relocation of harvesting schedules to increase sequestration while simultaneously satisfying market demands.

The estimated AFOLU mitigation potentials include N_2O from the application of synthetic fertilizer, manure applied to soils and dropped on pastures, and from manure management, CH_4 from rice cultivation, enteric fermentation, and manure management, CO_2 emissions from above- and below-ground biomass changes and dead organic matter related to land use changes and forest management as well as soil carbon emissions from deforestation/afforestation. Remaining soil carbon emissions/removals (aside following afforestation/deforestation) as well as mitigation potentials from wetlands are not considered currently in the model.

2.11 Undernourishment

GLOBIOM projects the under-nourished population (Hasegawa et al., 2019). It is a multiple of the prevalence of under-nourishment and the total population. Following the FAO methodology, the prevalence of under-nourishment is calculated using three key factors: the mean dietary energy availability (kcal per person per day), the mean minimum dietary energy requirement (MDER) and the coefficient of variation of the domestic distribution of dietary energy availability in a country. The food distribution in a country is assumed to obey a log-normal distribution, which is determined by the mean food calorie availability (mean) and the equity of the food distribution (variance). The proportion of the population under the cut- off point (MDER) is then defined as the prevalence of under-nourishment (Hasegawa et al., 2019). The calorie-based food consumption (kcal per person per day) output from the model is used for the mean food calorie availability. The future mean MDER is calculated for each year and country using the mean MDER in the base year at the country, adjusted for the MDER in different age and sex groups and future population demographics to reflect differences in the MDER across age and sex. The future equity of food distribution is estimated by applying the historical trend of income growth and the improved coefficient of variation of the food distribution to the future, such that the equity is improved along with income growth in future at historical rates up to the present best value (0.2). We assumed no risk of hunger for high-income countries where hunger is not currently reported.

2.12 Ecological conservation and restoration interventions

2.12.1 Land protection interventions

The effect of protected areas and other area-based effective conservation measures are implemented in GLOBIOM via restrictions to possible land uses and land use changes in specific gridcells. The various available implementations of current and assumed future protection levels are described below.

Current protection
By default, we assume that the area of forest and other natural vegetation land covers covered by the protected areas under IUCN category Ia (Strict Nature Reserve), Ib (Wilderness Area) and II (National Park) as identified by the intersection of CLC2000 land cover dataset and the World Dataset on Protected Areas (as of 2015, covering about 13% of terretrial areas) cannot be used for agricultural or forestry activities.

SSP-specific expansion of protected areas
The Shared Socioeconomic Pathways (SSPs) scenarios assume various levels of increased protection efforts from the year 2020 onwards, and their default implementation range from a weak level of protection in SSP3 (no change compared to current protection, extent of WDPA remains below the target of Aichi target 11, i.e. 17% of global terrestrial area) to an ambitious increase by protection in SSP1 (doubling of Aichi target 11, i.e., 34% of global terrestrial areas, leading to an increase in the areas under strict protection, in priority nearby existing protected areas).

Other scenarios of protected areas expansion
Additional scenarios can be designed, as detailed in the two following examples:

- *Enhanced sustainability climate pathway*
  As featured in Frank et al. (2021), this includes an increase of all protected areas to 17% of terrestrial areas (i.e., Aichi target 11, similar to SSP2) with additional increases in effectiveness (all forest and other natural vegetation areas under IUCN categories I-VI protected from conversion to managed land use) and an additional protection of areas where three or more biodiversity priority schemes (Conservation International's Hotspots,

WWF Global 200 terrestrial and freshwater eco-regions, Birdlife International Endemic Bird Areas, WWF/IUCN Centres of Plant Diversity and Amphibian Diversity Areas) from the UNEP-WCMC Carbon and Biodiversity Report (UNEP-WCMC, 2008) overlap, where no land use chaneg transition can occur but land abandonment. Additional sensitivity analysis can vary the number of overlapping schemes required for protection.

- *Bending the curve pathway*
  As featured in Leclère et al. (2020), this includes an increase of protected areas to the intersection of all protected areas under WDPA (2018 version, all IUCN protection categories), Key Biodiversity Areas and Wilderness Areas, accumulating to about 40% of terrestrial areas. Based on a further intersect of this combined layer to CLC2000 remote sensing land cover product, the area of forest and other natural vegetation under this area cannot be converted to productive land use. In the article, this was combined with increased restoration and land use planning efforts (see below).

2.12.2 Freshwater conservation interventions

In GLOBIOM, agriculture is considered the residual user of water, however, without strongly enforced streamflow protection measures, the water withdrawals for irrigation and from other uses could exceed the quantity of water that should be left for the environment, called environmental flow requirement (EFR). EFRs are estimated as 40 percent of the monthly streamflows (Smakhtin et al., 2004). he monthly level is critical to evaluate environmental flow protections since more than half of the river basins have at least one month in a year of unsustainable water withdrawals (Hoekstra et al., 2012) and minimum flows that do not consider the variable flow patterns of river systems will fail to protect the riverine ecosystem (Pastor et al., 2014; Arthington et al., 2006). GLOBIOM applies specific restrictions to water withdrawals for the agriculture sector at gridcell and monthly level based on the environmental flow requirements and enforcement for streamflow protections (Pastor et al., 2019).

2.12.3 Restoration and land use planning interventions

As described in Leclère et al. (2020), future projections can assume increased restoration efforts, combined with landscape-level land-use conservation planning. This relies on two modeling features:

- A new land cover class *restoration land* is created, to endogenously represent conversions from productive land uses (cropland, pasture, managed forests) to land set-aside (with no possibility for conversion back to productive use) and managed for restoration purposes (without specific assumption about restoration activities).

- A subsidy to gains in a potential biodiversity score through all modeled land changes (including e.g., conversion from cropland to restoration land but also pasture or forestry) is assumed, excluding land abandonment (i.e., to favor restoration over land abandonment). The potential biodiversity change score is measured at the gridcell level as the land use change area variable, multiplied by i) the difference in PREDICTS' Biodiversity Intactness Index (BII, with a score close to primary vegetation for restoration land) between final and initial land uses, and ii) a gridcell speficic priority score for restoration within the region (based on regional relative range rarity-weighted species richness). The potential biodiversity change score is summed across gridcells, multiplied by a positive price (to reflect a landscape-level land-use conservation and restoration planning) and added to the objective function.

2.13 Biodiversity indicators

The land use projected by the model can be translated into various biodiversity indicators using models of how biodiversity responds to land use, as illustrated in Leclère et al. (2020). As biodiversity has many dimensions, providing multiple indicators (such as the extent of suitable habitat, the wildlife population density, the intactness of the local species composition, or the regional and global extinction of species) can be useful, and using the downscaling module allows linking the projected land use to biodiversity models at fine spatial resolution (up to 5 arcminutes).

Two of the indicators estimated in Leclère et al. (2020) have been routinely implemented in the model: the Biodiversity Intactness Index BII (based on PREDICTS model), and the fraction of global species at risk of extinction (based on a Countryside Species-Area Relationship). These indicators can be generated with the use of downscaling techniques (as done in Leclère et al. (2020), see Subsection 2.17 for most recent development) or without, as done in Spillias et al. (2023) for BII.

2.14 Climate Change Implementation

The productivity and input requirements for agriculture sector activities depend on the local future climatic conditions. We assess the impact of changes to climatic conditions and the potential agriculture adaptation options through the systematic integration of three types of models – climate, biophysical and economic – to inform the adaptation response of the agriculture system. An overview of the impacts modeling chain is shown in 9.

The implementation of climate change impacts in GLOBIOM is done through adjusting key biophysical parameters. Crop productivity potential and input requirements by crop, production system and simulation unit are computed by EPIC using projections on precipitation, air temperature, and atmospheric CO_2 concentrations. EPIC uses the most current drivers of global change: the CMIP6 climate change projections to 2100 from various global climate models (GCMs) and the combined Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) as highly localised climatic conditions to calculating climate uncertainty ranges (for example between climate models) and simulating crop productivity under different management conditions. Through comparing the output from EPIC using future projections with those using climate re-analysis data to reconstruct historical yields, shifters (multipliers) are calculated for yield and input requirements in each simulation unit - for each crop - for each production system. The Community Water Model (CWatM) utilizes the highly localized climatic conditions from the CMIP6 GCM projections to simulate changes in the aggregated runoff and other hydrological parameters (e.g., environmental flow requirements) at a 0.5 deg (around 50 x 50 km) level. These changes in aggregated runoff and environmental flow as well as the changes in water demand from other water sectors, are used to calculate the change in water available for use by irrigation as the agriculture sector is considered the residual user of water.

Through exogenously applying these shifters to the prior estimated parameters in GLOBIOM (thus including any changes not caused by climate change) and changes in water available to be used for irrigation purposes, the model accounts for direct climate change impacts on i) yields for each simulation unit and each production system for each crop, ii) production costs through different input requirement levels and iii) the emissions from fertilizer use in crop production, iv) change in the surface water available for irrigation. The input component has been extracted from the total crop production costs in order to represent the impact of climate change on the costs related to water, nitrogen and phosphorous use separately. Through the model setup, GLOBIOM is also capable to identify indirect effects of climate change (e.g. on food availability, land use changes or trade patterns).

Since GLOBIOM has a detailed representation of the agriculture sector and pixel level differences in management practices, productivity and profitability, the adaptation to climate impacts are represented through simulated changes in management (crop reallocation within available land); management change within rainfed systems (intensification though fertilizer application); change from rainfed to irrigated systems on available cropland; or cropland expansion. Changes in international trade flows can help to offset the impacts from climate change. GLOBIOM has been used to assess the impacts of climate change impacts across the agriculture sector including under impacts of alternative climate adaptation strategies (Leclère et al., 2014), the role of trade and trade policies(Mosnier et al., 2014b; Janssens et al., 2020; Guerrero et al., 2022), the long term productivity of the agriculture sector (Nelson et al., 2014) including grassland productivity (Havlik et al., 2015) and the sustainable use of water resources (Pastor et al., 2019; Palazzo et al., 2019), and food demand and security at global (Valin et al., 2013, 2014; Hasegawa et al., 2015) and regional (Palazzo et al., 2017; Mason-D'Croz et al., 2016) scales.

2.15 Scenarios

Scenario-guided planning allows decision-makers to engage with uncertain futures and assess and improve the feasibility, flexibility and concreteness of their plans (Vervoort et al., 2014). The international climate change community is developing a set of global scenarios, consisting of various combinations of radiative forcing scenarios (Representative Concentration Pathways or RCPs) and socioeconomic and policy scenarios (Shared Socioeconomic Pathways; SSPs, and Shared Policy Assumptions; SPAs) that when combined can be used to examine the impacts of

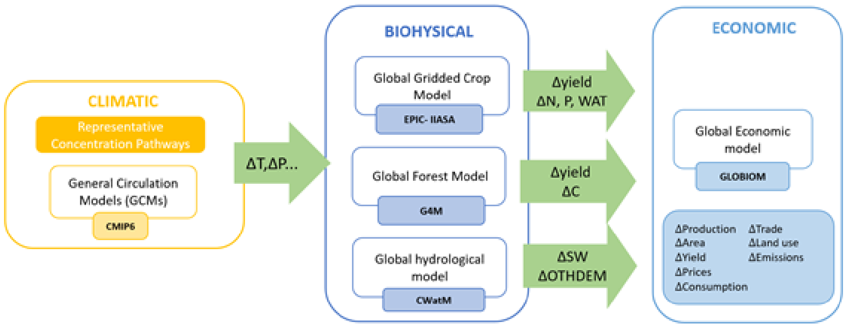

Figure 9: Climate Impacts Modeling Chain

climate change. These scenarios also provide a global context and/or template for processes at lower geographical levels that seek to use scenarios to guide regional, national or sub-national planning (O'Neill et al., 2014)). Conversely, there is scope for sub-global processes to complement the shared socioeconomic pathways (SSPs) with more regional contextualization of assumptions and results, even when using scenarios in the global setting. Regionally specific scenarios serve to assist policy makers in developing robust agriculture and climate adaptation strategies, while also providing the scientific community working at the regional, national, and sub-national level with multiple pathways for development that can be disaggregated or linked to adaptation assessments (Antle et al., 2015; Kihara et al., 2015; Valdivia et al., 2015). Through its shifter approach, GLOBIOM is flexible in which climate models, climate scenarios, or crop models are being used to quantify climate change impacts and therefore allows for the use of alternative scenarios (e.g. to identify impacts of a specific mitigation policy) or for the identification of climate model - or scenario uncertainties in indirect climate change effects.

The frameworks to develop the global SSPs have been thoroughly documented (O'Neill et al., 2014; Schweizer & O'Neill, 2014; van Ruijven et al., 2014; van Vuuren et al., 2014), linked to previous scenario assessments (van Vuuren & Carter, 2014), and integrated with climate change impacts and quantified (Riahi et al., 2017). They have been contextualized through regional (Palazzo et al., 2017) and national (Absar & Preston, 2015), and human impact (Hasegawa et al., 2015) lenses. The different scenarios as highlighted by Fricko et al. (2017) is seen in table 6 below, where the storyline of the different scenarios are quantified by the different SSPs and sectors within GLOBIOM.

Table 6: Quantifying the elements in SSP baselines

	SSP1	SSP2	SSP3
Net Deforestation	Afforestation *(No net deforestation by 2050, +3% forest area by 2100 compared to 2010)*	Deforestation/Afforestation *(Forest loss of 1% by 2050, back to 2010 area by 2100)*	Deforestation *(Net forest loss of 3% by 2050 and 6% by 2100 compared to 2010)*
Land Productivity Growth			
Crops: Yields	High yield growth *(Annual yield growth from 0.51% per annum in the North and 0.66% in the South)*	Moderate yield growth *(Annual yield growth from 0.46% per annum in the North and 0.6% in the South)*	Slow yield growth *(Annual yield growth from 0.35% per annum in the North and 0.35% in the South)*
Crops: Input Intensity	Low intensity *(Elasticity of variable inputs including fertilizer use with respect to technological change: 0.75)*	Medium intensity *(Elasticity of variable inputs including fertilizer use with respect to technological change: 1.00)*	High intensity *(Elasticity of variable inputs including fertilizer use with respect to technological change: 1.25)*
Livestock: Feed Conversion Efficiency	Enhanced efficiency growth *(Annual feed conversion efficiency change from 0.10% in the North to 0.26% in the South)*	Moderate efficiency growth *(Annual feed conversion efficiency change from 0.10% in the North to 0.24% in the South)*	Slow efficiency growth *(Annual feed conversion efficiency change from 0.07% in the North to 0.14% in the South)*

Livestock: Endogenous Productivity Growth	High livestock systems transition *(Annually, up to 5% of livestock production systems can be converted to an alternative system or the activity can be abandoned)*	Medium livestock systems transition *(Annually, up to 2.5% of livestock production systems can be converted to an alternative system or the activity can be abandoned)*	Low livestock systems transition *(No adjustment in the ruminant production system structure)*
Environmental Impact of Food Consumption			
Food Demand	Slow consumption growth and more sustainable and healthy diets *(Calorie consumption per capita growing – North: 1%, South: 16%. Livestock product share decreases in North by one-third but increases in the South, leading to a stable share of 15% globally)*	Moderate consumption growth and increasing share of livestock products in diet *(Calorie consumption per capita growing by 11% in the North and 22% in the South. Livestock product share in the diet growing from 15% to 18%)*	Substantial consumption growth but lagging demand for animal proteins in diet in the South *Calorie consumption per capita growing by 5% in the North and 15% in the South. Livestock product share stays at 15%)*
Losses and Waste	Fast reduction of losses and waste (L&W) *(L&W in the processing chains reduced from 12% to 7% in the Oilseed and Pulses sector and from 7% to 2.5% in the dairy sector over 2000 and 2050)*	Medium reduction of losses and waste (L&W) *(L&W in the processing chains reduced from 12% to 7.5% in the Oilseed and Pulses sector and from 7% to 3% in the dairy sector over 2000 and 2050)*	Slow reduction of losses and waste (L&W) *(L&W in the processing chains reduced from 12% to 9% in the Oilseed and Pulses sector and from 7% to 4.5% in the dairy sector over 2000 and 2050)*

2.16 Developing a Methodology for Regional Studies with GLOBIOM

- *Changing regional aggregation and spatial scale* The bottom-up approach of the database construction for GLOBIOM allows a flexible spatial resolution of the land use activities and a flexible aggregation of countries into regions. The first step of the regional analysis with GLOBIOM is to change the mapping between countries and region to the new one. Then, we change the spatial resolution level in the focus region. Countries are split into two groups: the first sub-group encompasses the countries in the focus region where the grid resolution level is set to 30 ArcMin, and the second sub-group encompasses all the other countries with a grid resolution level of 120 ArcMin. Then all the data processing needs to be performed again to ensure that all the balances hold for the new definition of regions and spatial resolution.

- *Computation and introduction of internal transportation costs based on current infrastructures*
  The second step is to include internal transportation costs. They have a strong impact in the allocation of the activities across the territory. The information on the time to access the closest big city is computed by using the same methodology as Nelson et al. (2006). Then, the transportation cost (TC) per ton of primary product (c) per simulation unit (i) and per mode of transport (m) is expressed as a function of a fixed component (a), a kilometric component ($e.d$), and a time component ($l.t$) as seen in equation 36 below,

$$TC_{i,m,c} = \frac{a_{m,c} + e_m.d_{i,m} + l.t_{i,m}}{s_{m,c}} \tag{36}$$

Where a is the constant cost which includes the depreciation cost and the loading/unloading cost, e is the kilometric cost which includes the fuel cost, the maintenance and the tires cost, d is the average distance in kilometers, l is the labor cost per hour which includes the driver salary, t is the time in hours, and s is the size of the shipment in tons.

- *Implementation of specific regional land use policies*
  Land conversion is partly determined by the rules which have been defined by the State. Each country delineates some areas with specific uses and conversion rules. Protected areas can be found in all the countries, while permanent forest domain, timber and agro-industrial concessions are more specific. Once the shape files of these areas are processed with a GIS software, the share of each simulation unit in a specific area is included in the model with associated rules for land use and land conversion that can be defined based on the law or on exchanges with the local stakeholders.

- *Improvement of the representation of local drivers of deforestation and forest degradation*
  In a regional study, we usually have more freedom to represent the main drivers of land use change in more details. For instance, in the Congo Basin

demand for fuel wood for cooking is a major driver of forest degradation and could even lead to some deforestation around large cities. In the Congo Basin study, the fuel wood demand is introduced at the grid cell level based on the population dynamics and a new land cover type which is "degraded forest" due to fuel wood collection. Coffee and cocoa which are important cash crops for the region have been introduced as well in Sub-Saharan Africa. The lack of spatially explicit data availability on harvested area for coffee and cocoa for the whole globe makes it difficult to draw conclusions on the future development of the sector in the Congo Basin countries but it gave the opportunity to explore the impact of potential future development of the sector on deforestation. In fact, regional studies can also serve as a "laboratory" for introducing new model features at the global level.

2.17 High-resolution land-use projections with downscalR

While GLOBIOM produces – depending on the specific version – land-use projections between the 2 degree and 5 arcminute, for policy evaluation of land-use change or biodiversity (see e.g. Leclère et al., 2020; Prestele et al., 2016; Hurtt et al., 2020), higher resolutions are required. This can be achieved using regional studies (see Section 2.16), where specific production and land use constraints, together with novel high-resolution input data, were used to produce more spatially explicit projections (Zilli et al., 2020). For global high-resolution output or output in other regions a reliable downscaling in the form of the downscalR[17] module is provided. The module is a statistical downscaling method, which can provide consistent high-resolution land use change projections. At the core of downscalR is an econometric high-resolution model, which relates observed land use change data to a set of driver variables. It is open-source and available as an easy-to use R package.

The advantage of the downscalR model is that its priors are estimated using an econometric model (when observations are available), which uses observed land use change patterns and relates them to a set of exogenous and dynamically updated endogenous variables. The latter are updated with each scenario and model output of GLOBIOM, thus allowing for dynamic scenario output. This approach allows for reproduction of observed land use change patterns, while still taking the dynamic nature of future land use change into account.

The main architecture and concept of the downscalR model follows Chakir (2009) in that an econometric model in conjunction with optimization techniques is employed to bridge the gap between observed land use change, drivers of land use change and aggregate land use change targets. However, the underlying econometric model (Krisztin et al., 2022) substantially expands on previous work by considering gross land use change, instead of land use, by expanding the econometric model, and allowing the modeller to define customized downscaling priors.

An overview of the downscalR module is depicted in Figure 10. The aggregate land use change (or potential other variable) projections stem from GLOBIOM (Aggregate projections). These are time-series of regional land use change

[17] https://github.com/tkrisztin/downscalR/tree/main

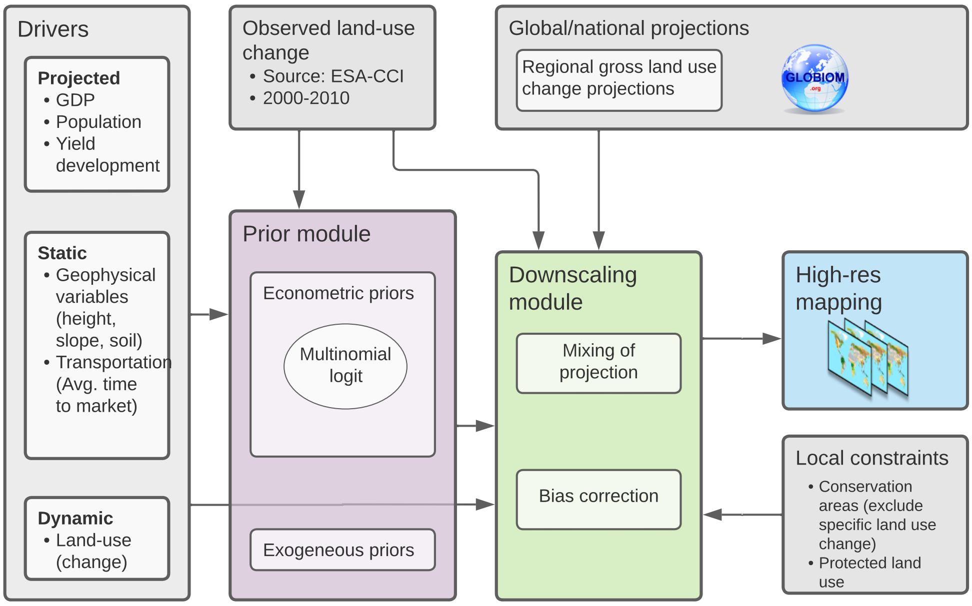

Figure 10: Conceptual outline of the downscalR module.

projections and downscaled higher resolution projections should exactly add up to them, when aggregated. The main components of downscalR are represented in three colored boxes. These are:

1. *Prior module*: This module provides a consistent way of formulating a priori information on how the spatial distribution of land use change is. It has two main subcomponents: the econometric models allow for prior construction when observed land use change patterns are available. The econometric models consists of multinomial logit type models, calibrated on global ESA-CCI land cover maps for the years 2000 and 2010. The module relies on a combination of static (as in not time variant) and projected high-resolution input data.
2. *Downscaling module*: The downscaling module takes as input the priors from the prior module (updated using projections of land use change drivers) and uses a bias correction optimization method to output high-resolution land use change data, consistent with the macro-level model targets.
3. *Mapping module*: The mapping module provides an interface for sharing the downscaled output in netCDF format.

Within the downscalR model, we track six separate land use classes: cropland, grassland, forest, wetland, artificial and other land. When downscaling GLOBIOM output, the allowed land-use change transitions of GLOBIOM are respected: only transitions between cropland, grassland, forest and other land allowed, artificial and wetland remain constant. All prior transitions are estimated using the econometric prior module.

SECTION

3 GLOBIOM Resources

3.1 GLOBIOM Source Code

GLOBIOM is mostly comprised of GAMS code and some R code. Prospective collaborating researchers can contact the IIASA GLOBIOM team by sending an email to *globiom.support@iiasa.ac.at*. Please mention your affiliation, research background, GitHub username, and the reason for your interest in collaborating on GLOBIOM. When a collaboration is agreed on, access will be provided to GLOBIOM source code and data repositories.

3.2 Installing GAMS

To begin working with GLOBIOM, a GAMS installation is required. Recent versions of GAMS can be downloaded here. The GAMS installer asks for a license file. GLOBIOM requires a license file that fully activates GAMS and the CPLEX and CONOPT solvers. Such a license can be acquired from GAMS Development Corporation.

3.3 Documentation Site

The GLOBIOM documentation site helps you get going with GLOBIOM. It includes among others training material, guidance on installing R and R packages required by GLOBIOM, and browsable documentation of the GLOBIOM source tree.

3.4 GLOBIOM Wiki

The GLOBIOM wiki (to access this and the following link, sign in to GitHub after obtaining access from the IIASA GLOBIOM team as detailed in section 3.1) provides further guidance on setting up your GLOBIOM development environment. The wiki is for collaborative sharing of GLOBIOM development knowledge. The issue tracker accessible from the wiki page can be used for raising issues or asking questions.

SECTION 4

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