Documentation for estimating LULUCF emissions / removals and mitigation potentials with GLOBIOM/G4M

Stefan Frank, Mykola Gusti, Andre Deppermann, Hugo Valin, Nicklas Forsell, Petr Havlík

Laxenburg, January, 2024

Science for
Global Insight
IIASA www.iiasa.ac.at

International Institute for Applied
Systems Analysis
Schlossplatz 1
A-2361 Laxenburg, Austria

Tel: +43 2236 807 0
Fax: +43 2236 71313
E-mail: info@iiasa.ac.at
Web: www.iiasa.ac.at

Contents

1 GLOBIOM

The **Glo**bal **Bio**sphere **M**anagement Model (GLOBIOM) is an economic model designed to address various land use related topics (bioenergy and climate policy impacts, deforestation dynamics, climate change adaptation and mitigation from agriculture, long term agricultural prospect). It belongs to the family of partial equilibrium models, as it focuses on a few economic sectors to represent them with a fine level of details. The main characteristics of GLOBIOM-EU, directly derived from GLOBIOM are summarized in Table 1 followed by an in-depth description of the main model features in the subsequent sections.

Table 1. Main structural characteristics of GLOBIOM-EU.

	GLOBIOM-EU [2022]
Model framework	Partial equilibrium, bottom-up, starts from spatially explicit land and technology representation
Sector coverage	Detailed focus on agriculture (including livestock), forestry and bioenergy
Regional coverage	Global (27 EU Member states + 31 regions)
Resolution on production side	Detailed grid-cell level (>10,000 units worldwide)
Time frame	2000-2070 (ten-year time step)
Market data source	EUROSTAT and FAOSTAT
Factor of production explicitly modelled	More detailed on natural resources (land, water)
Land use change mechanisms	Grid-based (aggregated to NUTS2 level for EU). 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 and soil organic carbon.

As a model specialized in land use based activities, GLOBIOM benefits from a detailed sectoral coverage, with an explicit representation of production technologies, a geographically explicit allocation of land cover and land use and their related carbon stocks and greenhouse gas emission flows (see Figure 2). GLOBIOM is a partial equilibrium, meaning that the only economic sectors represented in details are agriculture (including livestock), forestry and bioenergy.

1.1 Model overview

GLOBIOM (www.iiasa.ac.at./GLOBIOM) is a global partial equilibrium model of the forest and agricultural sectors (Havlík et al., 2014). The supply side of the model is built-up from the bottom (spatially explicit land cover, land use, management systems information) to the top (regional markets). Figure 2 presents an overview of the model framework. The model is solved recursively dynamic and can provide projections up to 2100. The agricultural and forest productivity is modeled at the level of Simulation Units (SimU), aggregates of 5 x 5 to 30 x 30 minutes of arc pixels belonging to the same country, altitude, slope, and soil class (Skalský et al., 2008). For the EU (except Croatia, Cyprus, and Malta) a more detailed SimU architecture (Balkovic *et al.*, 2009) is used (i.e. basic spatial unit is a 1x1 km pixel, six altitude and seven slope classes, soil classes are characterized by soil texture compositions, depth, and coarse fragment content, NUTS2 regions boundaries plus additional dimensions for land cover category, presence of irrigation equipment, and river catchment reference). Demand and international trade occur at regional level (58 regions), covering all EU27 member states and 31 regions in the rest of the world. Besides primary products for the different sectors, the model has several final and by-products, for which the processing activities are defined.

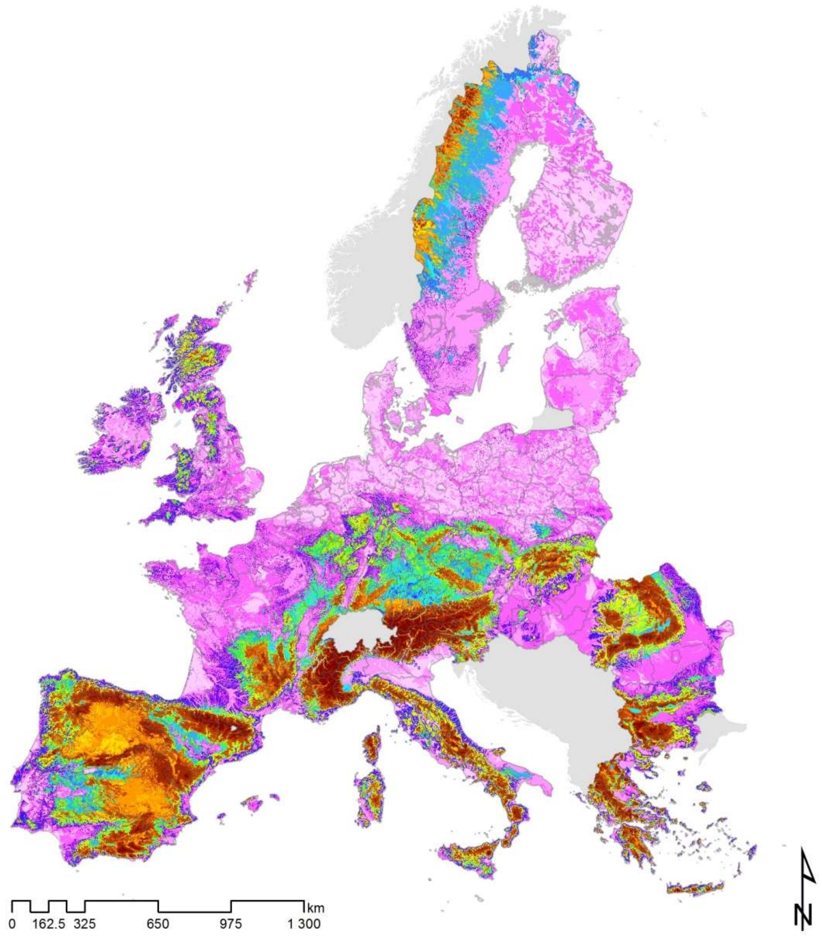

Figure 1. Simulation Unit representation in GLOBIOM-EU. Pixels with the same colour have same biophysical soil properties.

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. The level of production in a given area is determined by the agricultural or forestry productivity in that area (dependent on suitability and management), by market prices (reflecting the level of demand), and by the conditions and cost associated to conversion of the land, to expansion of the production and, when relevant, to international market access. Trade is modelled following the spatial equilibrium approach (Takayama and Judge, 1971), which means that the trade flows are balanced out between different specific geographical regions. Trade is furthermore based purely on cost competitiveness as goods are assumed to be homogenous. This allows tracing of bilateral trade flows between individual regions.

The model allows for a full account of all agriculture and forestry GHG sources. GLOBIOM accounts from main sources of GHG emissions, including N_2O emissions from fertilizer use, CH_4 from rice cultivation, livestock CH_4 emissions from enteric fermentation, CH_4 and N_2O emissions from manure management, N_2O from manure applied and dropped on pasture, above and below ground biomass CO_2 emissions from biomass following land use or management changes, and CO_2 emissions from soil carbon. The emissions inventories are based on IPCC accounting guidelines. In addition, GLOBIOM endogenously represents three major mitigation mechanisms in the agricultural sector at global scale: i) technological mitigation options, ii) structural changes such as switches in production systems (tillage, fertilizer, water management etc.) or international trade, and iii) feedback on the demand side through consumers' response to price changes (Frank et al., 2018). For the EU, GLOBIOM covers explicitly agricultural carbon sequestration options (Frank et al., 2015; Frank et al., 2016).

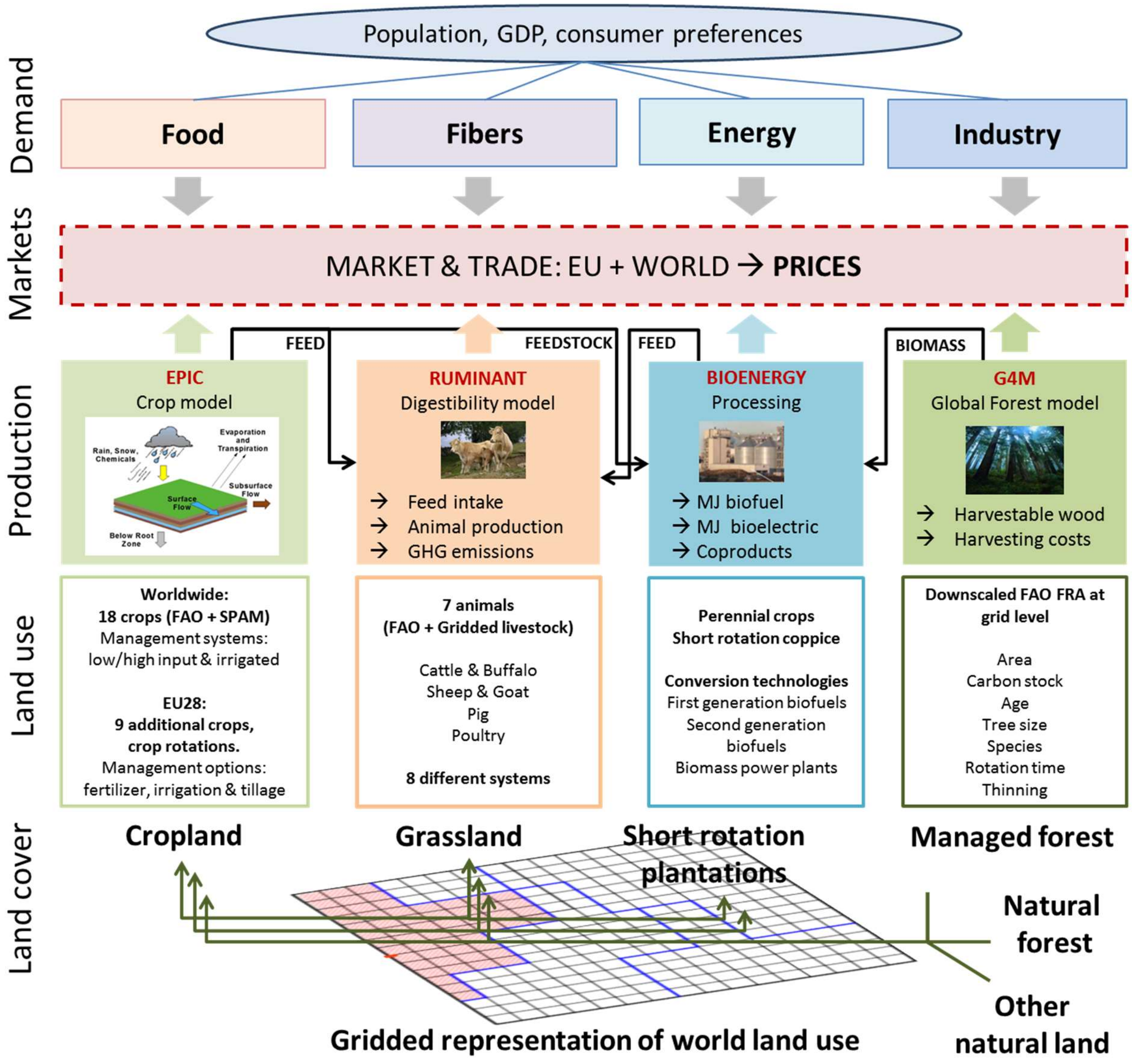

Figure 2. Overview of the GLOBIOM model structure.

1.2 Demand side representation

In GLOBIOM, agricultural and forest biomass demand (for energy and non-energy uses such as food, feed, industrial uses) is based on the interaction of different drivers over time:

(i) Bioenergy demand growth
(ii) Population growth
(iii) GDP per capita growth (income elasticities)
(iv) Response to prices (own-price elasticities)

Drivers (i), (ii), and (iii) are exogenously introduced in the model while (iv) is computed endogenously. Bioenergy demand projections (i) are based on PRIMES biomass model for the EU27 and POLES for the rest of the world in the reference scenario context. Population growth (ii) is provided by the GEM-E3 model and non-energy related demand increases linearly with population growth. GDP per capita changes (iii) determine non-energy demand variation depending on income elasticity values. For the agricultural sector the income elasticities area calibrated to mimic anticipated FAO projections of diets (Alexandratos and Bruinsma, 2012). Income elasticities for the forest sector are taken from Buongiorno et al. (2003) and Buongiorno (2015). The response of non-energy related demand to commodity prices (iv) is endogenously computed in GLOBIOM. Price elasticities for the agricultural commodities are taken from a global database from USDA (Muhammad et al., 2011) and for the forest sector from Buongiorno et al. (2003) and Buongiorno (2015).

1.3 Land use and land use change representation

The model includes six land cover types endogenously: cropland, grassland, short rotation plantations, managed forests, unmanaged forests, and other natural vegetation land. Managed forest refers to all forest areas where harvesting operations take place, while unmanaged forest refers to undisturbed or primary forests. There are other three land cover types represented exogenously in the model to cover the total land area: other agricultural land, wetlands, and not relevant (bare areas, water bodies, snow and ice, and artificial surfaces). These three categories are currently kept constant at their initial level. Economic activities are associated with the first four land cover types. Depending on the relative profitability of primary, by-, and final products production activities, the model can switch from one land cover type to another. Land conversion over the simulation period is endogenously determined for each gridcell within the available land resources. Such conversion implies a conversion cost – increasing with the area of land converted - that is taken into account in the producer optimization behavior. Productivity of land for each type of crop is specific in GLOBIOM to the grid cell level, also for land not currently used as cropland. Therefore, it is possible to consider conversion of other land to cropland on the basis of the expected profitability associated to productivity and input costs in the new locations. A similar approach is used for grassland and grass productivity. This allows for direct calculation of the value of the marginal productivity of land in the model. This value is in the case of GLOBIOM the direct results of productivity estimates from EPIC (Williams, 1995; Balkovič et al., 2013).

Land conversion possibilities are further restricted through biophysical land suitability and production potentials, and through a matrix of potential land cover transitions. Land expansion in GLOBIOM is described at the level of each spatial unit. Land use change is considered at the local level, on a one to one hectare basis, through a conversion ruled by a matrix of land use conversion possibilities between land use types, and associated conversion costs (Figure 3). The land transition matrix offers the possibility to reflect land conversion patterns specific to a region, and to vary conversion costs depending on the land type to convert.

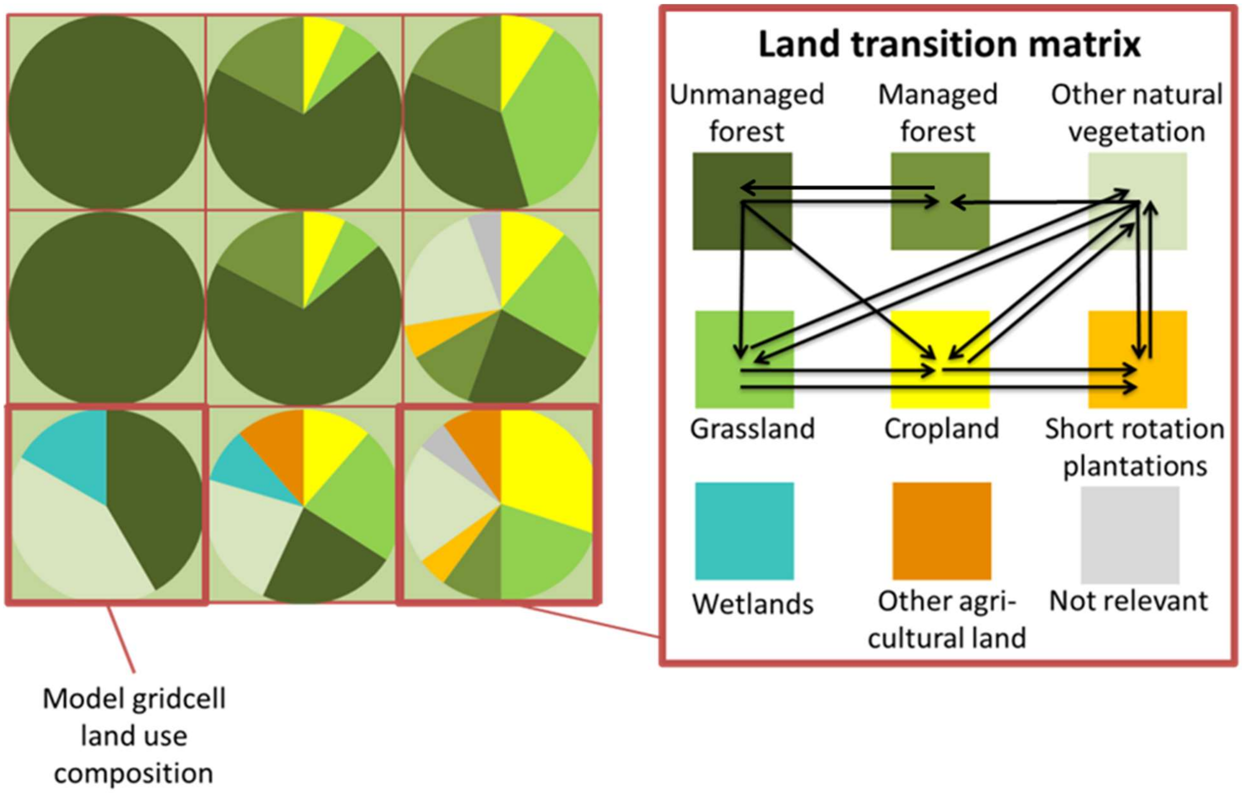

Figure 3. Land cover representation in GLOBIOM and land transition matrix. Afforestation is not a standard feature of the GLOBIOM model but introduced via the link with G4M described below in this document.

1.4 Agricultural sector

GLOBIOM explicitly covers production of each of the 18 world major crops globally representing more than 70% of the total harvested area and 85% of the vegetal calorie supply as reported by FAOSTAT. Each crop can be produced under different management systems depending on their relative profitability: subsistence, low input rainfed, high input rainfed, and high input irrigated, when water resources are available. Crop yields are generated at the grid cell level on the basis of soil, slope, altitude and climate information, using the EPIC model (Williams, 1995; Balkovič et al., 2013). Within each management system, input structure is fixed following a Leontief production function. However, crop yields can change in reaction to external socio-economic drivers through switch to another management system or reallocation of the production to a more or less productive gridcell. Besides the endogenous mechanisms, an exogenous component representing long-term technological change is also considered.

For the EU crop sector, EPIC simulations are performed with three alternative tillage systems (conventional, reduced, and minimum tillage) with statistically computed fertilizer rates and irrigation management. Initial distribution of tillage systems are calibrated using country level data from the PICCMAT project (PICCMAT, 2008). Crop rotations and additional crops have been incorporated for the EU. The model covers currently 18 crops i.e. barley, corn, corn silage, cotton, fallow, flax, oats, other green fodder, peas, potato, rapeseed, rice, rye, soybeans, sugar beet, sunflower, soft- and durum wheat. Crop rotations have been derived from crop shares calculated from EUROSTAT statistics on crop areas in NUTS2 regions using the crop rotation model CropRota (Schönhart *et al.*, 2011). CropRota explicitly takes into account data on relative crop shares, agronomic constraints such as maximum frequency in a rotation and a score matrix of the agronomic desirability of a pre-crop – main-crop sequence.

The GLOBIOM model also incorporates a particularly detailed representation of the global livestock sector. With respect to animal species, distinction is made between dairy and other bovines, dairy and other sheep and goats, laying hens and broilers, and pigs. Livestock production activities are defined in several alternative production systems adapted from Seré and Steinfeld (1996): for ruminants, grass based (arid, humid, temperate/highlands), mixed crop-livestock (arid, humid, temperate/ highlands), and other; for monogastrics, smallholders and industrial. For each species, production system, and region, a set of input-output parameters is calculated based on the approach in Herrero et al. (2008).

Feed rations in GLOBIOM are defined with a digestion model (RUMINANT, see (Havlík et al., 2014)) consisting of grass, stovers, feed crops aggregates, and other feedstuffs. Outputs include four meat types, milk, and eggs, and environmental factors (manure production, N-excretion, and GHG emissions). The initial distribution of the production systems is based on Robinson et al. (2011). Switches between production systems allow for feedstuff substitution and for intensification or extensification of livestock production. The representation of the grass feed intake is an important component of the system representation as grassland productivity is explicitly represented in the model. Therefore, the model can represent a full interdependency between grassland and livestock. A detailed description of the livestock sector representation is also provided in Havlík et al. (2014).

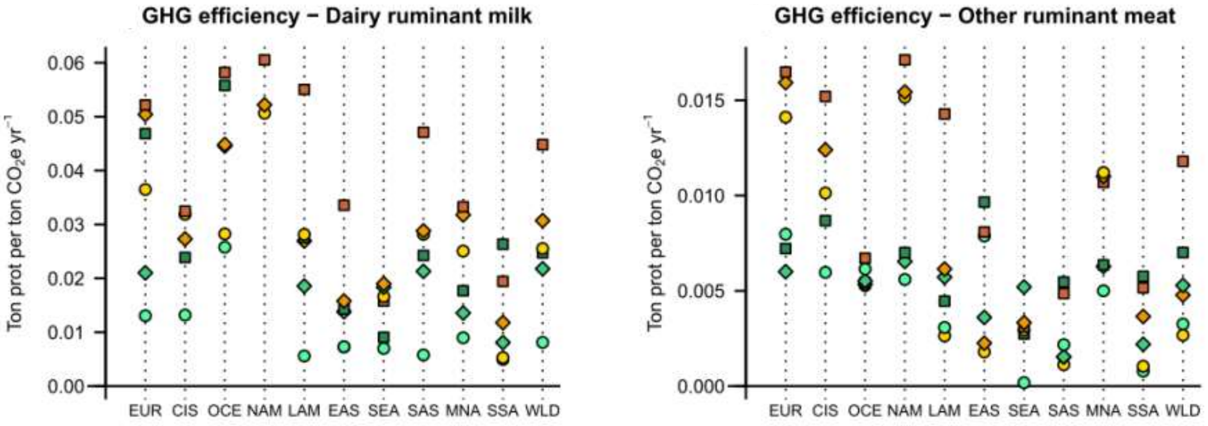

Figure 4. Main production efficiency indicators for ruminant milk and other ruminant meat by production system and region for 2000. Panels represent quantity of proteins produced divided by non-CO2 GHG emissions from enteric fermentation and manure related sources. Region acronyms: EUR = Europe, CIS = Russia and West Asia, OCE = Oceania, NAM = North America, LAM = Latin America, EAS = East Asia, SEA = South-East Asia, SAS = South Asia, MNA = Middle-East and North-Africa, SSA = Sub-Saharan Africa. Source: Havlík et al. (2014)

1.5 Biomass feedstocks and forestry

Short rotation tree plantations are covered in GLOBIOM in the form of energy crop plantations, dedicated to produce wood for energy purposes. Plantation yields are based on NPP maps and model's own calculations, as described in Havlík et al. (2011). Plantation area expansion depends on the land-use change constraints and economic trade-offs between alternative land-use options. Land-use change constraints define which land areas are allowed to be changed to plantations and how much of these areas can be changed within each period and region (so-called inertia conditions). Permitted land-cover types for plantations expansion include cropland, grassland, and other natural vegetation areas, and they exclude forest areas. Within each land-cover type the plantation expansion is additionally limited by land suitability criteria based on aridity, temperature, elevation, population, and land-cover data, as described in Havlík et al. (2011). The model also covers biomass production from grassy crops such as miscanthus or switchgrass simulated where productivities are simulated by the EPIC model.

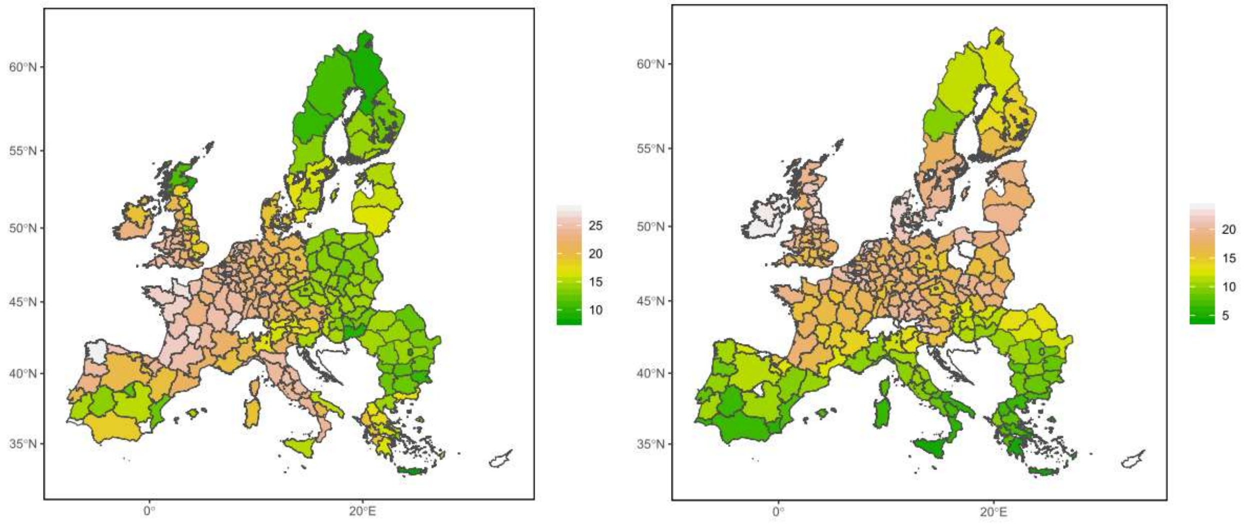

Figure 5. Short rotation tree plantation (left) and miscanthus (right) productivities in m3/ha in GLOBIOM.

Total forest area in GLOBIOM is calibrated according to Forest Europe (2020) country level data and divided into managed and unmanaged forest utilizing a downscaling routine based on human activity impact on the forest areas (Kindermann et al., 2008). The available woody biomass resources are provided by G4M for each forest area unit, and are presented by mean annual increments. Commercial roundwood is stemwood that is suitable for industrial roundwood (sawlogs, pulplogs and other industrial roundwood). The amount of harvest losses is based on G4M estimates. In addition to stemwood, available woody biomass resources also include branches and stumps; however, environmental and sustainability considerations constraint their availability and use for energy purposes.

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

The forest sector is modeled to have seven final products (chemical pulp, mechanical pulp, sawnwood, plywood, fiberboard, other industrial roundwood, and household fuelwood). Demand for the various final products is modeled using regional level constant elasticity demand functions. Forest industrial products (chemical pulp, mechanical pulp, sawnwood, plywood and fiberboard) are produced by Leontief production technologies, which input-output coefficients are based on the engineering literature (e.g. FAO 2010). By-products of these technologies (bark, black liquor, sawdust, and sawchips) can be used for energy production or as raw material for pulp and fiberboard. Initial production capacities for forest industry final products are based on production quantities from FAOSTAT (2012). After the base year the capacities evolve according to investment dynamics, which depend on depreciation rate and investment costs.

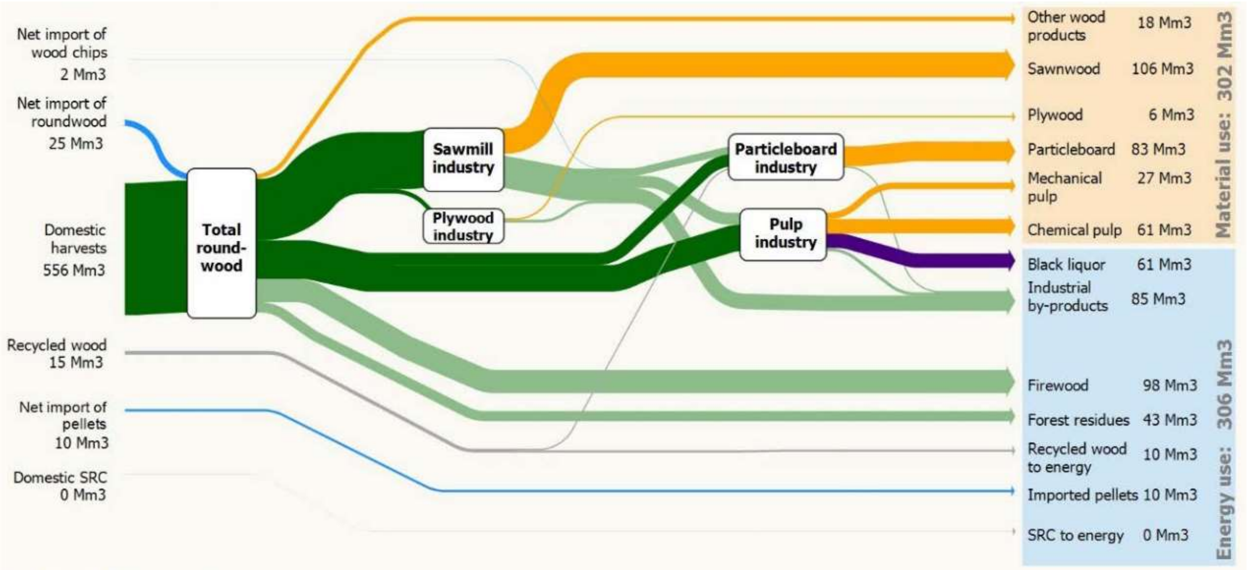

Figure 6. EU forest industry representation in GLOBIOM for the year 2010. Source: Forsell et al. (2016)

1.6 Bioenergy supply chains

At the level of primary sectors, GLOBIOM-EU represents, in total, 27 crops, 7 animal products and 5 primary wood products. These products can then be directly sent to markets to satisfy the demand of households and various industries and services (food industry, seeds, cosmetic industry, etc. – which are not explicitly represented in the model).[1] Part of the commodities can also be used as animal feed in the livestock sector, which is the case for a significant share of many crops. Some other products are transformed explicitly in the model into intermediate or final products, before being sent to the market. This is the case for oilseeds, some wood primary products and products used as bioenergy feedstocks. For these products, all processing industries are explicitly represented in the model, with their transformation coefficients, their co-products and processing costs. The role of processing industries in the supply chain is illustrated in Figure 7.

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

---

[1] Industrial uses are captured in the FAOSTAT database in the category "Other uses" of the Supply Utilisation Accounts.

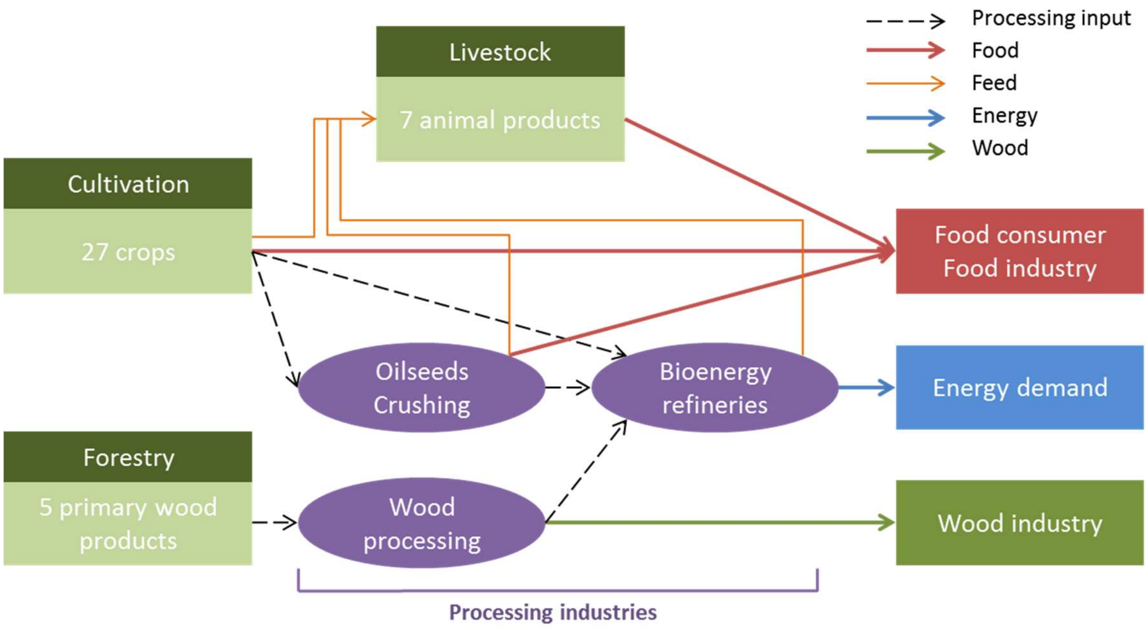

Figure 7. Supply chain in GLOBIOM and role of processing industries

GLOBIOM represents a number of conventional and advanced agricultural and forestry biofuel feedstocks:

- 27 different crops including 4 vegetable oil types[2];
- Co-products: 3 oilseed meal types, wheat and corn DDGS;
- Perennials and short rotation plantations: Miscanthus, switchgrass, short rotation coppice;
- Managed forest: 4 types of stem wood, primary forestry residues from wood harvest;
- Wood processing residues: bark, black liquor, sawdust, sawchips;
- Recovered wood products;

Various energy **conversion processes** are modelled in GLOBIOM and implemented with specific technological costs, conversion efficiencies and co-products:

- Wood (forestry): sawnwood, plywood, fiberboard, pulp and paper production, combustion, fermentation, gasification;
- Lignocellulose (energy crop plantations): combustion, fermentation, gasification;
- Conventional ethanol: corn, sugar cane, sugar beet and wheat ethanol processing;
- Conventional biodiesel: rapeseed oil, soybean oil, soya oil and palm oil to FAME processing;
- Oilseed crushing activities: rapeseed, soybeans, and sunflower crushing activities.

This allows ethanol, methanol, biodiesel, heat, electricity and gas to be distinguished and traced according to their feedstocks. Furthermore, competition for biomass resources as considered is also taken into account between the various sectors in term of the demand for food, feed, timber, and energy.

---

[2] Palm oil, rapeseed oil, soy oil and sunflower oil

The main processing industries currently represented in GLOBIOM-EU are the oilseed crushing industry, forestry industry, and a certain number of bioenergy industries. Table 2 provide a detailed overview of these processing activities.

Table 2. List of current processing activities in GLOBIOM.

Processing activity	Input product	Output product
Oilseed crushing		
Rapeseed crushing	Rapeseed	Rape oil Rape meal
Sunflower crushing	Sunflower	Sunflower oil Sunflower meal
Soybean crushing	Soybeans	Soybean oil Soybean meal
Palm fruit processing	Palm fruit	Palm oil Palm fruit fiber
Wood processing		
Sawmill	Sawn wood biomass	Sawn wood Saw dust Saw chips Bark
Mechanical pulping	Pulp wood biomass Saw chips	Mechanical pulp Bark
Chemical pulping	Pulp wood biomass Saw chips	Chemical pulp Black Liquor Bark
Plywood production	Sawn wood biomass	Plywood Sawdust Saw chips Bark
Fiberboard production	Pulp wood biomass Saw chips Sawdust	Fiberboards
Bioenergy		
Combustion	Energy biomass Sawdust Saw chips Black Liquor Bark	Electricity Heat
Cooking	Traditional biomass	Stove energy
Biofuel corn based	Corn	Ethanol DDGS
Biofuel wheat based	Wheat	Ethanol DDGS
Biofuel sugar based	Sugar cane	Ethanol
	Sugar beet	Ethanol Sugar pulp
Biofuel FAME	Vegetable oil	Biodiesel (FAME)
Cellulosic ethanol	Woody biomass Grassy crops Cereal straw	Ethanol
Fischer-Tropsch biodiesel	Woody biomass Grassy crops Cereal straw	Biodiesel
Biogas fermentation	Corn silage	Biogas

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

Oilseed meals, cereals dried distillers' grains with solubles (DDGSs) and sugar beet fibers are explicitly modeled in GLOBIOM-EU and integrated to some dedicated rations represented in the livestock sector. Increase in production in one type of meal (e.g. rape) can substitute with other type of oilseed meals (e.g. soybean) or increase the share of livestock with protein complement. The substitution is handled under a double constraint of minimum protein and energy requirement, differentiated by animal species. This means for instance that DDGS can be incorporated in high quantities to substitute some oilseed meals on a protein content basis, but it generates at the same time a deficit in energy needs that requires other feed items to be added in the ration. In addition, maximum incorporation constraints are considered for different animal types.

1.7 GHG mitigation options

Agricultural soil carbon (SOC) emissions are represented dynamically through carbon response functions estimated by the biophysical crop growth model EPIC. The model allows to consider the dynamics of the following SOC options explicitly: alternative tillage systems and crop rotations, set aside, perennial grasses and bioenergy plantations (miscanthus, switchgrass, other green fodder on arable land) and short rotation tree plantations. Dynamic sequestration/emission rates over time are explicitly taken into account in the modeling framework for the different land management systems as well as the conversion of land cover types or abandonment of agricultural areas.

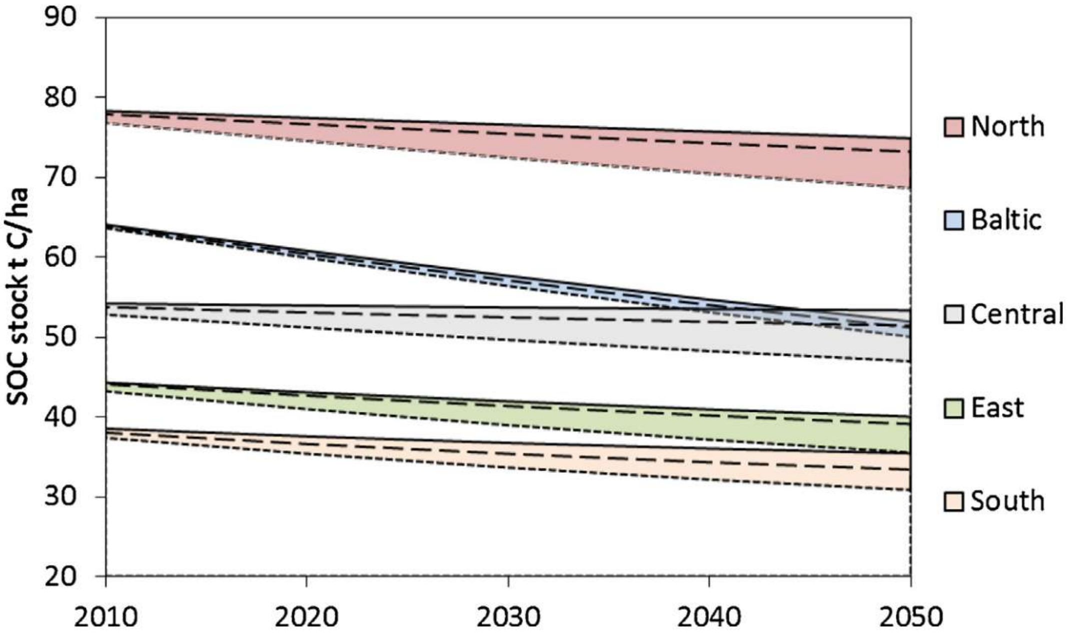

Figure 8. Cropland remaining cropland SOC stock developments in GLOBIOM-EU for 5 European regions using dynamic SOC response functions when applying one tillage system and base year crop shares on the initial carbon stock over time. Pointed lines – conventional tillage, dashed lines – reduced tillage, solid lines – minimum tillage. Source: Frank et al. (2015).

Technical non-CO_2 mitigation options are based on the mitigation option database from EPA (Beach et al., 2015) and include options such as improved fertilizer management, nitrogen inhibitors, improved feed, conversion efficiency, feed supplements (i.e. propionate precursors, anti-methanogen), changes in herd management (i.e. intensive grazing), improved manure management(i.e. anaerobic digesters). Furthermore, two explicit silvo-pastural systems (one for bioenergy production and one for carbon sequestration purposes) are available in GLOBIOM and based on bio-physical simulations with the forest model 3-PGmix, which simulated productivities, carbon sequestration in above- and belowground biomass, and nitrogen inputs of short rotation tree plantations for a 10-year rotation period (bioenergy system) and fast-growing tree species for a 30-year period (sequestration option). This data was combined with pasture productivities in GLOBIOM (Havlík et al. 2014) assuming 25% of the pasture area to be planted with trees. Adoption of silvo-pasture systems is limited to 50% of the total pasture area in a region. In addition, since the model does not represent different management systems for grassland explicitly, the mitigation potential might be underestimated, mainly when it comes to the restoration of degraded grassland. Thus, to give the model an option to change grassland management for restoration purposes, the area of degraded grassland is included for the EU member countries based on area data from Roe et al. (2021). As a mitigation option, the implementation of a higher plant diversity associated with C4 grasses and/or legumes is available with an assumed mitigation potential of 0.7 tCO_2/ha/yr, which is in line with e.g. Bai and Cotrufo (2022) and Conant et al. (2017).

The model also includes the option of rewetting drained organic soils currently used in agriculture, as a mitigation option. The technical implementation relies on UNFCCC (2023) inventory data and for the spatial allocation of areas on information from the CAPRI model. Emission factors per hectare are derived from UNFCCC (2023) where available and complemented with emissions factors presented in Wilson et al (2016). The rewetting decision depends on a comparison of the respective opportunity costs of farming in a specific NUTS2 region plus conversion costs (including explicitly planning and construction costs) with a monetary value occurring from a carbon price that can be implemented in the model for various scenarios.

Structural mitigation options (Havlík et al., 2014) are explicitly represented in the model via different crop- and livestock management systems. For example, for the livestock sector, an extensive set of production systems from extensive to intensive management practises is available based on Herrero et al. (2013). This allows the model to switch between management practises in response to e.g. a carbon price and hence decrease emissions through GHG efficient intensification. The model may also reallocate production to more productive areas within a region or even across regions through international trade.

The impact of changes in commodity prices on the demand side e.g. in response to a mitigation policy (Valin et al., 2013; Frank et al., 2017), is explicitly considered and consumers' react to increasing prices by decreasing consumption depending on the region specific price elasticities (Muhammad et al., 2011)

2 G4M model description

2.1 Model overview

The Global Forest Model (G4M)[3] is applied and developed by IIASA (Kindermann et al., 2006; Gusti et al., 2008; Kindermann et al., 2008; Gusti, 2010; Gusti, 2010; Gusti and Kindermann, 2011) and estimates the impact of forestry activities (afforestation, deforestation, residue harvest and forest management) on biomass and carbon stocks. By comparing the net present value of managed forest (difference of wood price and harvesting costs, income by storing carbon in forests) with income by alternative land use on the same place, a decision on afforestation or deforestation is made. The model incorporates empirical forest growth functions for major tree species. G4M is spatially explicit and runs on a 0.5° x 0.5° resolution. Since the model does not represent either forest markets or other economic sectors, it has to rely on information from other sources – (i.e. GLOBIOM or other databases) – for wood prices, land rents, urban sprawl etc. Similarly, information about natural disturbances comes as input to the model. As outputs, G4M produces estimates of forest area change, carbon sequestration and emissions in forests, impacts of carbon incentives (e.g. avoided deforestation) and supply of biomass for bio-energy and timber.

2.2 Forest management option and impacts

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 forest is used for intensive wood production (further is called managed) or not (further called unmanaged), and for the intensively used forest the harvest is determined by the choice of rotation length. The rotation length can be individually chosen but the model can estimate optimal rotation lengths to maximize increment, stocking biomass or harvestable biomass.

---

[3] See also: www.iiasa.ac.at/G4M

The model uses projections of wood demand per country estimated by GLOBIOM to calculate total harvest iteratively. G4M uses 2000-2010 average wood production map by Verkerk et al. (2015) to initialize spatially explicit wood production. In initial year G4M selects the minimum amount of intensively used cells necessary for sustainable production of demanded amount of wood on country scale. In consequent years, if total harvest is smaller than wood demand, the model changes grid per grid (starting from the most productive forest) the management to a rotation length that optimizes forest mean annual increment and thus allows for more harvest. The rotation length is changed at maximum by 20 years per time step.

If harvest is still too small and unmanaged (non-intensively used) forest is available the status of the unmanaged forest will change to managed, however, the NPV of the forestry must be greater than zero. The NPV calculation accounts for investing into forest road construction to increase the road density from 13.4 m/ha (EU average for multifunctional forest) to 40 m/ha (average in wood production forests in Austria) (the forest road densities are taken from (ARANGE, 2015)). EU average costs for road construction in 2005 were 15 th. Euro/m (Živojinović et al. 2015). The costs were scaled by countries' PPP.

If total harvest exceeds demand the model extends rotation time up to maximum biomass rotation length, i.e. manages forests for carbon sequestration. When extending rotation length over the one maximizing mean annual increment, we account for the risk of losing forest value due to disturbances. If wood demand is still lower than potential harvest, managed forest can be transferred into unmanaged forest. Rotation length can be changed only if the net present value of forestry with the new rotation is not less than with the current rotation (1-5% tolerance is allowed), i.e., the change in forest management must be economically feasible. Thinning is applied to all managed forests and the stands are thinned to maintain a stocking degree specified. The default value is 1 where thinning mimics natural mortality along the self-thinning line. Soil carbon losses due to a harvesting of logging residues are modelled following Repo et al. (2015) who assumed a sustainable share of extractable residues from 2 to 44% of the potential, depending on the country and various ecological harvesting constraints. The carbon losses are based on decomposition time of soil litter, which is function of temperature and precipitation and total demand for forest residue harvest levels is based on PRIMES projections.

G4M can simulate the impact of disturbances on the forest dynamics and estimate respective emissions. The disturbance intensity, approximate location, tree species, vulnerable tree species, age classes etc. should be specified exogenously.

2.3 Afforestation and deforestation

Starting from the calibrated afforestation and deforestation rates based on UNFCCC (2023) submissions, G4M projects the development of future forest area based on the development of basic drivers received from GLOBIOM, i.e. projections of land prices and wood prices but also input from Member States when relevant. The potential value of forestry activities on a grid cell based on wood prices is compared to the land price and a decision on afforestation or deforestation taken by the model. Future demand for wood influences afforestation rates through the wood price estimated by GLOBIOM. Newly established forests contribute to wood production after reaching a certain maturity, i.e. smaller dimensioned timber from thinning after 10 to 15 years and sawn wood after 30 to 50 years in Central Europe. In the longer run increased wood demand also increases afforestation rates.

To ensure consistency in the total land area balance between GLOBIOM and G4M, GLOBIOM supplies G4M with the maximum area that can be afforested which excludes cultivated cropland or grassland necessary for food and feed production (e.g. fallow land, abandoned grassland and cropland, etc.) or areas not suitable. Once G4M has estimated afforestation areas, these are fed back and implemented GLOBIOM in a final iteration.

The forest established on afforested land has the same properties, i.e. growth rates, management rules as the forest already existing in neighboring grid cells. This means that forest growth rates of afforested land are rather moderate compared to dedicated short rotation tree plantations established for energy production. Such plantations established on cropland or grassland have high growth rates and short rotations and are not considered to fall into the definition of forest and hence are covered by GLOBIOM.

2.4 Carbon price and forest mitigation

Introducing a carbon price incentive means that the forest owner is paid for the carbon stored in forest living biomass if its amount is above a baseline, or pays a tax if the amount of carbon in forest living biomass is below the baseline. The baseline is estimated assuming forest management without the carbon price incentive. The measures considered as mitigation measures in forest management in G4M are:

- 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; and
- Change of harvest intensity (amount of biomass extracted in thinning, residue collection, and final felling activity).

These activities are not adopted independently by the forest owner. The model manages land dynamically and one activity affects the other. The model then calculates the optimal combination of measures. The introduction of a CO_2 price gives an additional value to the forest through the carbon stored and accumulated in the forest. The increased value of forests in a regime with a CO_2 price hence changes the balance of land use change through the net present value (NPV) generated by land use activities toward forestry. In general, it is therefore assumed that an introduction of a CO_2 price leads to a decrease of deforestation and an increase of afforestation. This might not happen at the same intensity though. Moreover, less deforestation increases land scarcity and might therefore decrease afforestation relative to the baseline. Forests managed for carbon sequestration will accumulate more carbon than in the baseline case and may cause greater emissions if they are deforested in the future.

Box 1 Abatement cost curves for forest management activities – detailed algorithm

For the generation of cost curves for forest management a two-step approach is used:

STEP 1. In the baseline run forest NPV in each cell is estimated for each year (NPV_{bau}). Every year, starting from the onset of mitigation measures, forest management in each cell is changed towards a state that maximises the forest NPV (forests used for wood production) or biomass. For the forest used for wood production, where the maximum NPV is estimated for current CO_2 price (NPV_{wc}) is greater than the BAU NPV (NPV_{bau}, $NPV_{bau}>=0$), rotation length maximizing the NPV is applied. In all cases the maximum rotation length is not allowed to be longer than the rotation length maximising biomass. NPV for the new rotation length is estimated (NPV_{wc}) and kept in memory. NPV in all cases is estimated for the next 50 years.

STEP 2. The production of wood to satisfy wood demand has higher priority than the carbon accumulation. After Step 1 the forest management of forests within each country is adjusted to harvest as much as the country wood production prescribed (by GLOBIOM). A precondition of the adjustment is that the new NPV multiplied by an adjustment hurdle coefficient to be greater or equal to NPV_{wc} estimated in Step 1. The adjustment hurdle varies from 1 to 1000000 and to -1. The forest management adjustment for the cells within each country starts with the hurdle=1. If the total harvest does not satisfy prescribed wood production, the hurdle is increased by 0.2 and the forest management adjustment is repeated for the forests within the country again. The last hurdle tried is minus one, allowing forest management leading to negative NPV in order to satisfy wood production.

3 LULUCF emissions/removals

The models GLOBIOM and G4M together cover all UNFCCC land use categories of relevance for CO_2 emissions. Only wetlands and settlements are not endogenously modelled. G4M covers the forestry sector and delivers emissions/removals from biomass and soil carbon changes from afforestation, deforestation and harvest residues collection activities and emissions/removals from forest management. GLOBIOM supplies emissions/removals from cropland and grassland management.

3.1 Emissions from forestry activities

The G4M model produces estimates for forest area change, carbon removals and emissions from forests, impacts of carbon incentives (e.g. avoided deforestation), and supply of forest biomass for bioenergy and non-energy uses. Initial land cover information (based on CORINE) for the year 2000 was harmonized with total forest area and forest available for wood supply from Forest Europe (2020) (except Austria and Sweden for which we used values recommended by national experts for EUCLIMIT project in 2013) (see Table 3). The model is calibrated to forest area changes for the period 2000 to 2020 from UNFCCC 2023 submissions.

Table 3: Data on afforestation, deforestation and forest area available for wood supply and harvest losses used as input to G4M for model calibration. The afforestation and deforestation rates are from the UNFCCC 2023 submissions and forest area is from Forest Europe (2020).

Country	Average reported area (2000-2020) [kha/year]	Forest area available for wood supply in 2000 [kha]	Harvest losses

	Afforestation	Deforestation		Share of fellings	Comment
Austria[4]	6.7	3.5	3,367	0.13	Based on fellings/removals data from UN-ECE/FAO (2000)
Belgium	1.1	1.2	663	0.05	Based on fellings/removals data from Forest Europe (2015)
Bulgaria	3.7	0.3	2,258	0.16	Based on fellings/removals data from Forest Europe (2015)
Croatia	3.2	0.2	1,749	0.07	Based on fellings/removals data from UN-ECE/FAO (2000)
Czech Republic	2.6	0.6	2,561	0.09	Based on data provided by national experts for the FMRL update in 2015
Denmark	3.2	0.7	567	0.15	Default value
Estonia	3.1	1.6	2,103	0.10	Based on fellings/removals data from Forest Europe (2015)
Finland	5.3	18.0	20,317	0.09	Based on fellings/removals data from UN-ECE/FAO (2000)
France	76.5	43.0	14,465	0.05	Based on information provided by national experts for the FMRL update in 2015
Germany	9.3	5.2	10,833	0.20	Based on fellings/removals data from UN-ECE/FAO (2000)
Greece	4.0	0.2	3,317	0.15	Default value
Hungary	8.7	1.7	1,622	0.12	Based on fellings/removals data from UN-ECE/FAO (2000)
Ireland[5]	7.5	0.9	580	0.15	Default value
Italy	56.7	3.1	7,396	0.04	Based on fellings/removals data from UN-ECE/FAO (2000)
Latvia	6.9	5.2	3,024	0.11	Based on fellings/removals data from Forest Europe (2015)
Lithuania	6.7	0.4	1,756	0.15	Based on information provided by national experts for the FMRL update in 2015
Luxembourg	0.0	0.0	87	0.15	Default value
Netherlands	2.8	3.0	288	0.14	Based on fellings/removals data from Forest Europe (2015)
Poland	28.2	1.2	8,342	0.12	Based on fellings/removals data from Forest Europe (2015)
Portugal	13.1	8.7	2,229	0.02	Based on fellings/removals data from UN-ECE/FAO (2000)
Romania	6.1	2.6	5,029	0.02	Based on fellings/removals data from Forest Europe (2015)
Slovakia	1.6	0.2	1,767	0.03	Based on fellings/removals data from Forest Europe (2015)
Slovenia	2.2	0.8	1,157	0.15	Default value
Spain[6]	86.8	4.0	13,804	0.04	Based on fellings/removals data from Forest Europe (2015)
Sweden[7]	18.3	14.6	23,300	0.07	Based on fellings/removals data from UN-ECE/FAO (2000)

---

[4] Area provided by national experts is used instead of (Forest Europe 2015) forest available for wood supply

[5] 2005 value of area of forest available for wood supply is used as values for earlier years are not provided in the (Forest Europe 2015)

[6] 2005 value of area of forest available for wood supply is used as values for earlier years are not provided in the (Forest Europe 2015)

[7] Area of productive forest provided by national experts is used instead of (Forest Europe 2015) forest available for wood supply

The initial forest growing stock (aboveground biomass) per grid cell was taken from the European forest biomass map from Gallaun et al. (2010) and scaled to total biomass using the biomass map of Kindermann et al. (2008). Increment is determined by a potential Net Primary Productivity (NPP) map (Cramer et al., 1999) and translated into Net annual increment (NAI). G4M uses forest growth functions specific for major tree species – fir, spruce, pine, birch, beech, oak and larch developed by Kindermann (2013). Tree species distribution in each grid cell are distinguished using a species map by Brus et al. (2012). The above and belowground biomass, carbon stock in dead wood, litter, soil as well as net annual increment averaged for the countries that are used in the model are listed in Table 4. For conversions from carbon stored in wood to wood volume we use country specific wood density (average over the species) as in the study by Boettcher et al. (2012) and carbon content in dry wood equal to 0.5 tC/tdm. When estimating the wood removals from forests country specific harvest losses are taken into account (Table 4).

Initial growing stock was scaled to the degree possible to correspond to reported data on these variables from either public sources (e.g. FAO, Forest Europe or national data). NAI and forest area available for wood supply were scaled to match 2000 values reported in the Forest Europe (2020). For initialization, the model uses the age class structure (Table 5) reported by countries or from Boettcher et al. (2012). The harmonisation of area, age class structure, biomass stock, wood harvest, and wood increment based on different sources is a challenge. These variables are not entirely independent. A change in one variable consequently implies changes in another.

Table 4: Above and belowground biomass, carbon stock in dead wood, litter and soil tC/ha, as well as net annual increment, m^3/ha year, averaged for the countries that are used in G4M. The aboveground biomass is based on the map from Gallaun et al. (2010) and scaled to total biomass using the biomass map of Kindermann et al. (2008). Dead wood, litter and SOC are based on the map by Kindermann et al. (2008). Increment is determined by a potential Net Primary Productivity (NPP) map (Cramer et al., 1999) and translated into net annual increment (NAI) and calibrated to the Forest Europe (2020).

Country	abm, tC/ha	bbm, tC/ha	dead wood, tC/ha	litter, tC/ha	SOC, tC/ha	increment, m^3/ha year
Austria	73	25	22	18	123	8.8
Belgium	73	19	1	21	70	6.9
Bulgaria	54	18	12	10	120	4.0
Croatia	69	19	13	10	110	4.6
Cyprus	12	6	4	4	23	1.0
Czech Republic	94	20	6	15	73	7.5
Denmark	39	12	11	10	108	6.7
Estonia	59	17	4	12	157	5.4
Finland	29	6	1	6	99	3.9
France	53	18	12	8	65	5.0
Germany	79	13	2	18	62	11.1
Greece	13	3	4	4	56	1.3
Hungary	56	21	13	28	36	4.7
Ireland	26	5	7	7	105	11.1
Italy	49	12	8	7	85	4.1
Latvia	53	18	2	22	97	5.5
Lithuania	55	13	2	7	79	6.3
Luxembourg	91	11	22	18	187	7.5
Netherlands	57	11	3	25	109	6.2
Poland	57	22	1	13	147	7.7
Portugal	19	11	8	6	69	8.5
Romania	71	18	14	9	113	5.7
Slovakia	81	19	8	11	139	6.9
Slovenia	87	25	19	17	70	6.3
Spain	16	5	5	3	50	2.1
Sweden	32	10	13	8	111	4.4

Table 5: Share of area of forests of different age groups, %. The data were provided by JRC in 2011 and adjusted based on information obtained from the national experts, forest inventory reports or from (Boettcher et al., 2012).

Country	1 to 20	21 to 40	41 to 60	61 to 80	81 to 100	101 to 120	121 to 140	over 141
Austria	16	23	18	13	10	8	5	7
Belgium	21	16	25	14	9	6	3	5
Bulgaria	18	22	28	15	6	5	3	2
Czech	17	17	16	18	15	10	4	2
Germany	11	15	20	16	13	9	5	10
Denmark	28	24	25	10	5	4	2	1
Spain	30	13	14	13	8	4	3	16
Estonia	19	19	29	21	9	2	1	0
Finland	20	21	20	16	11	5	3	4
France	19	19	20	17	10	7	4	3
Croatia	19	26	32	13	8	3	1	0
Hungary	31	27	17	13	8	2	2	1
Ireland	52	34	14	0	0	0	0	0
Italy	9	38	19	19	5	5	3	3
Lithuania	14	18	31	22	10	4	1	1
Luxemburg	12	10	19	11	8	10	14	16
Latvia	20	22	25	18	9	4	3	0
Netherlands	9	23	28	20	10	4	4	2
Poland	11	24	20	21	15	6	2	2
Portugal	58	21	15	4	1	0	0	0
Romania	21	16	20	15	11	17	0	0
Slovakia	24	9	15	21	18	9	2	1
Slovenia	6	5	14	19	20	19	11	7
Sweden	23	21	16	11	9	8	6	6

Forest management (Forest land remaining Forest land)

Forest management (FM) activities can increase or decrease the biomass carbon stock in the forest. G4M tracks the development of carbon stored in forest biomass. By multiplying the area of forest land remaining forest land (FL r FL) per grid cell with changes in biomass carbon stocks at an annual basis, annual biomass carbon emissions are derived (see Equation 1).

$$\text{Biomass C emissions FM} = \text{Area FL r FL} * \text{Total biomass C stock changes} \qquad (1)$$

To estimate the emissions from deadwood when changing the forest from multifunctional to production or set-aside we take into account the differences in average deadwood amount in multifunctional, production, and protected forests and apply IPCC default transition time of 20 years[8].

Aggregated at country level the model produces emission projections that are driven by the forest growth model, the age class distribution of the forest, management activities and wood and forest residue removals.

In order to ensure consistency between model results and historical data reported by the country, the emissions and removals estimated by the models for the entire time series (up to 2070) were rescaled ("calibrated") using historical UNFCCC data from the countries for the period 2000-2021 (period of overlapping data from UNFCCC and model projection). An "offset" was calculated as difference between [average of country's emissions and removals from biomass, soils and dead organic matter for the period 2000-2021] and [average of models' estimated emissions and removals from biomass for the period 2000-2021].[9] The "offset" was added to the model's original value (thereafter referred to as "calibrated" model) which ensures consistency between country data and models' data in terms of:

i. Absolute level of emissions and removals from biomass, i.e. the calibration „reconciles" differences in estimates which may be due to a large variety of factors, including different input data, different parameters, different estimation methods (e.g., some country uses a „stock-change approach", while the models use a „gain-loss approach");
ii. Coverage of non-biomass pools and GHG sources (soils and dead organic matter).

The calibration procedure automatically incorporates into the projections the average GHG impact (for the period 2000-2021) of past natural disturbances, which are not explicitly estimated by G4M (e.g. emissions from fires etc.). The future trend of emissions and removals up to 2070 as predicted by the G4M is not affected by this ex-post procedure, but only by the current (and projected) forest characteristics (e.g., age structure, etc.) and the future harvest demand (for which no ex-post processing is applied).

Afforestation

Starting from the calibrated afforestation rates based on UNFCCC (2023) submissions, G4M projects the development of future afforestation area based on the development of basic drivers received from GLOBIOM, i.e. projections of land prices and wood prices[10]. The potential value of forestry activities on a grid cell based on wood prices is compared to the land price and a decision on afforestation taken by the model. Future demand for wood influences afforestation rates only indirectly through the wood price estimated by GLOBIOM. Newly established forests contribute to wood production only after reaching a certain maturity, i.e. smaller dimensioned timber from thinning after 10 to 15 years and sawn wood after

---

[8] Average deadwood amount in protected forest is assumed to be 19 tC/ha, in multifunctional 6 tC/ha and in production 3 tC/ha based on studies by Bujoczek et al. (2021), Doerfler et al. (2017), Korhonen et al. (2021), Paletto et al. (2014), Siitonen et al. (2000) and Vandekerkhove et al. (2009).

[9] UNFCCC (2023) forest management emissions for France show a structural break which could not be explained and followed by the model, so the offset calibration period was split into two periods: 2000-2015 and 2016-2021 to not deviate too much in the final year of the historical period.

[10] For Latvia we take into account a planned deforestation in 2020-2024 due to railway construction.

30 to 50 years in Central Europe. In the longer run increased wood demand also increases afforestation rates.

To ensure consistency in the total land area balance between GLOBIOM and G4M, GLOBIOM supplies G4M with the maximum area that can be afforested. This consists of the category “Other natural vegetation” which includes natural vegetation not occupied by cultivated cropland or grassland necessary for food and feed production (e.g. fallow land, abandoned grassland and cropland, etc.). The category can also include other natural vegetation that is not suitable for afforestation or areas on which afforestation is not allowed. In practice it is difficult to identify other natural vegetation that is not available for afforestation. Therefore, we assume generally that 50% of the other natural vegetation identified by GLOBIOM can be afforested by G4M.

In general, the emissions from afforestation and reforestation (AR) can be described by the area of other land converted to forest land (FL) and an emission factor for afforestation (see Equation 2).

$$\text{Biomass C removals AR} = \text{Other land area converted to FL} * \text{Biomass C increment} \tag{2}$$

The biomass C increment on afforested area is estimated by G4M based on the forest growth model. The increment first increases with forest age and declines thereafter. Afforestation area can be established every year in a certain fraction of the grid cell. The forest age, biomass and carbon stock development are tracked over the simulation period for each grid cell afforested and differ due to grid specific growth rates. This dynamic accounting of carbon removals through afforestation is different from accounting in many Member States that apply an average growth rate of forests over the rotation period, leading to a constant removal rate. This can lead to an underestimation of the model of carbon accumulation by early stage afforestation areas and an overestimation of the rate in later stage compared to country reported data. However, the dynamic development of carbon accumulating in new forests is more realistic.

Afforestation also leads to changes in soil organic carbon (SOC). Initial soil carbon is taken from Kindermann (2008). The accumulation rate depends on the amount of litter, the maximum accumulation speed is 0.04 tC/ha/year for coniferous, 0.2 tC/ha/year for mixed and 0.35 tC/ha/year for deciduous forests (Czimczik et al., 2005). Carbon in litter accumulates with maximum speed 0.95tC/ha/year (Czimczik et al., 2005) and depends on aboveground biomass in forest age cohorts. To ensure consistency with UNFCCC reporting which starts in 1990, we reallocated the afforested area and emissions before 2000 from the G4M forest management accounts in 2000 to afforestation. A reclassification of afforestation areas and emissions into forest management takes place after 20 years (in line with UNFCCC accounting rules for most countries).

Deforestation

Land and wood prices that G4M receives from GLOBIOM are also used to project trends in deforestation. The deforestation rates in G4M have been calibrated to the data based on UNFCCC 2023 submissions. Emissions from deforestation (D) are calculated as the sum of area of forest land (FL) converted to other land per grid cell times the average biomass stock per grid cell, aggregated to country level (see Equation 3).

$$\text{Biomass C emissions D} = \text{FL area converted to other land} * \text{Average biomass C stock} \tag{3}$$

It is assumed that the entire biomass carbon is released immediately at the point of forest conversion. We assume that after a site is deforested up to 40% of soil organic matter is lost (Czimczik et al., 2005). The rate of soil organic matter decomposition is a function of long-term average annual temperature and precipitations in each grid cell (Willmott et al., 1998) according to (Esser, 1991). Emissions from deforestation have not undergone rescaling as performed for forest management emissions.

3.2 Emissions from harvested wood products

Emissions from harvested wood products (HWP) are estimated following the Durban Accords (Decision 2/CMP.7) and respective Tier 2 IPCC guidelines. We use FAOSTAT data on historical wood use for sawn wood, pulpwood, energy wood and other wood from 1961 to 2014 and GLOBIOM projections onwards until 2070. On the basis of these variables the HWP C stock is calculated using first-order decay functions with category specific default half-lives (HL, 35 years for sawn wood, 25 years for wood-based panels and other wood products, 2 years for paper and 0 years for energy production; no accounting for imported wood, supply side approach according to guidelines). The following equation is applied.

$$HWP\ C\ stock_{i+1} = e^{-k} * HWP\ C\ stock_i + [(1-e^{-k})/k] * Inflow_i \qquad (4)$$

Where i is the year, HWP C stock the carbon stock in the particular HWP category at the beginning of year i, k is the decay constant of first-order decay for HWP category (k = ln(2)/HL), Inflow is the annual inflow to the particular HWP category. It is assumed that the HWP pools are in steady state at the initial time in 1961. The emissions from HWP are finally estimated until 2070 by calculating the differences between the yearly carbon stocks as provided by GLOBIOM averaged for each 5 year period.

3.3 Emissions from cropland management

Emissions from cropland remaining cropland are calculated by multiplying the area under cropland management with an emission factor (see Equation 5).

$$SOC\ emissions\ CL\ management = Area\ CL\ r\ CL * Emission\ factor\ CL \qquad (5)$$

To estimate the emission factor for cropland (CL) and represent SOC dynamics and SOC emissions accurately, the approach presented in Frank et al. (2015) in detail was used. SOC response functions for each of the crop rotation and tillage system represented in GLOBIOM were estimated at the grid level using a biophysical process-based crop model EPIC. The estimated SOC response functions for the different crop rotations and tillage systems are implemented in GLOBIOM using Markov Chains and allow explicit representation of SOC dynamics over time for land remaining cropland, land converted to cropland (including perennial crops for energy production). Besides SOC emissions, biomass accumulation from short rotation tree plantations and above- and belowground biomass changes due to land use change to cropland are reported under cropland management.

To ensure consistency between model results and historical UNFCCC (2023) data reported by the member states, cropland emissions estimated by GLOBIOM for the entire time series (up to 2070) were rescaled ("calibrated") using historical data from the country for the period 2000-2021 (period of overlapping data from UNFCCC and model projection) as done for the forest management emissions.[11] Total cropland emissions used for rescaling exclude emissions from deforestation to avoid double counting (these are reported by G4M separately). The approach ensures consistency with latest UNFCCC (2023) data and allows to account also for emissions from organic soils which are currently underestimated in the model. Also, cropland areas have been harmonized with UNFCCC (2023) data.

3.4 Emissions from grassland management

In GLOBIOM, grassland areas do not represent total existing grasslands but productive grassland for animal feeding only. The grassland area in GLOBIOM thus depends on animal feed demand, grassland productivity estimated by EPIC for each SimU and total grassland area according to CORINE. Grassland not needed to satisfy fodder demand or natural grasslands are reported under the category "other natural vegetation" and is therefore available for afforestation.

To ensure consistency with reported UNFCCC data the category "other natural vegetation" in the model (which contains natural grasslands) was disaggregated ex-post based on UNFCCC data on total grassland area. If reported grassland area exceeded the GLOBIOM 2000 areas, missing area was reallocated from the "other natural vegetation" if available. This allows to more accurately represent total grassland area for most countries and improved the consistency of emissions with UNFCCC reporting. To avoid overestimation of the grassland sink (especially for land converted to grassland), areas were reallocated from land converted to grassland to grassland remaining grassland after a 20 year period (in line with IPCC accounting).

SOC emissions from grassland management (GL) are calculated by multiplying grassland area (grassland remaining grassland, GL r GL) with a country specific emission factor GL (see Equation 7).

$$\textit{SOC emissions GL management} = \textit{Area GL r GL} * \textit{Emission factor GL} \tag{7}$$

The emission factor is for grassland is based on reported UNFCCC data by dividing reported emissions from grassland remaining grassland by existing grassland area. The emission factor for other land converted to grassland (excluding emissions from deforestation in order to avoid double counting as reported by G4M) was calculated as well. Development of grassland carbon stocks is traced dynamically at the grid level over time and emissions/removals converge towards zero once grasslands reach their equilibrium carbon stocks.

The grassland emission factor contains large uncertainties. It can be expected that emissions per ha differ between countries with different climate and soil conditions. Countries can apply quite different methods to report grassland emissions so that emissions from different countries are likely to differ also due to different methods applied. Inconsistency in reporting methods between member states may lead to assignment of diverging emission factors even for countries with similar grassland properties and management. It is further assumed that the emission factor for grassland is not affected by the change in grassland areas. In principle it can be expected that the emissions per ha change when areas more or less productive than the average grassland area leave the grassland category. This is a simplification to

---

[11] UNFCCC (2023) cropland emissions show a structural break for Romania which could not be explained and followed by the model, so the offset calibration period was split into two periods for cropland emissions in Romania: 2000-2009 and 2010-2021 to not deviate too much in the final year of the historical period.

overcome data gaps. However, deriving the emission factor from UNFCCC data leads overall to a better comparability with historical data at hectare level.

Since the model does not represent different management systems for grassland explicitly, the mitigation potential might be underestimated, mainly when it comes to the restoration of degraded grassland. Thus, to give the model an option to change grassland management for restoration purposes, the area of degraded grassland is included for the EU member countries in the model and the implementation of a higher plant diversity associated with C4 grasses and/or legumes is available, as a mitigation option. The amount of additionally sequestered carbon from this measure is removed from the other SOC emissions from grassland.

On top of the changes in SOC from grassland, the model has the option for EU countries to apply silvo-pastoral systems as a mitigation measure. The amount of sequestered carbon is determined by the uptake rate of the systems (which can be triggered either by income from wood sales or by the implementation of a carbon price). The total amount of sequestered carbon from the application of silvo-pastoral systems is eventually removed from the other emissions in the grassland category.

3.5 Emissions from wetlands, settlements and other lands

Wetland emissions and areas are not endogenously modelled and kept constant at 2021 levels as reported in UNFCCC (2023) data. However, rewetting of drained organic soils which are used in agriculture is available in the model, as a mitigation option. Thus, in respective scenarios, when cropland or pasture areas are rewetted, the respective areas are taken away from the productive agricultural land and are added in the wetland category. The impact on emissions is reported in a separate category ("rewetting of organic soils").

Settlement area is assumed to increase at a smaller pace over time following a logarithmic expansion trend based on historical UNFCCC data (period 2011-2021). Emissions are estimated using an average emission factor (2000-2021) based on UNFCCC (2023) data. Emissions from other land are besides few exceptions based on reported UNFCCC (2023) data and kept constant beyond 2021.

4 References

Alexandratos, N. and J. Bruinsma (2012). World Agriculture Towards 2030/2050 The 2012 Revision. Rome, FAO**:** 160.

ARANGE (2015). Recommendations for multifunctional forest management strategies. ARANGE Deliverable D5.2. FP7-289437-ARANGE / D5.2. ARANGE - Grant no. 289437- Advanced multifunctional forest management in European mountain ranges http://www.arange-project.eu/wp-content/uploads/ARANGE-D5.2_recommendations.pdf

Bai, Y., Cotrufo, M.F (2022). Grassland soil carbon sequestration: Current understanding, challenges, and solutions, Science, Vol 377, Issue 6606, pp. 603-608, DOI: 10.1126/science.abo238

Balkovic, J., R. Skalsky, E. Schmid, Z. Tarasovicova and B. Jurani (2009). D2100 of the cc-tame project: Database and data strategy report. Technical report. Laxenburg, IIASA**:** 24.

Balkovič, J., M. van der Velde, E. Schmid, R. Skalský, N. Khabarov, M. Obersteiner, B. Stürmer and W. Xiong (2013). "Pan-European crop modelling with EPIC: Implementation, up-scaling and regional crop yield validation." Agricultural Systems **120**(0): 61-75.

Beach, R. H., J. Creason, S. B. Ohrel, S. Ragnauth, S. Ogle, C. Li, P. Ingraham and W. Salas (2015). "Global mitigation potential and costs of reducing agricultural non-CO2 greenhouse gas emissions through 2030." Journal of Integrative Environmental Sciences 12(sup1): 87-105.

Bujoczek L, Bujoczek M, Zieba S (2021) How much, why and where? Deadwood in forest ecosystems: the case of Poland. Ecol Indic 121:107027. https://doi.org/10.1016/j.ecolind.2020.107027

Böttcher, H., Verkerk, P.J., Gusti, M., HavlÍk, P. and Grassi, G. (2012), Projection of the future EU forest CO2 sink as affected by recent bioenergy policies using two advanced forest management models. Glob. Change Biol. Bioenergy, 4: 773-783. https://doi.org/10.1111/j.1757-1707.2011.01152.x

Buongiorno, J., Zhu, S., Zhang, D., Turner, J. and D. Tomberlin (2003). The Global Forest Products Model, Elsevier.

Buongiorno, J. (2015). Income and time dependence of forest product demand elasticities and implications for forecasting, Silva Fennica 49 (5), 1395.

Brus, D. J., G. M. Hengeveld, D. J. J. Walvoort, P. W. Goedhart, A. H. Heidema, G. J. Nabuurs and K. Gunia (2012). "Statistical mapping of tree species over Europe." European Journal of Forest Research **131**(1): 145-157.

Conant, R.T., Cerri, C.E.P., Osborne, B.B., Paustian, K. (2017). Grassland management impacts on soil carbon stocks: a new synthesis. Ecological Applications 27, 662–668. https://doi.org/10.1002/eap.1473

Cramer, W., D. W. Kicklighter, A. Bondeau, B. Moore, C. Churkina, B. Nemry, A. Ruimy, A. L. Schloss and the Participants of the Potsdam NPP Model Intercomparison (1999). "Comparing global models of terrestrial net primary productivity (NPP): overview and key results." Global Change Biology **5**: 1-15.

Czimczik, C. I., M. Mund, S. E.D. and C. Wirth (2005). Effects of reforestation, deforestation, and afforestation on carbon storage in soils. The Carbon Balance of Forest Biomes. H. Griffith. Milton Park, Taylor and Francis: 319-330.

Doerfler, I.; Müller, J.; Gossner, M.M.; Hofner, B.; Weisser, W.W. Success of a deadwood enrichment strategy in production forests depends on stand type and management intensity. For. Ecol. Manag. 2017, 400, 607–620.

Esser, G. (1991). Osnabrück Biosphere Model: structure, construction, results. Modern Ecology, Basic and Applied Aspects. G. Esser and D. Overdieck. Amsterdam, Elsevier**:** 773-804.

Forsell, N., A. Korosuo, P. Havlík, H. Valin, P. Lauri, M. Gusti, G. Kindermann, M. Obersteiner, H. Böttcher, K. Hennenberg, K. Hünecke, K. Wiegmann , M. Pekkanen, P. Nuolivirta, C. Bowyer, S. Nanni, B. Allen, J. Poláková, J. Fitzgerald and M. Lindner (2016). Study on impacts on resource efficiency of future EU demand for bioenergy (ReceBio). Final report. . Luxembourg**:** 43.

Frank, S., R. Beach, P. Havlík, H. Valin, M. Herrero, A. Mosnier, T. Hasegawa, J. Creason, S. Ragnauth and M. Obersteiner (2018). "Structural change as a key component for agricultural non-CO2 mitigation efforts." Nature Communications **9**(1): 1060.

Frank, S., H. Böttcher, M. Gusti, P. Havlík, G. Klaassen, G. Kindermann and M. Obersteiner (2016). "Dynamics of the land use, land use change, and forestry sink in the European Union: the impacts of energy and climate targets for 2030." Climatic Change: 1-14.

Frank, S., P. Havlík, J. F. Soussana, A. Levesque, H. Valin, E. Wollenberg, U. Kleinwechter, O. Fricko, M. Gusti, M. Herrero, P. Smith, T. Hasegawa, F. Kraxner and M. Obersteiner (2017). "Reducing greenhouse gas emissions in agriculture without compromising food security?" Environmental Research Letters **12**(10): 105004.

Frank, S., E. Schmid, P. Havlík, U. A. Schneider, H. Böttcher, J. Balkovič and M. Obersteiner (2015). "The dynamic soil organic carbon mitigation potential of European cropland." Global Environmental Change **35**: 269-278.

Gallaun, H., G. Zanchi, G. J. Nabuurs, G. Hengeveld, M. Schardt and P. J. Verkerk (2010). "EU-wide maps of growing stock and above-ground biomass in forests based on remote sensing and field measurements." Forest Ecology and Management **260**(3): 252-261.

Gusti, M. (2010). "An algorithm for simulation of forest management decisions in the global forest model." Artificial Intelligence **N4**: 45-49.

Gusti, M. (2010). Uncertainty of BAU emissions in LULUCF sector: Sensitivity analysis of the Global Forest Model. Proceedings of the 3rd International Workshop on Uncertainty in Greenhouse Gas Inventories, Lviv Polytechnic National University, Lviv, Ukraine.

Gusti, M., P. Havlik and M. Obersteiner (2008). Technical Description of the IIASA Model Cluster, The Eliasch Review; Office of Climate Change, UK [2008].

Gusti, M. and G. Kindermann (2011). An approach to modeling landuse change and forest management on a global scale. SIMULTECH-2011. Proceedings of 1st International Conference on Simulation and Modeling Methodologies, Technologies and Applications, Noordwijkerhout, The Netherlands July 29 - 31 2011, SciTePress - Science and Technology Publications, Portugal.

Havlík, P., H. Valin, M. Herrero, M. Obersteiner, E. Schmid, M. C. Rufino, A. Mosnier, P. K. Thornton, H. Böttcher, R. T. Conant, S. Frank, S. Fritz, S. Fuss, F. Kraxner and A. Notenbaert (2014). "Climate change mitigation through livestock system transitions." Proceedings of the National Academy of Sciences **111**(10): 3709-3714.

Herrero, M., P. Havlík, H. Valin, A. Notenbaert, M. C. Rufino, P. K. Thornton, M. Blümmel, F. Weiss, D. Grace and M. Obersteiner (2013). "Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems." Proceedings of the National Academy of Sciences **110**(52): 20888-20893.

Kindermann, G., M. Obersteiner, B. Sohngen, J. Sathaye, K. Andrasko, E. Rametsteiner, B. Schlamadinger, S. Wunder and R. Beach (2008). "Global cost estimates of reducing carbon emissions through avoided deforestation." Proceedings of the National Academy of Sciences of the United States of America **105**(30): 10302-10307.

Kindermann, G. E., I. McCallum, S. Fritz and M. Obersteiner (2008). "A global forest growing stock, biomass and carbon map based on FAO statistics." Silva Fennica **42**(3): 387.

Kindermann, G. E., I. McCallum, S. Fritz and M. Obersteiner (2008). "A global forest growing stock, biomass and carbon map based on FAO statistics." Silva Fennica **42**(3): 387-396.

Kindermann, G. E., M. Obersteiner, E. Rametsteiner and I. McCallum (2006). "Predicting the deforestation-trend under different carbon-prices." Carbon Balance and Management **1**(1): Art. no. 15.

Kindermann, G. E., S. Schörghuber, T. Linkosalo, A. Sanchez, W. Rammer, R. Seidl and M. J. Lexer (2013). "Potential stocks and increments of woody biomass in the European Union under different management and climate scenarios." Carbon Balance and Management 8(1): 1-20.

Korhonen K.T., Ahola A., Heikkinen J., Henttonen H.M., Hotanen J.-P., Ihalainen A., Melin M., Pitkänen J., Räty M., Sirviö M., Strandström M. (2021). Forests of Finland 2014–2018 and their development 1921–2018. Silva Fennica vol. 55 no. 5 article id 10662. 49 p. https://doi.org/10.14214/sf.10662

Forest Europe (2020). Forest Europe, 2020: State of Europe's Forests 2020. Ministerial Conference on the Protection of Forests in Europe, 2020.

Muhammad, A., J. Seale, B. Meade and A. Regmi (2011). International Evidence on Food Consumption Patterns: An Update Using 2005 International Comparison Program Data.Technical Bulletin (1929) Washington, D.C. , USDA-ERS**:** 53.

Paletto, A.; De Meo, I.; Cantiani, P.; Ferretti, F. Effects of forest management on the amount of deadwood in Mediterranean oak ecosystems. Ann. For. Sci. 2014, 71, 791–800.

PICCMAT (2008). Deliverable D7: European quantification results. Wageningen, Alterra**:** 42.

Rametsteiner, E., S. Nilsson, H. Böttcher, P. Havlik, F. Kraxner, S. Leduc, M. Obersteiner, F. Rydzak, U. Schneider, D. Schwab and L. Willmore (2007). Study of the Effects of Globalization on the Economic Viability of EU Forestry. Final Report of the AGRI Tender Project: AGRI-G4-2006-06 [2007]. EC Contract Number 30-CE-0097579/00-89**:** 291.

Repo, A., H. Böttcher, G. Kindermann and J. Liski (2015). "Sustainability of forest bioenergy in Europe: land-use-related carbon dioxide emissions of forest harvest residues." GCB Bioenergy **7**(4): 877-887.

Roe, S., Streck, C., Beach, R., Busch, J., Chapman, M., Daioglou, V., Deppermann, A., Doelman, J., Emmet-Booth, J., Engelmann, J., Fricko, O., Frischmann, C., Funk, J., Grassi, G., Griscom, B., Havlik, P., Hanssen, S., Humpenöder, F., Landholm, D., Lomax, G., Lehmann, J., Mesnildrey, L., Nabuurs, G.-J., Popp, A., Rivard, C., Sanderman, J., Sohngen, B., Smith, P., Stehfest, E., Woolf, D., Lawrence, D. (2021). Land-based measures to mitigate climate change: Potential and feasibility by country. Global Change Biology 27, 6025–6058. https://doi.org/10.1111/gcb.15873

Schönhart, M., E. Schmid and U. A. Schneider (2011). "CropRota - A crop rotation model to support integrated land use assessments." European Journal of Agronomy **34**(4): 263-277.

Siitonen, J.; Martikainen, P.; Punttila, P.; Rauh, J. Coarse woody debris and stand characteristics in mature managed and old-growth boreal mesic forests in southern Finland. For. Ecol. Manag. 2000, 128, 211–225.

Skalský, R., Z. Tarasovičová, J. Balkovič, E. Schmid, M. Fuchs, E. Moltchanova, G. Kindermann and P. Scholtz (2008). GEO-BENE global database for bio-physical modeling v. 1.0 - concepts, methodologies and data. The GEO-BENE database report., International Institute for Applied Systems Analysis (IIASA), Austria**:** 58.

Takayama, T. and G. G. Judge, Eds. (1971). Spatial and Temporal Price Allocation Models.

Vandekerkhove, K.; De Keersmaeker, L.; Menke, N.; Meyer, P.; Verschelde, P. When nature takes over from man: Dead wood accumulation in previously managed oak and beech woodlands in North-western and Central Europe. For. Ecol. Manag. 2009, 258, 425–435.

Valin, H., P. Havlík, A. Mosnier, M. Herrero, E. Schmid and M. Obersteiner (2013). "Agricultural productivity and greenhouse gas emissions: trade-offs or synergies between mitigation and food security?" Environmental Research Letters **8**(3): 035019.

Verkerk, P. J., C. Levers, T. Kuemmerle, M. Lindner, R. Valbuena, P. H. Verburg and S. Zudin (2015). "Mapping wood production in European forests." Forest Ecology and Management **357**: 228-238.

Williams, J. R. (1995). The EPIC Model. Computer Models of Watershed Hydrology. V. P. Singh, Water Resources Publications, Highlands Ranch, Colorado**:** 909-1000.

Willmott, C., K. Matsuura and D. Legates (1998). Global Air Temperature and Precipitation: Regridded Monthly and Annual Climatologies (Version 2.01). U. o. D. Center for Climatic Research Department of Geography.

Wilson, D. Blain, D., Couwenberg, J., Evans, C.D., Murdiyarso, D., Page, S.E., Renou-Wilson, F., Rieley, J.O., Sirin, Strack, A. M. & Tuittila, E.-S. (2016). Greenhouse gas emission factors associated with rewetting of organic soils. Mires and Peat, 17, Article 04, 1–28. http://mires-and-peat.net/ pages/ volumes/map17/map1704.php.

Živojinović, I., Weiss, G., Lidestav, G., Feliciano, D.*, Hujala, T., Dobšinská, Z., Lawrence, A.,Nybakk, E., Quiroga, S., Schraml, U. (2015). Forest Land Ownership Change in Europe. COSTAction FP1201*

FACESMAP Country Reports, Joint Volume. EFICEEC-EFISEE ResearchReport. University of Natural Resources and Life Sciences, Vienna (BOKU), Vienna, Austria.693 pages.