Methodology for estimation and modelling of EU LULUCF greenhouse gas emissions and removals until 2050

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1 Introduction

This report provides details on the methodology of projections and data sets used for the estimation of emissions of the land use, land use change and forestry (LULUCF) sector for the 28 EU member states. It also describes the interplay and roles of the CAPRI, GLOBIOM and G4M models in this task within the EUCLIMIT project (Development and application of EU economy-wide climate change mitigation modelling capacity) on behalf of the European Commission, DG Climate Action. CAPRI and GLOBIOM are applied to model the agricultural sector of the EU countries and estimate the supply and demand of agricultural products as well as emissions from production and soil. This area forms an overlap of the models that have quite different orientation and structure. However, despite this overlap in area and function the models complement each other and give the user additional information when they are applied to the same scenarios. G4M projects the EU forest area development and emissions from afforestation, deforestation and forest management.

The report is structured in the following way. Section 2 presents the general modelling methodology for estimating LULUCF CO_2 emissions for EU-28 at member state level. Section 3 describes how the EU reference and "baseline with adopted measures" (hereafter: baseline) scenarios 2012-13 were constructed. Section 4 provides information on how the actual emissions were calculated for each activity. Finally, two Annexes provide detailed model descriptions.

2 Description of models and modelling approach

This section briefly describes the most important features and roles of the models involved. It also describes model differences and the interplay of models.

2.1 Overview of general model interaction

To respond to the project tasks regarding emission projections from LULUCF activities, the involved forest, agricultural and economic land use models communicate as shown in Figure 1. Basic driver information (in particular on GDP, population development, bioenergy demand and productivity changes) is generated by outside models (PRIMES and GEM-E3) or given by global databases is taken up by the economic land use model GLOBIOM. The agricultural sector model CAPRI processes GLOBIOM projected longer-term driver information (2030-2050). Demand is endogenously produced by the model (see section I of Appendix A.3. of the main report, paragraph Driver Data) and contrasted by supply of food, fodder, timber and energy estimated by CAPRI's supply module and the forestry model G4M. Through the detailed forestry and agriculture models the resulting projection of supply and demand is translated into emissions and removals of GHGs. For non- CO_2 emissions this step is done via CAPRI and GAINS (see GAINS methodology report). For LULUCF emissions and removals this step is done via GLOBIOM and G4M. The information between models flows not only in one direction but is circulated between modelling levels (economic land use and detailed sector models) iteratively where relevant.

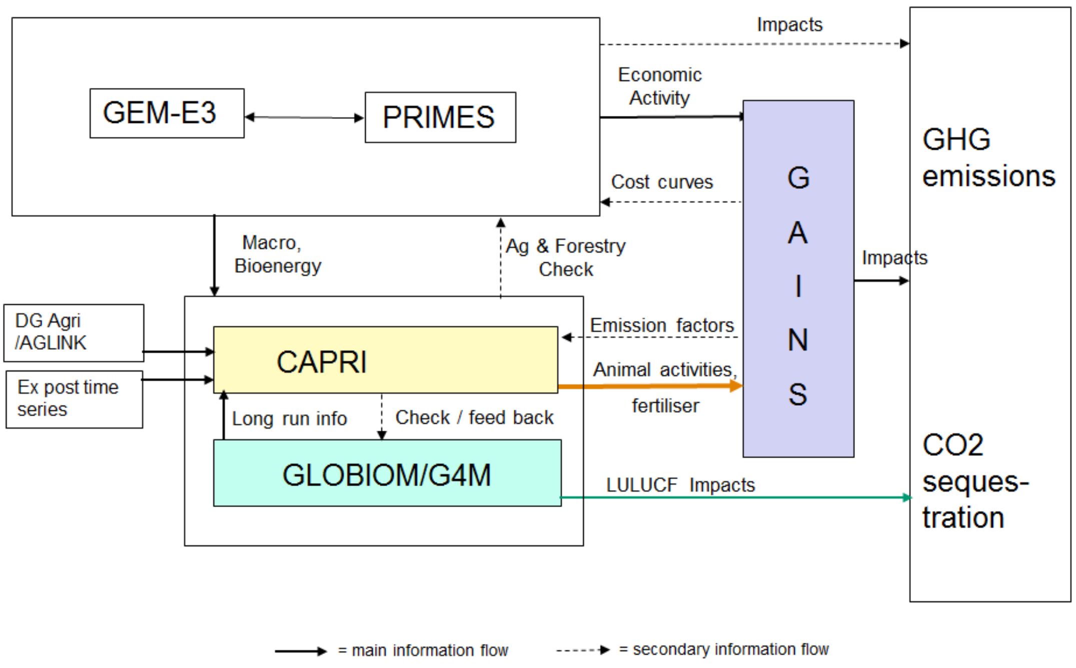

Figure 1: Overview of EUCLIMIT model interactions.

2.2 CAPRI

CAPRI models the response of the European agricultural system to a range of policy interventions. It is a comparative static equilibrium global agricultural sector model with focus on EU28 and Norway. Its supply module consists of separate, regional, non-linear programming models which cover about 250 regions (NUTS 2 level) or even up to six farm types for each region (in total 1000 farm-regional models). Its market module is a spatial, global multi-commodity model for agricultural products, 40 product, and 40 countries in 18 trade blocks. For further information see http://www.capri-model.org/.

- The model provides a detailed representation of the European Union
- It is a programming model with a nonlinear objective function specified to ensure calibration to a given set of ex post data and projections.
- The model design tries to ensure smooth responses to changes in economic incentives.
- CAPRI has a detailed coverage of the Common Agricultural Policy (CAP) and agricultural trade policies
- So far no non-agricultural sectors are included but there is the possibility and some experience to link the model to relevant CGE (Computable General Equilibrium) models.
- The livestock sector is represented in great detail.

2.3 GLOBIOM

The Global Biosphere Management Model (GLOBIOM) has been developed and is used at the International Institute for Applied Systems Analysis (IIASA). GLOBIOM is a global recursive dynamic partial equilibrium model integrating the agricultural, bioenergy and forestry sectors with the aim to provide policy analysis on global issues concerning land use competition between the major land-based production sectors. It is global in the sense that it encompasses all world regions aggregated in a way that can be altered. GLOBIOM covers now 30 (or 53, including all EU28 Member States) world regions. Partial denotes that the model does not include the whole range of economic sectors in a country or region but specialises on agricultural and forestry production as well as bioenergy production. These sectors are, however, modelled in a detailed way accounting for about 25 globally most important crops, a range of livestock production activities, forestry commodities as well as different energy transformation pathways. A more detailed model description is provided in the Annex, including also lists of crops and products covered. In short GLOBIOM has the following characteristics:

- Global bottom-up partial equilibrium land use model.
- It covers the main land based sectors (agriculture, livestock, forestry and bioenergy).
- The model is comparatively strong in technological detail (detailed representation of cropland management (input and management systems) and livestock sector (FAO system classification))
- Compared to CAPRI less policy coverage.
- The linear programming character tends to give a specialization for small simulation units, but the aggregation to countries and larger regions and constraints at the simulation unit level tend to smooth out this feature to some extent.
- The model can relatively easily also be applied for scenarios up to the year 2100.
- The emissions estimated by the model rely on exogenous emission factors.

- There is substantive experience with linkages to other biophysical and economic models (EPIC, G4M, RUMINANT, PRIMES, POLES etc.)

2.4 G4M

For the forestry sector, emissions and removals as well as biomass supply are projected by the Global Forestry Model (G4M), a geographically explicit agent-based model that assesses afforestation-deforestation-forest management decisions.

- Geographically explicit agent based forestry model
- Estimates afforestation, deforestation and forest management area and associated emissions and removals per EU Member State
- Is calibrated to historic data reported by Member States on afforestation and deforestation and therefore includes policies on these activities. Explicit future targets of forest area development can be included
- Informs GLOBIOM about potential wood supply and initial land prices
- Receives information from GLOBIOM on the development of wood demand, wood prices and land prices

2.5 Consistency of models

This section documents briefly the basic data used in CAPRI and GLOBIOM. It shows that most databases are commonly used. However, due to differences in coverage and scope, both models use additional datasets not used by the other model.

Table 1: List of common and model specific datasets.

Variable, parameter	CAPRI	GLOBIOM
Land cover data	Corine	Corine
Cropland	Eurostat	Eurostat
Grassland	Eurostat	Corine/Eurostat
Livestock numbers	Eurostat	FAO
Production quantities	Eurostat	Eurostat
Demand quantities	Eurostat	Eurostat
Initial prices	Eurostat	Eurostat

With the switch from GLC-2000 land cover information (used in the global version of GLOBIOM) to CORINE for the EU28 consistency with the CAPRI model improved further in GLOBIOM-EU since total land balances are now consistent. Moreover, the implementation of additional crops in GLOBIOM-EU (soft and durum wheat (previously wheat), rye, oats, sugar beet, peas, corn silage, other green fodder, fallow and flax) decreases the difference in total cropland areas. Overall GLOBIOM-EU represents now about 80% of total cropland area in CAPRI. FAO country level data has been replaced with harmonized EUROSTAT data based on the CAPRI database. CAPRI database is used for initial yields, areas, prices and demand and supply quantities for the crop and livestock sector. Besides cropland areas, also other cropland areas (crops currently not covered by GLOBIOM-EU) have been harmonized. For cropland and forest areas overall harmonization has been achieved even though for some countries differences remain as some crops are not represented by GLOBIOM (e.g. fruits, nursery, other permanent crops etc.). Moreover, EPIC simulations for some crops are not available for every EU country e.g. other green fodder on arable land in Ireland, Hungary and Romania, fallow in Bulgaria and Romania as well as oats in Bulgaria and the UK.

In the forest sector small area differences between the models CAPRI and GLOBIOM/G4M result from harmonization of GLOBIOM with G4M model in terms of forest area and mean annual increment while CAPRI uses FAO data. However, absolute differences are negligible. For the remaining land categories (other natural vegetation and grassland) small consistency issues persist. Since in GLOBIOM-EU grassland areas represent not existing grasslands but used grassland for animal feeding, they depend on animal feed demand, grassland productivity estimated by EPIC for each Simulation Unit and total grassland area provided from CORINE land cover. Despite the different approaches used by CAPRI and GLOBIOM-EU, consistency increased significantly and grassland areas are now within reasonable ranges for most countries. Total grassland of GLOBIOM-EU represents 81% of total grassland are in CAPRI.

An area balance database was created that lists all available sources of land use/cover information per MS and the mapping to model areas (see Table 2). This database can be used for the interpretation of results of both models. Remaining differences are typically differences due to omission of certain land use types or crops in one or the other model and not due to differences in the input database (which was harmonised, i.e. both models use the same). These differences can be diminished with common aggregate classes.

Table 2: Mapping of area categories between the two models. Differences in the representation of land use categories are bridged with common aggregate classes (lightest grey shaded boxes) that allow for comparison, consistency checks and easier exchange of data.

CAPRI					GLOBIOM		
Paddy rice	Arable crops	Crop area - arable and permanent	Utilizable agricultural area	Total area including marine waters	Cropland	Cropland	Cropland
Fallow land							Heterogenous areas
(Other) Arable crops - all arable crops excluding rice and fallow							
Temporary grassland						Other cropland	Other cropland
Fruit and citrus	Fruits, nursery and (other) permanent crops				Permanent crops	Permanent crops	Permanent crops
Olive groves							
Nursery and permanent crops							
Vineyard							
Grassland - no tree cover	Grassland				Grassland	Productive grassland	Pastures
Grassland - tree cover							Heterogenous areas
							Scrub/herbaceous areas
Artificial	Artificial - buildings or roads				Artificial	Artificial	Artificial
Board leaved wood	Forest	Total wooded land - forest + other wooded land			Forest	Forest	Broad leaved forest
Coniferous wood							Coniferous forest
Mixed wood							Mixed forest
Plantations							Scrub/herbaceous areas
Other wooded land	Other land - shrub, sparsely vegetated or bare				Other natural vegetation	Other wooded land	
Other sparsely vegetated or bare						Unproductive grassland	Unused pastures
						Natural land	Remaining scrub/herbaceous areas
							Remaining heterogenous areas
							Unused cropland
Shrub land - no tree cover					Open space	Open space	Open space
Inland waters	Inland or marine waters				Water	Water	Inland and marine waters
Marine waters					Wetlands	Wetlands	Wetlands

3 EU reference and baseline scenario development

3.1 PRIMES energy scenarios and projection of wood demand

An important basis for producing LULUCF emission scenarios for the EU reference and baseline scenarios 2012-3 are PRIMES bioenergy demand projections in combination with consistent biomass supply projection by the PRIMES biomass model that are taken up by GLOBIOM.

The PRIMES projections of bioenergy production provide only one part of total wood demand projection in Europe. The model GLOBIOM was used to integrate energy wood demand from PRIMES and demand for other wood products. This was done in the following way.

The energy wood production in GLOBIOM was first set to match the amount projected by the PRIMES biomass model. This was implemented as a minimum constraint. This means that a country can produce more but not less wood for energy use than prescribed by PRIMES biomass. By doing this it is assured that the production of biomass projected by PRIMES in the EU is achieved but allows for flexibility to produce more if demanded, e.g. through international trade. Other (non-energy) wood products were left competing for the wood resource. This means that GLOBIOM treats them as variables in the model. An increase in biomass production prescribed by the output of the PRIMES biomass model is entirely reproduced in GLOBIOM. However, trade and the demand from other sectors can lead to higher production above the PRIMES projection in countries with competitive production potentials. An increase in wood harvest for energy purposes can also mean that the production of wood for non-energy purposes in a country is affected. A country might thus produce more wood for energy from its (limited) domestic forest resources and produce the amount prescribed by PRIMES biomass but reduce non-energy wood harvest, leading to constant total wood harvest in the future. The reduction in production of non-energy wood affects the trade of wood between countries but can also affect total demand depending on wood demand in other countries and the countries wood price elasticity. GLOBIOM demand for non-energy wood is driven by population and GDP growth.

Historical data on wood production in EU28 was collected from individual country submissions and FAOstat data (http://faostat3.fao.org/home/index.html#HOME, download Nov 2012). Values for the years 2000 to 2010 were taken from these historic data. Estimates for the years 2020, 2030, 2040 and 2050 are results from the GLOBIOM projection and were interpolated to obtain annual harvest data. The time series of historic data and model projections was used as input to G4M.

3.2 Additional specific country assumptions

A policy questionnaire among EU member states answered in spring 2012 resulted in general information on the LULUCF sector and planned and implemented policies by member states. In almost all cases the information was too general to detect concrete policies that could be implemented directly into the model. The information collected through the survey in 2012 was included in the emission projections of individual countries where the information was relevant for the model.

Table 3: List of specific country information regarding policies to be considered in the scenarios. Information is labelled “relevant” in cases where the information provided by the country can be used either as an input into the model (e.g. concrete area targets for afforestation) or can be used to assess the model output (e.g. consistency check between model result and a certain policy aim). When the information requires a further discussion and interpretation through country consultations it is marked with “follow up”.

Country name	Info on LULUCF provided	Information relevance
Austria	Yes	relevant
Belgium	Yes	
Bulgaria	Yes	
Cyprus	No	
Czech Republic	Yes	relevant
Germany	Yes	relevant
Denmark	Yes	relevant
Estonia	Yes	relevant
Greece	Yes	
Spain	Yes	
Finland	Yes	
France	Yes	
Croatia	No	
Hungary	Yes	
Ireland	Yes	relevant
Italy	Yes	
Lithuania	Yes	relevant
Luxembourg	Yes	
Latvia	Yes	relevant
Malta	Yes	
Netherlands	Yes	
Poland	Yes	
Portugal	Yes	
Romania	Yes	
Sweden	Yes	
Slovenia	Yes	
Slovakia	Yes	
United Kingdom	Yes	

3.3 Global drivers

Outside Europe, POLES Baseline scenario (EC, 2011) is implemented for bioenergy demand, population and GDP growth. This baseline does not reflect any explicit biofuel or climate change mitigation policies outside the EU. Until 2050, GDP increases in the rest of the world from 35 Billion USD in 2000 by 142% to about 165 Billion USD. Population grows by 53% to 8.6 Billion in 2050 in the rest of the world. The scenario projects the demand for total bioenergy in the rest of the world to increase from 10.8 EJ to 49.1 EJ in 2050 (+353%). Assumptions on technological change are in line with the Shared Socio-economic Pathways (SSPs)[1] (O'Neill et al., 2012) as being used for the 4th IPCC Assessment Reports. To estimate crop sector productivity changes we used semi-quantitative information from SSP2 (moderate "Business as usual" scenario) and transformed it into crop and livestock productivity growth rates. For the crop sector yield response functions to GDP per capita have been estimated for 18 crops using a fixed effects model with panel data. For the livestock sector efficiency increases for livestock products (ruminant, pig and poultry meat, milk and eggs) are based on CAPRI for Europe and outside Europe on Bouwman et al. (2005).

Table 4: List of global driver information used for the projections.

Drivers	EU28	ROW
Population	GEME3	POLES Baseline (EC, 2011)
GDP	GEME3	POLES Baseline (EC, 2011)
Bioenergy demand	PRIMES	POLES Baseline (EC, 2011)
Exogenous yield growth crop sector	Own econometric estimate	Own econometric estimate
Exogenous yield growth livestock sector	CAPRI	Bouwman (2005)
Human diets	Alexandratos (2006)	Alexandratos (2006)

Food demand can be influenced by many different factors in interplay at different levels (society, industrial sector, households and individual). Among the various drivers can be listed: population, income, urbanization, trade regime, agro-food market structure, retailing and marketing practices, consumer preference etc.

In GLOBIOM, we focus on the most important factors and our food demand projections are based on the interaction of three different drivers:

(i) population growth
(ii) income per capita growth
(iii) response to prices

Drivers (i) and (ii) are exogenously introduced in the model baseline. Demand increases linearly with population in each of the 53 GLOBIOM regions (including the 28 EU countries). GDP per capita changes determine demand variation depending on income elasticity values associated to each scenario. Price effect (iii) is endogenously computed, and the final demand in the model is therefore influenced by some other assumptions on technology, natural resources, etc. that shape price patterns.

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. Income elasticities used in GLOBIOM rely on two main sources: USDA elasticity dataset (Muhammad et al., 2011) and the Food Balance Sheets (FBS) from FAO. To complement this dataset with more accurate information, we performed regressions on the FAO FBS versus the change in income per capita on the period 1995-2005. When a robust trend was observed, the corresponding income elasticity was used to calibrate the initial year of GLOBIOM.

[1] Detailed description and relevant references can be found at https://www.isp.ucar.edu/sites/default/files/Boulder%20Workshop%20Report_0.pdf.

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).

4 Calculation of emissions

Figure 2 provides an overview of land use categories, land conversions, processes, products and emissions covered by the modelling approach for LULUCF. The models GLOBIOM and G4M together cover all UNFCCC land use categories of relevance for CO_2 emissions. Only wetlands and settlements are not included. G4M covers the forestry sector and delivers emissions from biomass and soil from afforestation and deforestation activities and biomass emissions from forest management. GLOBIOM supplies emissions from cropland and grassland management.

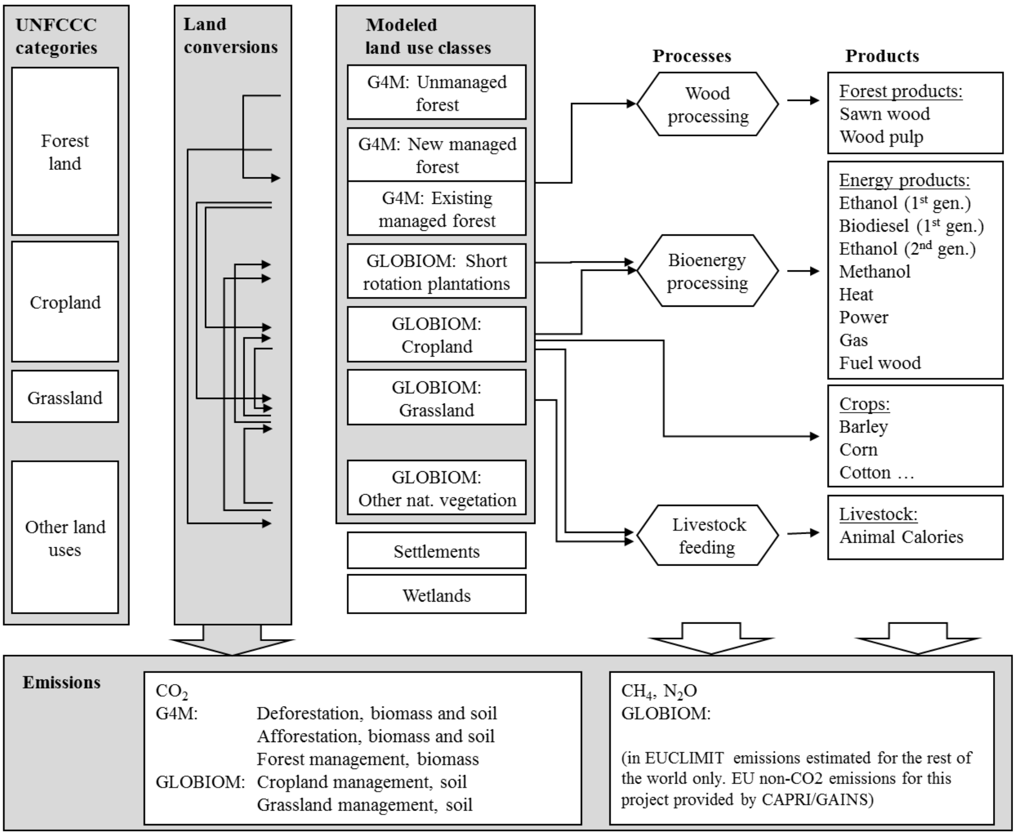

Figure 2: Overview of land use categories, land conversions, processes, products and emissions covered by the modelling approach for LULUCF.

4.1 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 biomass for bio-energy and non-energy uses. The model is calibrated to historic observed forest area changes. Data collected by JRC in 2012 were used to calibrate G4M to the period 2000 to 2010 using average deforestation and afforestation data. The forest area was set to match the reported forest area in 2008 (see Table 5).

Table 5: Data on afforestation, deforestation and forest area used as input to G4M for model calibration. The values were collected by JRC in 2010.

Country	Average reported area (1990-2008) [kha]		Forest area in 2008 [kha]	Source/ Comment on forest area data
	Afforestation	Deforestation		
Austria	10	5	3793	JRC estimate from UNFCCC reporting
Belgium	1	2	681	JRC estimate from UNFCCC reporting
Bulgaria	23	1	3752	JRC estimate from Convention reporting
Czech Republic	2	0	2563	Value for 2008 from KP[1] tables
Denmark	4	0	533	Value for 2008 from KP[1]tables
Estonia	0	0	2081	JRC estimate from UNFCCC reporting
Finland	3	15	21873	Value for 2008 from KP[1]tables
France	81	45	12884	Value for 2008 from KP[1]tables (excludes 1690 kha from overseas territories)
Germany	64	35	10710	Value for 2008 from KP tables
Greece	0	0	3752	MCPFE (2005)
Hungary	9	0	1872	Value for 2008 from KP[1]tables
Ireland	6	0	465	Value for 2008 from KP[1]tables
Italy	78	1	7451	Value for 2008 from KP[1]tables
Latvia	0		3221	Value for 2008 from KP[1]tables
Lithuania			2000	JRC estimate from UNFCCC reporting
Luxembourg	0	0	86	JRC estimate from UNFCCC reporting
Netherlands	3	2	346	JRC estimate from UNFCCC reporting
Poland	8	0	8546	JRC estimate from UNFCCC reporting
Portugal	46	45	2408	Value for 2008 from KP[1]tables
Romania			6685	JRC estimate from UNFCCC reporting
Slovakia	1	0	1916	JRC estimate from UNFCCC reporting
Slovenia		0	1185	Value for 2008 from KP[1]tables
Spain	0	1	12577	Value for 2008 from KP[1]tables
Sweden	84	21	27644	Value for 2008 from KP[1]tables
United Kingdom	6	1	2845	MCPFE (2005)

[1] KP – Kyoto Protocol, available only for countries that elected Forest Management as activity under Article 3.4 of the Kyoto Protocol.

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. (2008b). Increment is determined by a potential Net Primary Productivity (NPP) map (Cramer et al., 1999) and translated into Net Annual Increment (NAI). The increment estimated by G4M was reviewed by member states during the consultation processes (in 2012 and early 2013) and adjusted to better reflect national circumstances based on forest inventory information provided by the member states. In the course of this project in the case of Austria the increment was adjusted based on new data that showed a deviation from the increment assumed by the model. G4M uses forest growth functions specific for major tree species – fir, spruce, pine, birch, beech, oak and larch developed by Kindermann (2012). Tree species distribution in each grid cell are distinguished using a species map by Brus et al. (2012).

Both, initial growing stock and increment were 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). The model uses the age class structure reported by countries for initialisation. 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.

Afforestation

Starting from the calibrated afforestation rates provided by JRC, 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. 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 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, 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.

The forest established on afforested land has the same properties, i.e. growth rates, management rules as the forest already existing in neighbouring grid cells. This means that forest growth rates of afforested land are rather moderate compared to dedicated forest plantations established for commercial timber production e.g. in Southern Europe. 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. They are covered by GLOBIOM and show up under the cropland category.

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 1).

*Biomass C removals AR = Other land area converted to FL * Biomass C increment* *(1)*

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 (2008b). 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.

Deforestation

Land and wood prices that G4M receives from GLOBIOM are also used to project trends in deforestation. 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 2).

$$\textit{Biomass C emissions D} = \textit{FL area converted to other land} * \textit{Average biomass C stock} \qquad (2)$$

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).

Forest management (Forest land remaining Forest land)

The main forest management options considered by G4M are variation of thinning and 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.

The model uses projections of wood demand per country estimated by GLOBIOM to calculate total harvest iteratively. The potential harvest amount per country under a scenario of rotation lengths that maintain current biomass stocks is estimated. If total harvest is smaller than wood demand the model changes grid per grid (starting from the most productive forest) management to a rotation length that optimizes forest increment and thus allows for more harvest. This mimics the typical observation that managed forests (in some regions) are currently not managed optimally with respect to yield. The rotation length is changed at maximum by five years per time step. If harvest is still too small and unmanaged forest is available the status of the unmanaged forest will change to managed. If total harvest exceeds demand the model changes management to maximum biomass rotation length, i.e. manages forests for carbon sequestration. If wood demand is still lower than potential harvest managed forest can be transferred into unmanaged forest. 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. The model can consider the use of harvest residues e.g. for bioenergy.

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 3).

*Biomass C emissions FM= Area FL r FL * Total biomass C stock changes* *(3)*

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 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 2050) were "calibrated" (i.e. adjusted) using historical data from the country for the period 2000-2010 (period of overlapping data from UNFCCC and model projection). To this aim, an "offset" was calculated as difference between [average of country's emissions and removals from biomass for the period 2000-2010] and [average of models' estimated emissions and removals from biomass for the period 2000-2010].

The calibrated model estimate is obtained by adding the offset to the model's original value. The model results were adjusted to match the average historical data provided by each country for the period 2000-2010. This 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.

The calibration procedure automatically incorporates into the projections the average rate (for the period 2000-2010) of the GHG impact of past natural disturbances, which are not explicitly estimated by the models (e.g. emissions from fires etc.). The future trend of emissions and removals up to 2050 as predicted by the models is not affected by this calibration 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).

4.2 Emissions from harvested wood products

Harvested wood products (HWP) form a carbon stock that is built up through the production of wood products produced from harvested wood and that is losing carbon through decay. Emissions from HWP are estimated following the Durban Accords (Decision 2/CMP.7) and respective Tier 2 IPCC guidelines. The guidelines specify that only domestically produced wood shall be accounted for. Imported wood is not included in the accounting. GLOBIOM provides specific categories of wood use; that are sawnwood, pulpwood, energy wood and other wood. On the basis of these variables the HWP carbon stock *HWP C stock* is calculated using first-order decay functions with category specific default half-lives (see Table 6) provided in the GPG-LULUCF. The following equation is applied.

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

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, where HL is the half-life of the HWP pool in years), *Inflow* is the inflow to the particular HWP category. It is assumed that the HWP pools are in steady state at the initial time *t0*. This means that emissions from HWP are assumed to be zero (inflow=outflow) in the first year of the estimation (2000). The steady state carbon stock for each HWP commodity category is approximated by applying Equation 5 using the average of inflow of the period 2000-2010.

$$HWP\ C\ stock_{t0} = k\ /\ inflow_{average\ 2000\text{-}2010} \quad (5)$$

The emissions from HWP are finally estimated by calculating the differences between the carbon stocks estimated for subsequent 10 year periods as provided by GLOBIOM, divided by 10, the number of years.

Table 6: Default half-lives of IPCC categories and GLOBIOM category mapping.

GLOBIOM category	IPCC category	Half-life default value [years]
Energy wood	-	0
Sawnwood	Sawnwood	35
Pulpwood	Paper	2
Other wood	Wood panels	25

4.3 Emissions from cropland management

Several studies have shown the dynamic interaction between SOC (soil organic carbon) sequestration rates, soil management decisions and SOC levels. Bellamy et al. (2005) concluded that carbon losses increased with soil carbon content over different land use activities. Moreover, soil management and land use change affect SOC sequestration rates. Management practices such as reduced and no-tillage, improved residue management and crop rotations potentially increase SOC content as well as the conversion of marginal cropland to native vegetation or conversion of cultivated land to permanent grassland (Dawson and Smith, 2007; West et al., 2004). Emissions from cropland remaining cropland are calculated by multiplying the area under cropland management with an emission factor (see Equation 6).

$$SOC\ emissions\ CL\ management = Area\ CL\ r\ CL * Emission\ factor\ CL \quad (6)$$

To estimate the emission factor for cropland (CL) and in order to represent SOC dynamics and estimate SOC emissions accurately we implement an approach developed by Schneider (2007). First, we associate each land use system (crop and management system) with a certain SOC state, which by definition corresponds to the SOC state at the beginning of a simulation period.

Second, carbon response functions for each of the crop rotation are estimated using EPIC, a biophysical crop model. SOC sequestration curves for the different crop rotations and management systems are estimated. The EPIC runs cover the whole spectrum of SOC states and enable to account for e.g. management or crop rotation change at any given SOC stock in the model.

Third, SOC state transition probabilities are calculated for the crop rotations, management systems and SOC states. State transition probabilities define the probability of moving from initial SOC state at the beginning of the period to another carbon state at the end given a certain management. For more detailed information we refer to Schneider (2007).

SOC emissions are calculated endogenously as the sum of sequestration rates over all land use activities per year. We account for emissions from cropland remaining cropland, perennials (lignocellulosic crops and short rotation tree plantations) and land converted to cropland or plantations. Biomass accumulation on short rotation tree plantations is also estimated by the model.

For the base year 2000, initial carbon stocks are scaled to match trends in UNFCCC reported data on soil carbon emissions. The rationale behind this scaling is that most European cropland has been cropland for a long time and should therefore be close to the equilibrium. However, carbon stocks reported by Jones et al. (2005) do not necessarily represent SOC equilibrium states as simulated by EPIC. This results in inconsistencies as SOC stocks converge rapidly towards the "new" equilibrium. Panagos et al. (2013) compared data from Jones et al. (2005) to measured LUCAS 2009 data and showed an underestimation of SOC in Southern Europe while in Central and Eastern Europe a net overestimation was visible. Therefore, rescaling stocks seems reasonable given the uncertainties surrounding initial SOC stocks (Ogle et al., 2003; Post and Kwon, 2000).

4.4 Emissions from grassland management

The uncertainty of grassland areas is addressed in the description of the CAPRI model. In GLOBIOM originally grassland areas did not represent total existing grasslands but productive grassland for animal feeding only. This was due to the fact that properties of low productive grasslands and their production to satisfy feed demand are not known. 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 is reported under other natural vegetation and is therefore available for afforestation. For some Member States grassland areas differ by a factor of three and more when comparing different sources of statistical land use information.

To improve the consistency with reported UNFCCC data the category of unproductive grassland was separated and added to total grasslands. This allows to present total grassland extent that is consistent with UNFCCC reporting.

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).

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

The emission factor is derived from UNFCCC reported data by dividing reported emissions from grassland remaining grassland by existing grassland area. SOC emissions from grasslands for countries where UNFCCC data are not available are calculated based on a generic emission factor of -

1.83 t CO_2/ha/y (Soussana et al., 2004). Other land converted to grassland is assumed to sequester SOC at the same rate as grassland remaining grassland if data specifically for this activity are not reported. The 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 method 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 overcome data gaps. However, deriving the emission factor from UNFCCC data leads overall to a better comparability with historic data at hectare level.

4.5 Emissions from wetlands, settlements and other lands

Emission projections for wetlands, settlements and other land are included in the methodology to provide a complete set of emissions and improve the comparability to total LULUCF emissions reported by countries to UNFCCC until 2012. Areas covered by wetlands, settlements and other lands are included in the GLOBIOM model. They are assumed to remain constant over the simulation period. There is a lack of information about the properties of these lands, especially regarding emissions, cost of conversion and detailed historical trends that would be needed to include them in the optimisation algorithm. Emission data for all three categories presented are based on UNFCCC reported data and kept constant in the future.

5 Calculation of mitigation cost curves

The EU reference scenario run was carried out to project the likely development of CO_2 sinks and sources in LULUCF for EU countries under baseline conditions, i.e. in the absence of market mechanisms to mitigate emissions and increase sinks. To assess the potential and associated costs of mitigation measures on top of the reference development, marginal abatement cost curves were calculated. These were constructed by applying management change scenarios with changing CO_2 prices. The calculations were done using G4M (forestry activities) and GLOBIOM-EU (agricultural activities, i.e. cropland management). Into both models a CO_2 price was inserted that typically affects the economic performance of forestry and agriculture and thus the behaviour of land owners to change land use. The CO_2 price was introduced as a carbon tax to be paid by land owners when emissions occur on their land. The CO_2 price is introduced in the model year 2020 and kept constant at steps of 5 or 10 EUR per tonne of CO_2 (for the levels of 5, 10, 15, 20, 30, 40 , 50, 60, and 70 EUR per t CO_2) over the entire simulation time.

5.1 Forestry activities

The measures considered as mitigation measures in forestry 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
- Change of harvest intensity (amount of biomass extracted in thinning and final felling activity)

These activities are not adopted independently by the forest owner. The model is managing land dynamically and one activity affects the other. The model is calculating 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 it. The increased value of forests in a regime with a CO_2 price changes the balance of land use change through the net present value (NPV) generated by land use activities towards forestry.

In general, it is therefore assumed that an introduction of CO_2 price leads to a decrease of deforestation and an increase of afforestation. This might not happen at the same intensity though. Less deforestation increases land scarcity and might therefore decrease afforestation relative to a baseline.

The existing forest under a CO_2 price is managed with longer rotations of productive forests, and shifting harvest to less productive forest. Where possible the model increases the area of forests used for wood production, meaning a relatively larger area is managed relatively less intensively. This model paradigm implies also changes of the thinning versus final felling ratio towards more thinnings (which affect the carbon balance less than final fellings). Forest management activities can have a feedback on emissions from deforestation because they might increase or decrease the average biomass in forests being deforested. It also influences biomass accumulation in newly planted forests depending on whether these forests are used for production or not.

For the generation of cost curves for forest management a two-step approach is used. In step 1 every year, starting from the onset of mitigation measures, forest management, i.e. the length of rotation and the frequency and intensity of thinnings, in each cell is changed towards a state that maximises the forest biomass. In all cases the maximum rotation length is not allowed to be higher than the rotation length maximising biomass. In step 2 measures are taken that ensure that the production of wood to satisfy wood demand has higher priority than the carbon accumulation. Therefore, after Step 1 the forest management of forests within each country is readjusted to match the wood production prescribed by GLOBIOM. This iterative process ensures that the forest management regime still delivers the required wood. This avoids leakage effects that would occur if a country would stop harvesting to store carbon in domestic forests but would start importing wood to satisfy demand.

5.2 Cropland management

Within GLOBIOM-EU the model determines how much area should be devoted to each management alternative. The levels of the endogenous land management variables are optimal when the sum of producer and consumer surplus over all regions and commodities is maximized. The product of the exogenously given per-hectare impacts times the endogenously determined area in hectares summed over all management alternatives gives the total impact of cropland management on production, input use, and environment. To generate abatement cost curves, GLOBIOM-EU is subjected to a range of carbon prices. These prices affect the revenues and costs of different land management strategies. For example, if a certain crop management increases emissions by 1 metric ton of carbon per hectare and year, a carbon price of 100 would increase the costs of this strategy by 100 Euros per hectare and year. Since different land management alternatives have different net emission values, the imposition of carbon prices leads to different costs impacts for different strategies. As a result, the optimal allocation of land management strategies increases the adoption of emission intensive strategies. Overall, the change in management then leads to reduced net carbon emissions. The following cropland management activities are considered in the model:

- Change in crop choice
- Change in crop distribution across land qualities
- Change in crop management
    - three tillage intensities (conventional, reduced, no tillage)
    - two irrigation alternatives (irrigation or rain-fed)

In order to avoid leakage effects through trade to countries outside the EU which do not implement a carbon price (e.g. ROW increasing production and exporting it to EU since prices for commodities rise due to the CO_2 tax inside EU), the net trade flows with the ROW are fixed to Reference scenario quantities.

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