European Commission

JRC TECHNICAL REPORT

Improved Modelling Framework for Assessing the Interactions between the Energy, Agriculture, Forestry and Land Use Change Sectors

Integrating the CAPRI, LUISA-BEES, CBM and POTEnCIA Models

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2021

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EUR 30514 EN

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https://ec.europa.eu/jrc

JRC123172

EUR 30514 EN

PDF	ISBN 978-92-76-27386-8	ISSN 1831-9424	doi:10.2760/900305

Luxembourg: Publications Office of the European Union, 2021

How to cite this report: Sahoo A., Pérez Domínguez I., Mubareka S., Fiorese G., Grassi, G., Pilli, R., Himics M., Blujdea, V., Follador M., Neuwahl F., Salvucci R., Rozsai M., Witzke P., Kesting M., *Improved modelling framework for assessing the interactions between energy, agriculture forestry and land use change sectors: integrating CAPRI, LUISA-BEES, CBM and POT*EnCIA, EUR 30514 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-27386-8, doi:10.2760/900305, JRC123172.

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Abstract

This report is an attempt to develop a modelling framework integrating different sectoral stand-alone models used at the JRC for policy impact assessment in the fields of agriculture, forestry, land use change and energy. The proposed quantitative framework should improve the capability of assessing greenhouse gas emissions and removals resulting from complex interactions between the agriculture, forestry, and other land use (AFOLU) sectors, and facilitate the analysis of policy scenarios relevant for a sustainable and carbon-neutral European economy. Four models are considered, for which a revised model specification and harmonization of relevant databases and model parameters is needed. The Common Agricultural Policy Regionalized Impact (CAPRI) Modelling System is a widely used large-scale multi-commodity agricultural economic model. The Land Use-based Integrated Sustainability Assessment modelling platform for BioEconomy and Ecosystem Services (LUISA-BEES) is primarily used for the ex-ante evaluation of European policies that have a direct or indirect territorial impact on the agricultural and forestry sectors. The Carbon Budget Model (CBM) is a stand-alone forestry model that simulates forest carbon dynamics. The Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA) model depicts a detailed EU energy system combining both techno-economic modules. As a 'proof of integration', this report describes the improvement of the CAPRI land use function and harmonization of related database such as to be linked to the output from the LUISA-BEES model. Moreover, forestry area projections and related carbon removals in CAPRI are improved by using direct information from the CBM model. Last but not least, the POTEnCIA model is improved by parameterizing a first generation biofuel supply curve based on CAPRI simulations.

In order to test the proposed modelling framework, the report proposes a set of exploratory policy scenarios based on each model's capabilities: reform of the Common Agricultural Policy, expansion of biofuel mandates and carbon pricing (CAPRI); implementation of spatially explicit sustainability criteria for the plantation of energy crops and afforestation (LUISA-BEES), different levels of forest harvesting (CBM) and strong decarbonisation policies (POTEnCIA).

1 Introduction

Globally, land use and forestry activities have been intensified and are expected to further expand to meet the future demand for food, feed and energy, but not without affecting the environment (Hurtt et al. 2020). Europe is not an exception will likely consume more biomass to meet its ambitious de-carbonization targets and scale-up its bio-economy sector. This additional biomass demand will be satisfied by increasing both domestic production and imports from third country supplies, with potential environmental impacts and spillovers still poorly understood (Fuchs et al., 2020). The agriculture, forestry and other land use (AFOLU) sectors are considered to be a significant net source of greenhouse gas (GHG) emissions globally, with land use change and forestry being responsible for both emissions and removals of carbon dioxide (CO_2), and agriculture representing a major source of methane (CH_4) and nitrous oxide (N_2O) emissions. A study by Strapasson et al. (2020) recognized the under-representation of land use as major option for carbon mitigation in EU policy and observed major long run mitigation impacts from reducing meat consumption as well as using efficient cropping techniques and re-allocating land mainly to forests and soil carbon storage. One of the main objectives of this report is to refine and improve the representation of existing methodologies covering emissions and removals from agriculture, including biofuel crops, and to better account for emissions and removals from forestry and land use change in the EU.

Within the JRC, several efforts have been done over the years to assess CO_2 emissions and removals in the AFOLU sector, such as the EcAMPA 3 study (Pérez-Domínguez et al, 2020) that incorporated endogenous GHG mitigation technologies in the CAPRI model and a preliminary inclusion of 'Land Use, Land Use Change and Forestry' (LULUCF) emissions/sinks following simple methods from the Intergovernmental Panel on Climate Change (IPCC) to the United Nations Framework Convention on Climate Change (UNFCCC). However, all these efforts were not harmonized and not tested within a specific policy scenario framework. Moreover, they were not framed within the renovated efforts of the Green Deal to move towards a more sustainable and carbon-neutral European economy, which requires important changes to the way energy is produced.

The proposed AFOLU integrated scenario framework builds on the respective strengths of different in-house models in the areas of agriculture, land use, forestry and energy. With this idea, active links between the Common Agricultural Policy Regionalized Impact (CAPRI) modelling system, the Land Use-based Integrated Sustainability Assessment modelling platform for BioEconomy and Ecosystem Services (LUISA—BEES), the Carbon Budget Model (CBM) and the Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA) are considered. CAPRI is a large-scale partial equilibrium economic model for the agricultural for sector suitable for comparative static ex-ante impact analysis of various agricultural policies (including environmental and climate change). It provides detailed farm level economic analysis for the EU while integrating at the global level through trade (www.capri-model.org). The Carbon Budget Model (CBM) is an inventory-based, yield-data driven model that simulates forest carbon dynamics and harvestable wood. The LUISA-BEES model provides estimates on land use change under different biomass demand scenarios, with a focus on agriculture and forested land. Last but not least, POTEnCIA is a modelling tool for energy system, designed to evaluate the impacts of alternative energy futures and policy instruments including, e.g., those fostering the replacement of fossil fuels with biomass and other renewables.

The AFO-CC study (Fiorese et al., 2015) was a first attempt to design an integrated modelling framework for the land-use sector built on stand-alone models in use at JRC and on their linkages. It was designed to link the POLES model (macro-economic data and the energy sector), the LUISA platform (land use changes), the CBM-CFS3 (forestry) and the CAPRI model (agriculture). In the context of the Biomass project, the forest sector has been modelled trying to capture both the demand side, with GFTM (Global Forest Trade Model), and the supply side, with CBM (Carbon Budget Model) (Jonsson et al., 2018, 2021).

The novelty of the proposed AFOLU framework is not only to harmonize and update the databases and specifications of these stand-alone models, but also to facilitate the implementation of several integrated policy scenarios, i.e. reform of the Common Agricultural Policy, expansion of biofuel mandates, carbon pricing, implementation of spatially explicit sustainability criteria for the plantation of energy crops and biofuel feedstock, afforestation policies, different levels of forest harvesting and strong decarbonisation policies among others. The main elements that allow these four models to 'communicate' are estimates of biomass demand for energy (including forest biomass for wood products), biomass supply, agricultural and forest land use allocation, food demand, land prices and forest dynamics, etc. (see Figure 1 in section 3). Beyond facilitating a novel integrated analysis of important policy questions, this exchange of information will improve the harmonization of model databases and results.

2 Modelling Systems in AFOLU

This section provides a brief technical description of the stand-alone models that support the AFOLU integrated modelling framework, namely the CAPRI, LUISA-BEEs, CBM and POTEnCIA models.

2.1 Modelling Agriculture: CAPRI

CAPRI model is a large-scale economic, global comparative static multi-commodity, agricultural sector model including 47 primary and secondary products (Britz and Witzke, 2014). This model allows assessing the impacts of agricultural, environmental and trade policies on agricultural production, farm prices and income, global agricultural trade and the agri-environment. CAPRI has a *supply module* with 280 representative regional farm models (i.e. profit maximizing behaviour) covering the EU-27 and some other European countries[1]. This supply model is linked iteratively with a global multi-commodity market module covering all regions in the world. Thus, it has global coverage, but is partial in nature, ignoring potential interactions with non-agricultural sectors. The *market module* simulates supply, demand, and price changes in global markets considering international trade. The inputs include land to crop and livestock production from other sectors and intermediate inputs produced by the farms such as feed and young animals.

The model has been designed for ex-ante impact assessment of agricultural, environmental and trade policies, e.g. subsidization of climate change mitigation technologies in the EU agricultural sector (Pérez Dominguez et al. 2016 and 2020; Fellmann et al. 2018), EU bilateral trade proposals (Burrell et al. 2011) and the assessment of the subsequent CAP reforms over time (EC, 2018d). The specific structure of the CAPRI model is suitable for the analysis of agri-environmental indicators, e.g. nutrient balances and GHG emissions, linked to changes in supply and demand triggered by policy changes. Some of the most recent studies have analysed exploratory scenarios looking at the potential of technologies for GHG emission mitigation (Van Doorslaer et al., 2014, 2015; Perez Dominguez et al, 2016), and have looked into the basic interactions between the LULUCF sectors in terms of GHG emissions and removals (Perez Dominguez et al, 2020).

The carbon cycle model in CAPRI quantifies relevant carbon flows in the agricultural production process related to both livestock and crop production. The carbon cycle model applies to 'cropland remaining cropland' and 'pasture land remaining in use. Carbon flows and CO_2 emissions from land use changes (LUC) are estimated based on simpler IPCC tier 1 default. Modelling GHG emissions in CAPRI considers three types of pollutants: methane (CH_4) from animal production, manure management and rice cultivation, nitrous oxide (N_2O) from agricultural soils and manure management, and carbon dioxide (CO_2) emissions from agricultural soils. Land use change emissions includes CH_4 and N_2O emissions from burning biomass, CO_2 emissions from below and above the ground biomass and soil carbon changes.

2.2 Modelling Forestry: CBM

The CBM-CFS3 model, developed by the Canadian Forest Service (CFS), can simulate the historical and future stand- and landscape-level C dynamics under different scenarios of harvest and natural disturbances (e.g. fires, storms), according to the standards described by the IPCC. Since 2009, the CBM-CFS3 has been tested and validated by the JRC, and adapted to the European forest conditions. CBM is an empiric model running on spatially referenced data (e.g., strata, defined at country or regional level, depending by the available data sources) (Kurz et. al., 2009, with CBM databases adapted to EU conditions, Pilli et al., 2018). It is currently applied to 26 EU Member States, both at country and NUTS2 level (Pilli et al., 2016a, 2016b, 2017, 2018). CBM runs with annual time steps.

[1] EU-28 plus Turkey, Norway and the Balkan countries.

Based on the model framework, each forest stand is described by area, age and land classes and up to 10 classifiers based on administrative and ecological information and on silvicultural parameters (as forest composition and management strategy). A set of yield tables define the merchantable volume production for each species while species-specific allometric equations[2] convert merchantable volume production into aboveground biomass at stand-level. The model provides data on the net primary production (NPP), C stocks and fluxes, as the annual C transfers between pools and to the forest product sector with an annual time step.

Other than the results related to the carbon stock change of forests, CBM may simulate for a specific set of silvicultural interventions rules that define forest management (i.e., thinnings of various intensities, clearcut, etc) and provide the amount of biomass removed from forests. Clearly, there is no *a priori* distinction on the final destination of the harvested biomass, specifically if it will be used for wood products or for energy production. The CBM model can potentially distinguish the total amount of harvest provided by forests at country or at regional level, according to different assumptions, distinguishing by species or species groupings (i.e., broadleaves and conifers), by wood components (i.e., stem, branches, tops and stumps), by management types (e.g., coppices, high forests), by silvicultural interventions type and intensity (e.g., thinnings, final cuts…). The implementation of all these further assumptions requires additional information provided by historical detailed data – or by other models, if referred to future harvest scenarios - on the harvest and the industrial processes, collected at national level, which are currently not available.

CBM integrates a soil module which initializes the carbon stock in nine dead organic matter pools through a semi-equilibrium procedure. The nine pools are further grouped in the IPCC DOM pools: dead wood, litter and organic matter in the mineral soils. Transfers between living biomass and DOM pools are implemented through turnovers specific to each biomass compartment. For the simulated period, CBM explicitly reports C stocks for each DOM pool with one-year time step. This allows estimating the change of the stock between successive years, and in a further step the values of the annual CO_2 emissions or removals from DOM pools.

The model is used to estimate the current and future forest carbon dynamics, both as a verification tool (i.e. to compare the results with the estimates provided by other models) and to support the current EU legislation (Grassi and Pilli, 2017; Grassi et al., 2018). In the biomass sector, the CBM-CFS3 can be used in combination with other models, to estimate the maximum wood potential and the forest carbon dynamic under different assumptions of harvest and land use change (Jonsson et al., 2018, 2021).

2.3 Modelling Land Use and Land Use Change: LUISA-BEES

The LUISA-BEES model is a fork of the LUISA territorial modelling platform described in Jacobs-Crisioni et al. (2017), modified for bioeconomy and ecosystem services applications. This model's origins, as they were developed for the European Commission in 2010, are described in Perez-Soba et al., 2010.

Land allocation in the LUISA-BEES model is based on the Dyna-CLUE model (Verburg et al., 2006; Verburg and Overmars, 2009). The main specifications are shown in Table 1.

Table 1. Summary of LUISA-BEES specifications

Spatial resolution	100m
Geographical coverage	European Union
Time step	5 years (with possibility 1 year)
Base map	Corine land cover 2018 , modified for forest area to match SOEF statistics, using Copernicus forest map
Range of simulation	2020-2050 (with possibility to extend to 2070)

The allocation is discrete, meaning each simulation unit, i.e. 1 ha cell, is assigned to a single land use type. What determines which land use is allocated, is a function of the suitability[3] of location for a land use type, the competition with other land use types and the land use requirement (demand for land).

2 Tree allometry establishes quantitative relations between some key characteristic dimensions of trees (usually fairly easy to measure, e.g. diameter at breast height) and other properties (often more difficult to assess, e.g. volume) (Wikipedia). In order to develop an allometric relationship there must be a strong relationship and an ability to quantify this relationship between the parts of the subject measured and the other quantities of interest.

3 The 'suitability' can also be referred to as transition potential or land use value (or utility).

The total suitability is the result of a combination of factors that express the added value of allocating land to a specific land use purpose. Each land use has its specific set of suitability rules, which is the result of a set of physical factors, neighbourhood potential, transition costs, location-specific subsidies or taxes, and any physical restrictions on transition. These are time-dependant in the configuration to allow for different behaviour for transitional classes (e.g. “young forest”).

The requirement for any given land area for given sectors (“demand) are exogenous to the model and are derived from different sources (Table 2).

Table 2. Land use classes in LUISA-BEES and associated source of demand

ID	Name	Source for demand	Exogenous / endogenous
1	Urban	Population growth (EUROPOP)	Exogenous
2	Industry	Extrapolation of trends in industrial land expansion	Exogenous
3	Arable	CAPRI model output	Exogenous
4	Permanent crops	CAPRI model output	Exogenous
5	Pastures	CAPRI model output	Exogenous
6	Mature forest	Endogenous to model, no demand. Land becomes mature forest as the result of natural succession	Endogenous
7	Transitional woodland & burnt areas	Corine 2018 land cover for first year of burnt areas and transitional woodland. For modelled years: no burnt areas subsequently; transitional woodland results after agricultural land is abandoned.	Endogenous
8	Abandoned arable	Endogenous to model, when demand for arable land < actual arable land	Endogenous
9	Abandoned permanent crops	Endogenous to model, when demand for permanent crops < actual permanent crops	Endogenous
10	Abandoned pastures	Endogenous to model, when demand for pastures < actual pastures	Endogenous
11	New energy crops	This is read from CAPRI model output, but is not available for all scenarios.	Exogenous
12	Semi-natural vegetation	Corine 2018 land cover for first year, no demand for this class but land may be taken from it	Endogenous
13	Young forest	Endogenous to model, no demand. Abandoned land becomes forested as the result of natural succession	Endogenous
14	Infrastructure (ports, airports, roads)	Not modelled	N/A
15	Other nature	Not modelled	N/A
16	Salines, bogs and marshes	Not modelled	N/A
17	Water courses, lagoons and estuaries	Not modelled	N/A
18	Urban green	Not modelled	N/A

2.4 Energy System Model: POTEnCIA

The Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA) is a hybrid recursive dynamic partial equilibrium simulation model designed for comparative scenario analysis to evaluate the impacts of alternative energy and climate policies on the energy sector in the EU([4]). It combines behavioural decisions with detailed techno-economic data. The typical period that can be analysed by POTEnCIA is up to year 2050 in annual steps. It is intended to represent the economically driven operation of the European energy markets and the corresponding interactions of supply and demand. Each country is modelled separately as to appropriately capture the existing differences in energy system structures, technological characteristics, resource constraints, etc. A representative agent seeks to maximize its benefit or minimize its cost under constraints related to behavioural preferences, technology availability, fuel availability, environmental considerations, etc. At the

[4] This section is largely based on the JRC Technical Report on POTEnCIA model description (Mantzos and Wiesenthal, 2016).

level of the overall energy system, the model determines the equilibrium across the different sectors by means of price signals for all scarce resources (traditional energy carriers, renewable energy, other efficiency and environmental related costs in relation to their potentials).

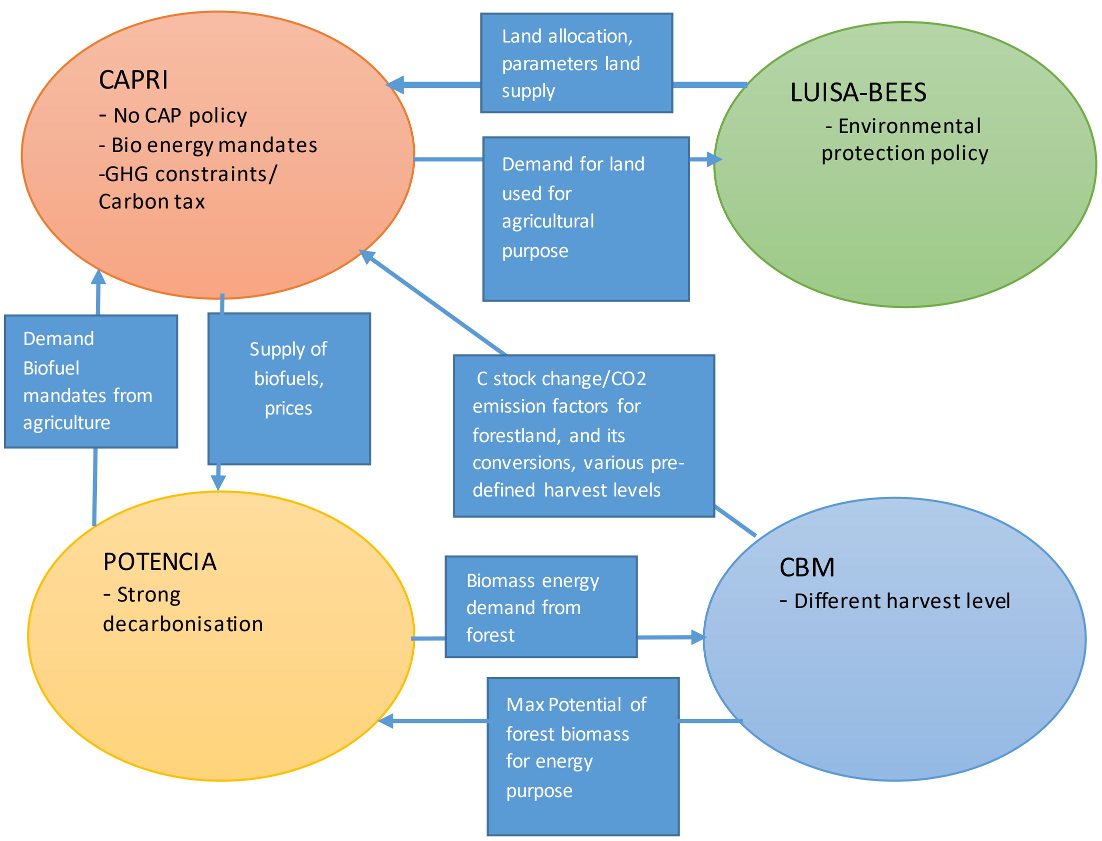
Given the complexity of the problem as such and taking advantage of the annual time steps in which the model solves, POTEnCIA makes use of the equilibrium prices with a one year lag. The model represents the physical energy-related equipment with an explicit structure of yearly vintages, whose characteristics dynamically evolve over time following technology evolution, while also talking into account possible premature scrapping and replacement of energy using equipment as well as the adoption of measures (e.g. insulation) that mainly affect the operation rather than the technological characteristics of the equipment. Equipment stocks are updated on an annual basis taking into account the investment performed in each specific year. POTEnCIA is capable of addressing to several useful policy scenarios:

- Energy taxation, support schemes (e.g. subsidies on capital costs of cars), feed-in-tariffs
- Minimum efficiency production standards (e.g. eco-design of energy-using products legislation)
- Targeting individual energy-using equipment
- Influencing consumer behaviour (decision making)
- Carbon market policies (Emission trading system; exogenous target carbon value or emissions achieved by endogenous carbon values in the non-ETS sector; emission standards, etc.)

3 Proposed Integrated Scenarios or the analysis of the AFOLU sectors

Given the structure and potential of the individual models (see section 2) the current AFOLU scenario framework is built on (1) the existing capabilities of these models to analyse a certain sector and (2) 'building bridges' across these models so that endogenous model responses are transmitted to the neighbouring ones (Figure 1).

Figure 1. Schematic structure and model links in the AFOLU scenario framework



The interaction between CAPRI and LUISA-BEES models will help improve the existing land allocation system in CAPRI. CAPRI will incorporate land allocation information from LUISA-BEES in the behavioural parameters for its land use supply function (see section 4.1 for details). In turn, the LUISA-BEES model will profit by incorporating the agriculture land conversion response of CAPRI in different scenarios (counterfactual changes to the baseline) between food and energy crops. In summary, any counterfactual policy shock in CAPRI will result in changes in demand for different land classes, and most prominently in agricultural land. It is the change in mix of how agricultural land is used in CAPRI that can be conveyed to the LUISA-BEES model to re-compute total land allocation within the Utilisable Agricultural Area (UAA). LUISA-BEES will maintain its own set of allocation rules for competition between UAA and the other land use classes. Given the advantage of the CAPRI model being an economic model with a detailed agricultural commodity classification, capturing supply and demand interactions across different activities and incorporating global trade, the model is suitable for evaluating various scenarios (see above). The impacts from these market and policy shocks are non-linear due to the cross effects (substitution/complimentary) between agricultural activities, which triggers changes in production, yield and land demand for different crops. Currently, the CAPRI data is used as direct input to the land use model of LUISA-BEES in the form of land requirements for the different classes of agricultural commodities. The mapping of CAPRI classes to LUISA-BEES classes is shown in Table A1.2 in Annex 1. CAPRI is more detailed regarding agriculture whereas LUISA-BEES is more disaggregated on non-agricultural areas

The land use and forestry module in CAPRI will incorporate a forestry baseline that is harmonized with the CBM model, for example on forest areas. Moreover, emissions/removal factors using forest carbon dynamics from CBM will also be used by CAPRI for the accounting of GHGs. For scenario purposes, CBM results for different harvest levels will be used to provide a sensitivity analysis on the resulting forest carbon sinks up to 2030; this analysis will provide different emission/removal factors to be used in CAPRI module (i.e. response function).

Although the LUISA-BEES model has a mechanism to compute GHG emissions from land use and land use change (Follador et al., forthcoming), it does not have a mechanism to compute forest carbon sinks, which is provided by CBM (see Mubareka et al 2018).

The interaction between the CAPRI and POTEnCIA models will include cost curves of first generation biofuels (i.e. biodiesel and bioethanol) and energy requirements of the crop production and transformation. The CAPRI model has energy costs as inputs in its supply model but does not currently compute energy balances for agriculture. For the generation of these curves, stylized scenarios will be implemented in CAPRI by running different biofuel mandates (for biodiesel and bioethanol) based on the estimated maximum potential biofuel use by Member States (see Section 3.2.3 below for detailed description). The information on feedstock supply and prices from CAPRI would allow for a better representation of first generation biofuel supply in POTEnCIA. Any policy leading to a more rapid decarbonisation would imply a change in the biofuel demand targets. Therefore, biofuel cost curves in CAPRI could be calculated sequentially with different demand targets from POTENCIA (response function).

Analysis of future scenarios will encompass also possible increases of harvest demand, coming from the ambition to move towards a largest share of renewables in the energy mix. Consequently, CBM will simulate the dynamics of biomass harvest and carbon flows in EU forests by using the demand prices of biomass for energy projected by POTEnCIA. However, since POTEnCIA simulates an aggregate of solid biomass (thus without explicitly distinguishing woody biomass), there is the need to define a way to distinguish the various sources of biomass, so that the woody component in POTEnCIA can be correctly linked to the CBM model. Furthermore, CBM will provide the maximum potential availability of forest biomass for energy purposes to POTEnCIA (response function). By doing this, it should be possible to assess and compare different future scenarios based on different contributions of forest biomass to the future energy mix.

Scenario interactions between the bioenergy models of CAPRI and POTEnCIA could indirectly affect the LUISA-BEES model through their impact on the demand for the agricultural land dedicated to biofuel production in the CAPRI model.

As we can see from the above discussion, through the AFOLU framework it is possible to implement several integrated scenarios. Based on this, we propose to analyse the following scenarios covering the time horizon 2030.

a) CAPRI model based scenarios

- Common Agricultural Policy (CAP) 2020 legal Proposal (i.e. lower pesticides, lower nitrogen leaching, higher share of organic production, etc.)
- Expansion of biofuel mandates (i.e. achievement of maximum mandates at MS level)
- GHG emission mitigation (i.e. carbon pricing scenarios)

b) LUISA-BEES model based scenarios

- Implementation of spatially explicit sustainability criteria for plantation of energy crops; RED II sustainability criteria and additional safeguards (where possible)
- Afforestation scenario (Forest Strategy Roadmap; 2030 Biodiversity Strategy), e.g. based on the "3 Billion Trees initiative"

c) CBM model based scenarios

- Different forest harvesting levels over time

d) POTEnCIA model based scenarios

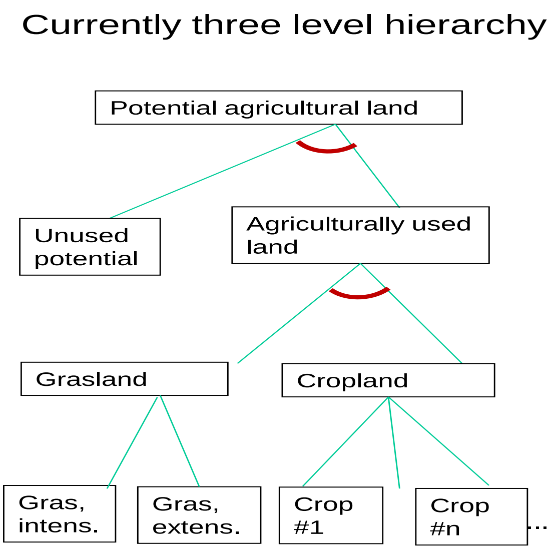
- Strong decarbonisation (i.e. in this context, increased replacement of fossil fuels by biofuels both in the transport sector and for thermal uses)

4 Model Harmonization and Implementation

4.1 Land Use Change: CAPRI and LUISA-BEES

The current land use module in CAPRI focuses on agricultural land use at the regional level, comprising two major components: (1) transformation of utilized arable and grassland, i.e. imperfect substitution between arable and grasslands depending on returns to the two types of agricultural land uses; and (2) a supply curve that determines the land available to agriculture as a function of the returns to land (Figure 2). There is substitution possibilities of single crops in for the arable land. A certain part of the non-agricultural land is considered in the form of an agricultural 'land buffer' or 'unused agricultural land' that gives, together with the 'agriculturally utilized land', the 'potential agricultural land', which has been the system boundary.

Figure 2. Current land use classification in CAPRI



For the parameterization of land supply for agricultural land classes, CAPRI used in the past information from the CLUE-S (the Conversion of Land Use and its Effects at Small regional extent) model to supplement information from GTAP, in particular for the regional disaggregation at Nuts 2 level (Verburg et al, 2002; Jansson et al, 2010). Land use is estimated in combination with a closed agricultural land balance, including the transition between land use classes.

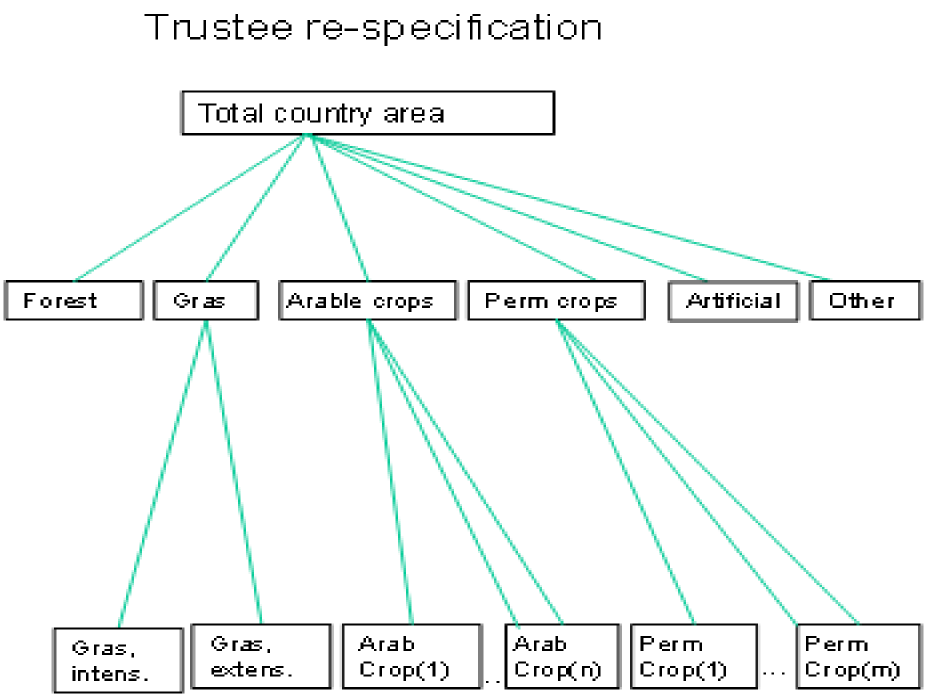
More recently, the land supply system in CAPRI was extended to cover a full regional area allocation, including transitions between all major land types. More precisely, non-agricultural land use was disaggregated into forestry, built up areas (urban or "artificial" land) and a remaining "other land" category. For the non-agricultural area types (other land, forest and artificial), some ad-hoc scaling mechanism plus some assumptions on the responsiveness of areas is used.

These land use categories integrate land use data from various sources (see Table A1.1 in Annex1). For carbon accounting, CAPRI relies on the six UNFCCC categories, e.g. cropland, grassland, forestland, settlements, wetlands, and residual land, which are mapped to agricultural activities. The UNFCCC category grassland is the sum of the productive grassland and some fraction of the "other land". Land allocation is performed as an optimization problem, ensuring adding up of single crop areas to land use aggregates and imposing constraints stemming from transition probabilities between different UNFCCC land-use categories.

Identifying these six UNFCCC land use categories also permits to estimate a 6 x 6 transition probability matrix between land uses. The simulated transitions are those transitions that maximise a Gamma density while being consistent with the simulated land use totals. As the mode values for the land transitions are taken from the historical database, this implies that CAPRI takes those land transitions as most likely that are most similar to historical patterns while being consistent with changing land use totals. Based on the transition matrix CAPRI performs carbon accounting relying strongly on IPCC default values.

The land use specification in CAPRI has also been extended and explored in projects like RURAGRI-TRUSTEE[5] and SUPREMA[6]. The TRUSTEE project relies on an extension of the CAPRI cost function, also covering non-agricultural land categories (see Figure 3).

Figure 3. TRUSTEE Land use Specification in CAPRI



The SUPREMA and TRUSTEE projects have many similarities, with just a marginal modification of the land use classification for types of grassland to include fallow land (following FAO data) (Figure 3). The main difference is the reduced form specification used in SUPREMA, where land use is represented as a function of land rents in a multinomial distribution (MNL) system for land supply of all major endogenous land types. Both specifications involve parameters for specific substitution possibilities between all pairs of land uses. It may be expected therefore that both would be able to approximately represent an arbitrary set of land supply elasticities that possibly might be derived from LUISA-BEES information. However, the SUPREMA specification could be preferred to TRUSTEE with respect to linking LUISA-BEES to CAPRI because of the use of MNL form.

The first decision to be made for the linkage of CAPRI to LUISA-BEES is the mapping of land use classes (see Table A1.2 in the Annex 1) and the specification of land supply in CAPRI. LUISA-BEES uses a series of land-use specific rules which may be applied either at the EU or country level There are rules that determine which land use can be converted to what (e.g. arable land can never become forest directly from one-time step to the next; urban land can never become arable land directly from one-time step to the next, etc.). When an agricultural land use is shrinking, meaning the CAPRI model shows a negative trend in the requirement of land area to produce an agricultural commodity, the land enters into a transitional phase labelled "abandoned". The land is easily converted to another land use while in this phase because it is no longer productive, yet it is already cleared. The land becomes progressively more expensive to convert as natural succession sets in as a function of time.

The LUISA-BEES model specifies land use decisions as utility maximising choices of land owners, where probabilities are partially expressed in a MNL form as a function of the utility (including its relative spatial location) of each single land use. In the standard case, the utility is measured by the net present value earned in some land use. The allocation of a land use class is determined by a combination of the suitability of the land to host that particular land use type, it's spatial location (i.e. neighbourhood), and the demand for the land use type.

The LUISA-BEES model will improve the land use module in CAPRI by incorporating all land allocation information in the behavioural parameters for land supply and/or demand with six endogenous aggregate classes: forestry, arable crops, permanent crops, permanent grassland, settlements and other land. However, even if LUISA-BEES also uses an MNL function, this cannot be directly used by CAPRI as LUISA-BEES applies the land allocation to the pixel level while CAPRI does it to the NUTS2 level.

5 https://www.trustee-project.eu/
6 https://www.suprema-project.eu/

Furthermore, there are two sets of coefficients that result from the LUISA-BEES calibration of the model: one referring to the biophysical suitability of a land use class and the second referring to the neighbourhood suitability.

Nonetheless the following procedure to indirectly use the information embedded in LUISA-BEES can be envisaged:

(i) LUISA-BEES could run a series of test scenarios where the land use of land types matching with the CAPRI classification at Nuts 2 level is increased or decreased by some percentage (say 1%) sequentially.

(ii) This would give a set of say 6 LUISA-BEES scenarios with pixel level results that permit to extract the set of endogenous average land rents across these land types for these auxiliary scenarios.

(iii) The changes in land rents cannot be directly taken to compute elasticities for land supply in CAPRI, because NUTS2 level areas will remain exogenous to LUISA-BEES[7]. However they could be used in the CAPRI calibration as auxiliary observations to be "fit" by suitable choice of parameters of the CAPRI land allocation system.

4.2 Forest simplified modelling: CAPRI and CBM

The Carbon Budget Model (CBM) is an empirical model running on spatially referenced data (e.g. strata, defined at country or regional level, depending by the available data sources) (Kurz et al., 2009) with CBM databases adapted to EU conditions (Pilli et al., 2018). CBM runs with annual time step. In the AFOLU project framework, CBM is supposed to interact mainly with the CAPRI model, feeding it with forest dynamic specific parameters for a more detailed and accurate analysis of LULUCF emissions. The CBM data used for this exercise was derived as part to an integrated assessment of the EU forest carbon (C) balance from 2000 to 2012, including: (i) estimates of the C stock and net CO_2 emissions for forest land remaining forest land (FL-FL), land converted to forest (L-FL) and deforestation (D, i.e. forest land converted to other uses), covering carbon in both the forest and the harvest wood product (HWP) pools.

The CBM results provided within this modelling framework are based on the "forest land remaining forest land" area reported by EU MS within their 2014 GHGI[8] for the historical period 2000 – 2012, further combined with data on deforestation and afforestation reported for the same period (Pilli et al. 2016a,b). Area is split between forest types (based on the leading species), management types (e.g., high forests and coppices) and according to other criteria (e.g. NUTS, climates types), thus creating numerous combinations of strata that allow for an accurate modelling of C dynamic in all forests pools. CBM runs are available for all EU MSs with the exception of Malta (no forest area) and Cyprus (no available data).

The net annual increment of forests and other parameters that serve as input into CBM are derived at country level from national forest inventories and other ancillary information at MS level. Harvest levels for each MS are exogenous to the CBM model. All these parameters are forest type dependent, age-dependent and/or volume-dependent (e.g. increment and yield tables, or allocation of biomass to other tree/stand compartments).

Development of lookup tables for carbon emission factors

CAPRI considers CO_2 emissions and removals of LULUCF mainly following the structure of the UNFCCC National Inventory Submissions. Land use change emissions/ removals follow the Tier 2 approach of IPCC. Biomass carbon stocks for assessing carbon effects of land use changes are based on the technical annex of the report to AA TREN/D1/464-2009-SI2.5393039, and the soil carbon stocks changes are based on FAO data. For each transition, the C stock changes are calculated as emissions from the previous class and removals from the new class, taking into account the climate zones. A special treatment is applied to biomass carbon dioxide emission/ removal factors for the remaining class "forest land remaining forest land" (Fl-FL). These net effects are directly taken over from the National Inventory Submissions of the UNFCCC in the capacity of net C stock changes in biomass and dead organic matter. C stock changes of soil resulting in CO_2 emissions/ removals from soil organic carbon for FORFOR are not taken into account (i.e. considered to be in equilibrium for the remaining class FORFOR).

One of the aims of this CAPRI-CBM linkage is to cross-check and project the factors of the Common Reporting Format (CRF) tables[10] used in CAPRI for FL with refined and also forecasted factors from CBM. For this purpose lookup tables with "emission factors", corresponding to "C stock change factors per ha" are constructed from CBM outputs (see Table A5 and Table A6Table 5A and Table 5B in Annex2). Factors are elaborated for the ecosystemic indicators (i.e. NPP, transfers from living biomass to dead organic matter pool through natural mortality and natural disturbances), for changes in C pools (dead wood, litter, mineral soils), and for the transfers associated to wood removals (as harvest). Emissions from organic soils are not considered. Factors

[7] At this point of communication it is unclear how (or if) LUISA-BEES can maintain the NUTS2 level area balance if NUTS2 level areas are exogenous inputs.

[8] When available, forest management (FM) country data from the KP-CRF tables was used for 2008-2012 (i.e., if FM had been elected during the first KP commitment period). Alternatively, country data were taken from the Convention CRF tables using 'forest land remaining forest land' (FL remaining FL) as a proxy for FM.

[9] "Background Guide for the Calculation of Land Carbon Stocks in the Biofuels Sustainability Scheme", https://esdac.jrc.ec.europa.eu/ESDB_Archive/eusoils_docs/other/EUR24573.pdf.

[10] The UNFCCC inventory submissions include Common Reporting Format (CRF) tables, a series of standardized data tables containing mainly quantitative information

are derived from the CBM runs corresponding to the historical period 2000 – 2012 for three harvest scenarios (as explained above).

In this exercise, three harvest levels have been considered for the period 2013 - 2030, creating three different scenarios:

(i) business as usual as reference, also assuming a constant afforestation rate,

(ii) +20% harvest in 2030 compared to the reference in 2012, combined with an increasing afforestation rate, and

(iii) -20% harvest in 2030 compared to the reference in 2012, combined with a decreasing afforestation rate

Basically, the reference implements a constant harvest corresponding to the 2000-2012 average period, thus representing the continuation of forest management practices as in the previous years. For each MS the whole range of harvest comprised between the +20% and the -20% compared to reference can be explored. Indeed, this allows producing a lookup table where each harvest level comprised in the range is matched with a corresponding carbon emission factor (i.e. gain and loss factors per ha), which can be applied in the CAPRI model. Harvest is identified with the sum of all transfers to HWP, FW and IRW (Figure A7 in Annex 2).

Many different scenarios can then be defined by CAPRI model assuming a reasonable range of harvest for each MS. Results may be valid for projections up to 2030, since after 2030 climate change impacts may not be neglected and, therefore, a different approach would be needed (e.g. changes of forest growth or presence of natural disturbances).

A major caveat of this approach is that such "carbon emission factors" derived from CBM outputs take into account the forest dynamics, forest management interventions and natural disturbances impacts in an implicit way. Moreover, emission factors are calculated at the national level through multiple average-weighting. Such simplifications using lookup table make any projections largely uncertain, especially as age-dynamics of forests are not considered explicitly in the final factors. However, uncertainty remains reasonable given the range of harvest included in the three scenarios, with the reference as the most likely one. All parameters extracted from CBM are provided as time series, in tons of carbon per year, from 2000 to 2030, based on the methodological assumptions and model output applied in Pilli et al. (2017). All details and methods are reported in Annex 2.

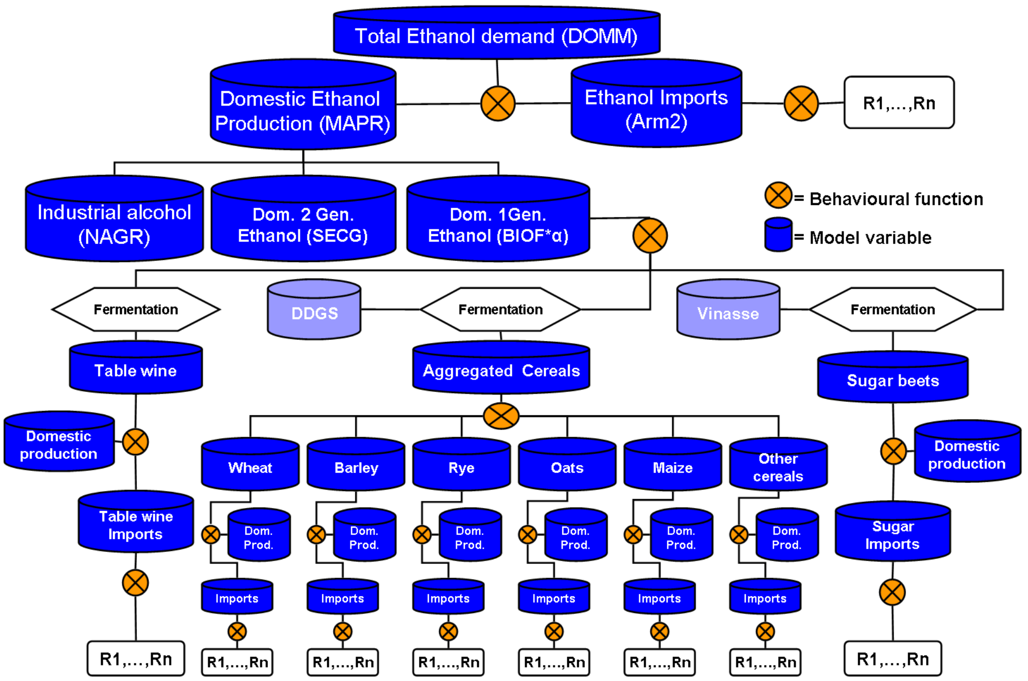
4.3 Biofuel: CAPRI and POTEnCIA

The CAPRI biofuel module covers two biofuel markets (biodiesel and bioethanol) and three technology pathways, first and second generation production from agricultural sources and production from non-agricultural sources (see Blanco et al., 2013; Britz and Delzeit 2013). The structure of the biofuel markets in CAPRI are presented in Figure 4 and Figure 5. The feedstock of the first generation bioethanol production includes cereals (wheat, barley, grain maize, oats and rye), table wine and sugar beet. The feedstock of first generation biodiesel production includes vegetable oils from rapeseed, sunflower seed, soybeans and palm oil[11]. The second generation biofuel production in CAPRI covers biofuels from agricultural residues (straw from cereals and oilseed production and sugar beet leaves) and from new energy crops (herbaceous and woody crops like poplar, willow and miscanthus). Non-agricultural biofuel production includes biodiesel production from cooking oils.

While the first generation biofuel production is fully embedded in the profit maximizing framework of CAPRI, the demand shares for second generation biofuel production are exogenously defined. The demand for agricultural residues from second generation biofuel production is historically low, having only a marginal impact on the market balances of cereals, oilseeds and sugar beet. Consequently, the biofuel demand shares for agricultural residues are set exogenously in the model, and the biofuel processing demand for agricultural residues does not enter the agricultural commodity market balances. The demand share for new energy crops is also set exogenously in the model. But unlike agricultural residues, the production of new energy crops might have an indirect effect on agricultural production in CAPRI through the competition for agricultural land. The available agricultural area for other agricultural production activities is reduced with the area devoted to energy crops in the land balance.

[11] In CAPRI, the processing demand for biodiesel enters the market balances of the individual vegetable oils. Biofuel processing demand is combined with other processing demands in the market balances of the seeds. The palm oil used in European biodiesel production is fully imported.

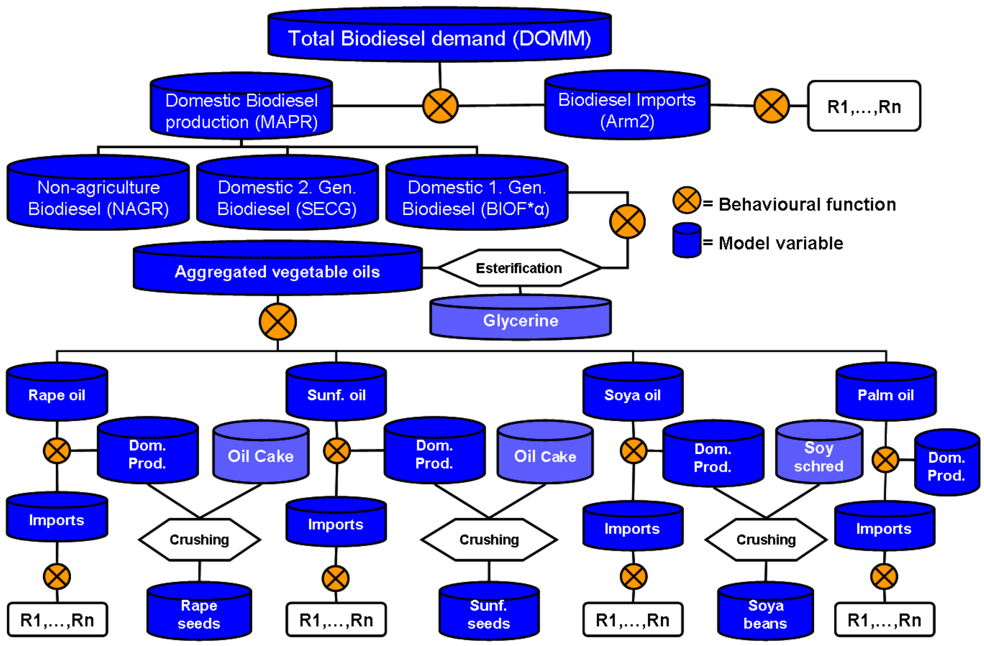
Figure 4. Construction of the bioethanol market in CAPRI



Source: Blanco et al. (2019)

Note: R1,...,Rn are regions

Figure 5. Construction of the biodiesel market in CAPRI



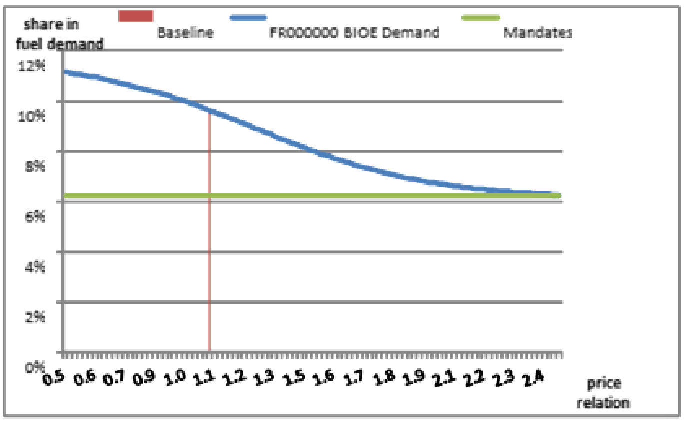
Source: Blanco et al. (2019)

Note: R1,...,Rn are regions

While biofuel supply and feedstock demand react to processing margins, biofuel demand and trade flows react to biofuel prices and other drivers. Feedstock demand is driven by per unit net input costs, i.e. feedstock prices minus by-product revenues per ton of input. The optimal feedstock mix defined by the first order conditions of a cost minimisation problem using CES cost functions for biofuel supply[12]. Biofuel production[13] is then derived by from the optimal of feedstock mix, based on biofuel processing coefficients.

The share of biofuels in total fuel demand is driven by the price relationship of biofuels to fossil fuels. Technically, sigmoid-shaped functions determine the demand shares, which are calibrated to reach at least the mandates (quota obligation or target) set by the different MS (Figure 6). An upper limit is also set during the calibration, representing the maximum potential biofuel demand above the quota obligation in a certain country. Total biofuel demand is then derived from the exogenous total fuel demand (including fossil fuels).

Figure 6. Biofuel demand share function in France



Source: Blanco et al. (2019)

The above specification of the biofuel demand shares is adjusted to various scenario assumptions on biofuel mandates, and on the maximum potential demand for biofuels in the Member States:

- The demand for biofuels from food crops is increased according to the targets in the RED II (Renewable Energy Directive recast) for each Member State. RED II sets a 7% target of the Final Energy Consumption of the land transport sector, which share can be approximated simply as 7% of the transport fuel sold in most cases, due to the low historical penetration of electric vehicles and small share of rail compared to road.
- After setting the biofuel demand shares equations to the RED II targets (7%), the biofuel demand curve is subject to sensitivity analysis. For this, CAPRI is solved repeatedly for different biofuel mandates below the RED II targets, by systematically decreasing the mandate parameter of the sigmoid function within a certain interval. With this the changes in the demand curve in the downward direction are investigated, since a further increase seems politically unrealistic.
- In an alternative set-up, biofuel demand from food crops is increased up to 7%, but the increase is limited to maximum +1% compared to biofuel demand shares in 2020. This scenario assumption is closer to the legal text of RED II. The same sensitivity analysis, as described above, explores a gradual decrease of the mandates from this second starting point.

To calibrate the CAPRI biofuel demand equations to this modelling exercise, current biofuel demand shares and biofuel mandates are taken from POTEnCIA. For this, the 7% EU target is broken down by MS, using current statistics on biofuel use and by estimating the potential for expanding biofuel use. The demand for biofuels from food crops is assigned fully to first generation production in CAPRI, without making further assumptions on advanced (second generation) biofuel production and use. Regarding the use of current biofuel use statistics, demand shares are assumed to remain steady over the period from 2020-2030, which follows current decarbonisation pathways.

Increasing biofuel use is expected to trigger substantial palm oil imports, which is against the sustainability criteria of the RED II. Furthermore, increasing biofuel demand can also trigger cross-sectoral effects, mainly through feed markets. For example, increased soybean imports might substitute domestically produced oilseeds in the feed mix, with indirect impacts on EU biodiesel

[12] Consequently, biofuel average costs are a CES-aggregate of the costs of individual feedstocks.

[13] A synthetic supply function is chosen for driving biofuel production, which satisfies some plausibility considerations: supply strongly decreases when the price relation gets below a certain "trigger" value and that this strong slope is not maintained throughout the whole function. This function consists of three parts: (i) the first part is linear guaranteeing a minimal slope, (ii) semi-log part that is active at processing margins, considerably higher than in the baseline point and (iii) sigmoid function part guaranteeing a steeper slope in a range where processing starts and production is close to zero when feedstock costs exceed output values.

production. Hence, we may consider extending the above scenario assumptions with import restrictions for specific products and from specific countries.

Food-crop based biofuel supply curves will be constructed with CAPRI based on a series of alternative biofuel mandate scenarios as described above. These will be used to calibrate the price formation mechanism for biofuel blends in POTEnCIA. The foreseen revision of this mechanism includes the explicit accounting of the following four components:

- Fossil fuels: the price trajectory over time is in this case taken as invariant with respect to demand (and therefore to the biofuel blending share), as it is considered to follow the (exogenous) evolution of international fuel prices rather than being driven by the European market.
- Biofuels from food waste feedstock, as included in the RED II Annex IX, part B. This corresponds essentially to waste cooking fats, and is assumed to be used only for biodiesel (absence of commercial pathways to turn this feedstock into bioethanol, and biogas not covered at this stage). Its cost is the lowest among all biofuel sources and considered constant, and its use is limited by supply. Supply limits are derived based on an extrapolation of the data submitted by the MS through the SHARES tool[14], and literature review.
- First generation biofuels based on food- and feed-crop feedstocks as referred to in the RED II Annex VIII, Part A: The cost of this biofuel component in POTEnCIA has to be calibrated to biofuel supply cost curves, both for bioethanol and biodiesel, produced with CAPRI by running a series of simulations covering the range of biofuel blending shares that would remain in compliance with RED II Article 26, paragraph 1.
- Advanced biofuels based on non-food feedstocks. Different types of such feedstock are listed in Annex IX, part A of the RED II. Separately accounting for each would not be a pragmatic option for a model of the entire energy system such as POTEnCIA; besides, the processes associated with several of those feedstock types are hardly developed at such a level that would allow their techno-economic characterisation at market-ready conditions. Consequently, we choose the approach to take a single feedstock type, lignocellulosic biomass, as representative of the entire category. Supply curves for lignocellulosic feedstock (including forestry residues as well as short-rotation coppice) should be determined through other models, while the techno-economic characterisation of the associated bio-refinery processes will be based on literature review. While advanced biofuels are expected to command a higher price than equivalent first generation biofuels, besides the supply-limited contribution of waste cooking fats, they remain the only option in the case of expanding biofuel shares beyond the limits of RED II Article 26, paragraph 1. Most importantly, minimum shares of advanced biofuels are required by Article 25, paragraph 1, of the RED II.

The functioning of this bottom-up based biofuel cost and feedstock-demand module in POTEnCIA is planned to be tested by developing a series of stylised short-to-mid-term CO_2 emission reduction scenarios for the EU, in which additional incentives are introduced in particular for bioenergy sources, boosting biomass demand especially in the following sub-sectors:

- District heating
- Transportation biofuels
- Space heating in the residential sector
- Industrial boilers for low- and medium-enthalpy heat e.g. in the food sector
- Partial substitution of coal and coke with biochar in energy intensive industries (integrated steelworks, cement kilns)
- Co-firing in solid-fuel fired power plants

The bioenergy quantity demand generated within the energy system under these conditions will then be fed back into CAPRI and other land-use models in order to determine the overall AFOLU impacts of the modelled energy scenario and thus further test the model linkages.

5 Conclusions

The EU territory holds almost three-quarters of agriculture and forest land and any policy action that affects the land use change in these sectors would contribute to the change of carbon stocks and GHG emissions/removals (https://ec.europa.eu/clima/policies/forests_en). Realizing the high priority for the climate ambition pronounced by the European Green Deal strategy, an integrated modelling framework covering agriculture, forestry, and other land use (AFOLU) is an effort that is capable of assessing emissions and removals from these sectors.

The presented integrated modelling framework is an attempt to bring together relevant models specialized in their respective domains, e.g. agriculture, forestry, land use and energy, such as to facilitate a comprehensive policy analysis. It covers four stand-alone models currently in use at the JRC. First, the agro-economic model CAPRI provides detailed farm level economic

[14] SHARES (SHort Assessment of Renewable Energy Sources) is the tool Eurostat developed to facilitate the use of a harmonized calculation methodology for Member States to report their shares of renewable energy in line with the concepts of the Renewable Energy Directive.

analysis for the EU international agricultural commodity trade. Second, LUISA-BEES is a spatially-explicit land use model capable of estimating land use changes and associated LULUCF emissions across the EU27 with 1ha resolution. Third, CBM is a stand-alone model for forestry and accounting of carbon dynamics. It accounts for the impacts of forest management, natural disturbances, and deforestation. Last but not least, the energy system model, POTEnCIA is a hybrid partial equilibrium simulation model designed to evaluate the impacts of energy and climate policies considering technological, economic, and environmental considerations.

By soft-coupling these models, the AFOLU modelling framework contemplates the harmonization of data flows between the models and the improvement of their simulation structures. The framework is designed to perform ex-ante policy scenarios relevant for a comprehensive analysis of the LULUCF sectors in terms of their contribution to a greener economy. This includes exploratory scenarios such as the reform of the CAP, expansion of bioenergy mandates, introduction of specific mitigation and environmental protection policies and changes in forest management.

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List of abbreviations and definitions

AFOLU	Agriculture, Forestry and Other Land Use
AR	Afforestation
CAP	Common Agricultural Policy
CAPRI	Common Agricultural Policy Regionalised Impact
CLC	Corine Land Cover
CBM	Carbon Budget Model
CES	Constant Elasticity of Substitution
CSC	Carbon Stock Change
CH_4	Methane
CLUE	Conversion of Land Use and its Effects (model)
CO_2	Carbon Dioxide
CRF	Conditional Random Field
CRPCRP	Crop Land Remaining Crop Land
DE	Deforestation
DOM	Dead organic matter from forest (i.e. dead wood and litter)
Dyna-CLUE	Dynamic Conversion of Land Use and its Effects (model)
EF	Emission factor
EUROSTAT	Statistical Office of the European Community
FAO	Food Agriculture Organization
FAWS	Forest Available for Wood Supply
Felling	Volume of standing growing stock affected by harvesting (in opposition to actual volume removed from forest by harvesting operations)
FL	Forest land
FL-FL	Forest land remaining forest land
FM	Forest Management
FORFOR	Forest Land Remaining Forest Land
FW	Firewood, i.e. roundwood destined for bioenergy/burning
GAIN	Gain of carbon by living biomass pool
GRSGRS	Grass land Remaining Grass land
GHGI	Greenhouse Gas Inventory
GTAP	Global Trade Analysis Project
HWP	Harvested Wood Product
IEF	Implied Emission Factor
IPCC	Intergovernmental Panel on Climate Change
L-FL	Land converted to forest land
IRW	Industrial roundwood, i.e. merchantable roundwood destined to industrial processing
LOSS	Loss of carbon from living biomass pool
LUCAS	Land Use Cover Area frame Survey
LUISA-BEES	Land Use Integrated Sustainability Assessment – BioEconomy & Ecosystem Services

LULUCF	Land use, land-use change and forestry
MCPFE	Ministerial Conference on the Protection of Forests in Europe
Merch	Merchantable wood, i.e. standing or harvested roundwood with dimensions above defined thresholds
MNL	Multinomial
N_2O	Nitrous Oxide
NBP	Net Biome Production
NFI	National Forest Inventory
NPP	Net Primary Production
OWC	Other woody components of the trees (i.e. bark, stump, small branches)
POLES	Prospective Outlook on Long-term Energy Systems
POTEnCIA	Policy Oriented Tool for Energy and Climate Change Impact Assessment
SoEF2015	State of Europe's Forest 2015 Report
SUPREMA	Support for Policy Relevant Modelling of Agriculture (H2020 project)
TRUSTEE	Towards Rural Synergies and Trade-offs between Economic development and Ecosystem services (RURAGR ERA-NET project
UAA	Utilisable Agricultural Area
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change

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Annexes

Annex 1. Land use change in CAPRI and LUISA-BEES

Table A3. Sources of land use data in CAPRI

Land use level	**Description**	**Source**
REGIO	Regional land use data; NUTS 2 level – 1984-2014	Statistical Office of the European Community (EUROSTAT)
ENVIO	Land cover data from the environment section; MS level - 1985, 1990,1995, 2000	EUROSTAT http://eu22.eu/land-use.2/land-use-by-main-category/
LANDCOVER	Land over data; MS level – 2009, 2012, 2015	EUROSTAT
FSS	Farm Structure Survey data; MS level - 1990, 2000, 2005, 2010, 2015	EUROSTAT
CLC	Land use data derived using a transformation matrix to LUCAS; NUTS2 level - 1990, 2000, 2006, 2012	Corine Land Cover (CLC)
MCPFE	Data on the forest sector and some non-forestry data (inland waters INLW, total country area ARTO); MS level - 1990, 2000, 2005, 2010, 2015	Ministerial Conference on the Protection of Forests in Europe (MCPFE), jointly published by Food Agricultural Organization (FAO) and United Nations Economic Commissions for Europe (UNECE)
CRF	Common Reporting Format land data (1990-2016), also covering land transitions and settlement data. Official data for LULUCF accounting	United Nations Framework Convention on Climate Change (UNFCCC)
FAO	Agricultural land use, but also some non-agricultural area categories (forest, inland waters, other land, total area); MS level – 1984-2016	FAOSTAT domain http://faostat3.fao.org/home/index.html#DOWNLOAD

Table A4. Mapping of generalized aggregated CAPRI land classes to LUISA-BEES

CAPRI		LUISA-BEES
CROP	Rape [RAPE]	
CROP	Sunflower [SUNF]	
CROP	Soya [SOYA]	
CROP	Other oils [OOIL]	
CROP	Pulses [PULS]	
CROP	Tomatoes [TOMA]	
CROP	Other Vegetables [OVEG]	
CROP	Fodder other on arable land [OFAR]	Arable
CROP	Set-aside voluntary [VSET]	
CROP	Fallow land [FALL]	
CROP	Flax and hemp [TEXT]	
CROP	Tobacco [TOBA]	
CROP	Other industrial crops [OIND]	
CROP	Other crops [OCRO]	
CROP	Soft wheat [SWHE]	
CROP	Durum wheat [DWHE]	
CROP	Rye and Meslin [RYEM]	Arable
CROP	Barley [BARL]	
CROP	Oats [OATS]	
CROP	Other cereals [OCER]	
CROP	Grain Maize [MAIZ]	Arable
CROP	Fodder maize [MAIF]	
CROP	Potatoes [POTA]	
CROP	Sugar Beet [SUGB]	Arable
CROP	Fodder root crops [ROOF]	
CROP	Apples Pears and Peaches [APPL]	
CROP	Other Fruits [OFRU]	Permanent Crops
CROP	Table Grapes [TAGR]	
CROP		ABANARABLE
CROP		ABANPERMAN
GRASLAND		Pastures
GRASLAND		SHVA
GRASLAND		ABANPASTUR
GRASLAND		URBANGREEN
FORE		ForestMature
FORE		TRANSWOODL
ARTIF		BUILTUP
ARTIF		INDUSTRIAL
ARTIF		URBAN
ARTIF		INFRASTRUC
RESLAND		OTHERNATUR
WETLAND		WETLANDS
WETLAND		WaterBodies

Annex 2. Methods for estimating emission factors from CBM

Parameters relevant for change of C stock in living biomass pool

On the one side, the CBM outputs allow reconstructing the growth of the living biomass through:

- NPP, net primary production, in tC/ha/year;
- ND_{LOSS}, losses through natural disturbances (e.g. transfers from living biomass to dead organic matter pool), in tC/ha/year and
- $MORT_{LOSS}$, losses through regular natural mortality (i.e. due to competition), in tC/ha/year.

Combining these parameters, GAIN can be estimated as a synthetic parameter that characterizes the total increase of the living biomass pool in a calendar year (letter in the parenthesis correspond to arrows in Figure A7).

GAIN = NPP (A) – ND_{LOSS} (C) – $MORT_{LOSS}$ (B)

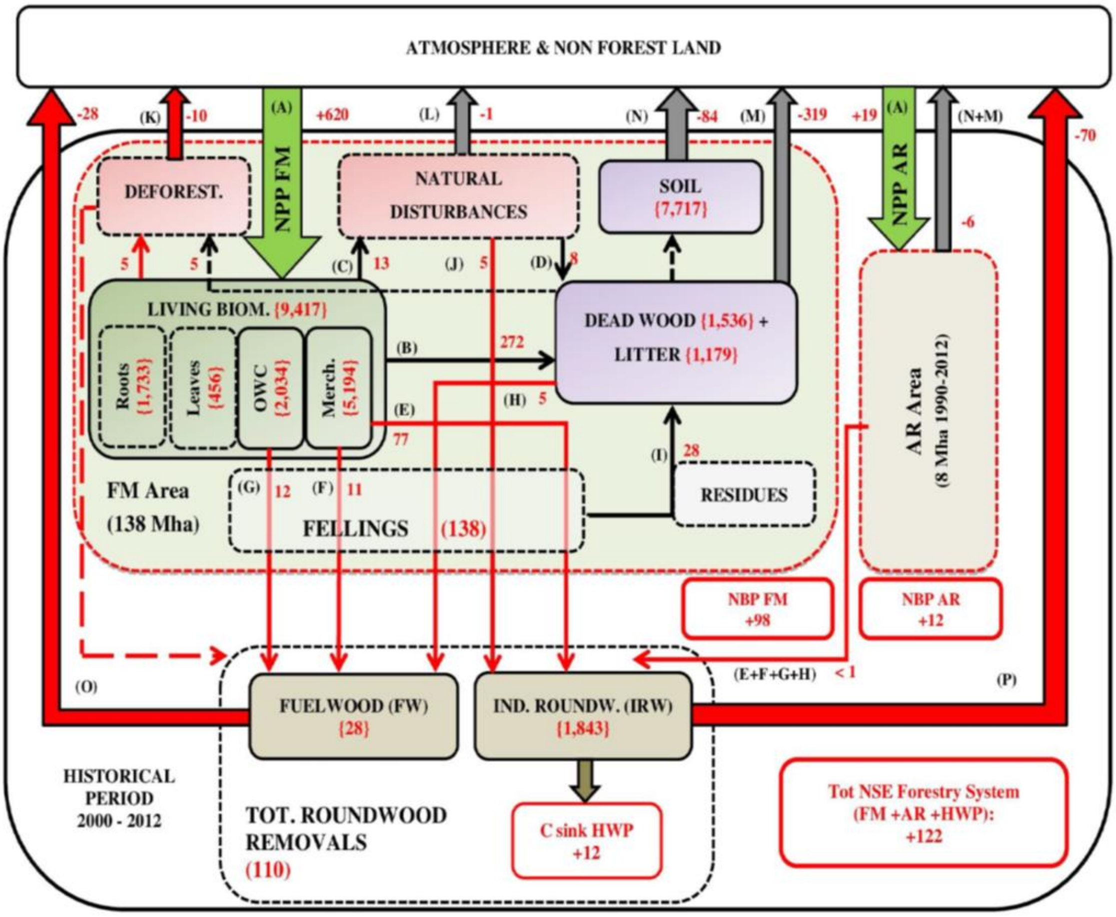
Noticeable, this value corresponds best to the gain from common reporting format Table 4A1 submitted to UNFCCC as part of the annual GHG Inventory.

On the other side, CBM outputs allow reconstructing the losses from the living biomass pool through the estimates of Merch (merchantable/standing wood) and OWC (other wood components) transferred from the living biomass to industrial roundwood (IRW), firewood (FW), and to dead organic matter pool (DOM) remaining on the ground as exploitation residues. All such indicators are expressed in tC/ha/year. Specifically, these transfers can be considered as (letter in the parenthesis correspond to arrows in Figure A7):

LOSS = (Merch-->IRW) (E) + (Merch-->FW) (F) + (OWC-->FW) (G) + (Felling-->DOM)(I)

Such estimate of the LOSS fits best to the “Loss” column from Table 4A1 of the GHG inventories.

Figure A7. C pools and fluxes as considered by CBM (from Pilli et al., 2017).



Factors for dead organic matter pools

The Annual dynamics of C stocks per hectare are estimated from CBM outputs as national average values for each of the three DOM pools (dead wood, litter and organic matter in mineral soils). The emission factors values corresponding to C stock change per ha per year should be derived as the differences between stocks estimated for successive years.

Carbon emission factor for deforested land

An aggregated value of losses from all C pools (living biomass and DOM) is calculated, for the easiness of development of the lookup tables. The value of the loss, per ha and per year, varies across years because CBM implements a random selection of forest types (e.g. carbon density, stand age) subject to deforestation.

Such value is valid for the year when the deforestation event takes place (so it is assumed that the entire conversion takes place in one year). As expected, such values are much higher than the corresponding values in the CRF tables (e.g. for conversion of forest to cropland, grassland, etc), as those values represent "implied emission factors" which cumulate the legacy emissions from past deforestation over the conversion period (which is usually 20 years for any type of conversion) on top of the emissions in the current year. For projection purpose, a deforestation factor defined as the average annual value (per year, per ha) from the CBM data pool for 2000-2012, can be used.

Table A5. Estimates of carbon emission factors from CBM output: examples of Denmark and Germany (2000-2030)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2030
Denmark																	
ef_bioGain	2.1435	2.6893	2.7030	2.7122	2.7206	2.4493	2.6966	2.6834	2.6669	2.6470	2.6262	2.6061	2.5738	2.5543	2.5235	2.4943	1.9953
ef_bioLoss	-0.9850	-0.7763	-0.6991	-0.7836	-0.6725	-1.0057	-1.0302	-1.1133	-1.2516	-1.2709	-1.2088	-1.1715	-1.1733	-1.0552	-1.0559	-1.0534	-1.0624
ef_bioNet	1.1584	1.9130	2.0039	1.9286	2.0481	1.4437	1.6665	1.5702	1.4152	1.3762	1.4174	1.4347	1.4005	1.4991	1.4676	1.4409	0.9328
ef_deadWoodNet	-0.2506	-0.2506	-0.2357	-0.1813	-0.2122	-0.0335	-0.1093	-0.0823	-0.0371	-0.0275	-0.0380	-0.0410	-0.0357	-0.0596	-0.0503	-0.0422	0.0155
ef_litterNet	-0.0815	-0.0815	-0.0669	-0.0313	-0.0480	0.0316	0.0149	0.0303	0.0439	0.0393	0.0268	0.0206	0.0215	0.0080	0.0118	0.0127	0.0139
ef_domNet	-0.3321	-0.3321	-0.3025	-0.2126	-0.2602	-0.0018	-0.0944	-0.0520	0.0068	0.0118	-0.0112	-0.0204	-0.0141	-0.0516	-0.0385	-0.0295	0.0294
ef_socNetMin	-0.0180	-0.0180	-0.0171	-0.0148	-0.0153	-0.0084	-0.0147	-0.0158	-0.0143	-0.0151	-0.0167	-0.0176	-0.0182	-0.0200	-0.0203	-0.0208	-0.0271
Germany																	
ef_bioGain	2.5603	3.5081	3.5010	3.4978	3.4925	3.4885	3.4892	2.6732	3.4787	3.4729	3.3723	3.4599	3.4480	3.4366	3.4349	3.4345	3.3898
ef_bioLoss	-2.1024	-1.4155	-1.3712	-1.4973	-1.7801	-2.0047	-2.1041	-2.4914	-1.8704	-1.7712	-1.8229	-1.9355	-1.8688	-1.8918	-1.8916	-1.9179	-1.9244
ef_bioNet	0.4579	2.0926	2.1298	2.0005	1.7124	1.4838	1.3851	0.1818	1.6083	1.7017	1.5494	1.5244	1.5792	1.5448	1.5433	1.5165	1.4655
ef_deadWoodNet	-0.1176	-0.1176	-0.1136	-0.0675	0.0632	0.0963	0.1111	0.7308	-0.0630	-0.0766	-0.0060	0.0004	0.0303	0.0104	0.0090	0.0174	0.0512
ef_litterNet	0.1412	0.1412	0.1505	0.1770	0.2201	0.2395	0.2372	0.2628	0.1699	0.1511	0.1607	0.1645	0.1577	0.1633	0.1546	0.1585	0.1426
ef_domNet	0.0236	0.0236	0.0369	0.1095	0.2832	0.3358	0.3484	0.9936	0.1069	0.0745	0.1547	0.1649	0.1880	0.1737	0.1635	0.1759	0.1939
ef_socNetMin	-0.0021	-0.0021	-0.0027	-0.0006	0.0020	0.0034	0.0044	0.0177	0.0020	0.0031	0.0060	0.0063	0.0069	0.0085	0.0095	0.0107	0.0194

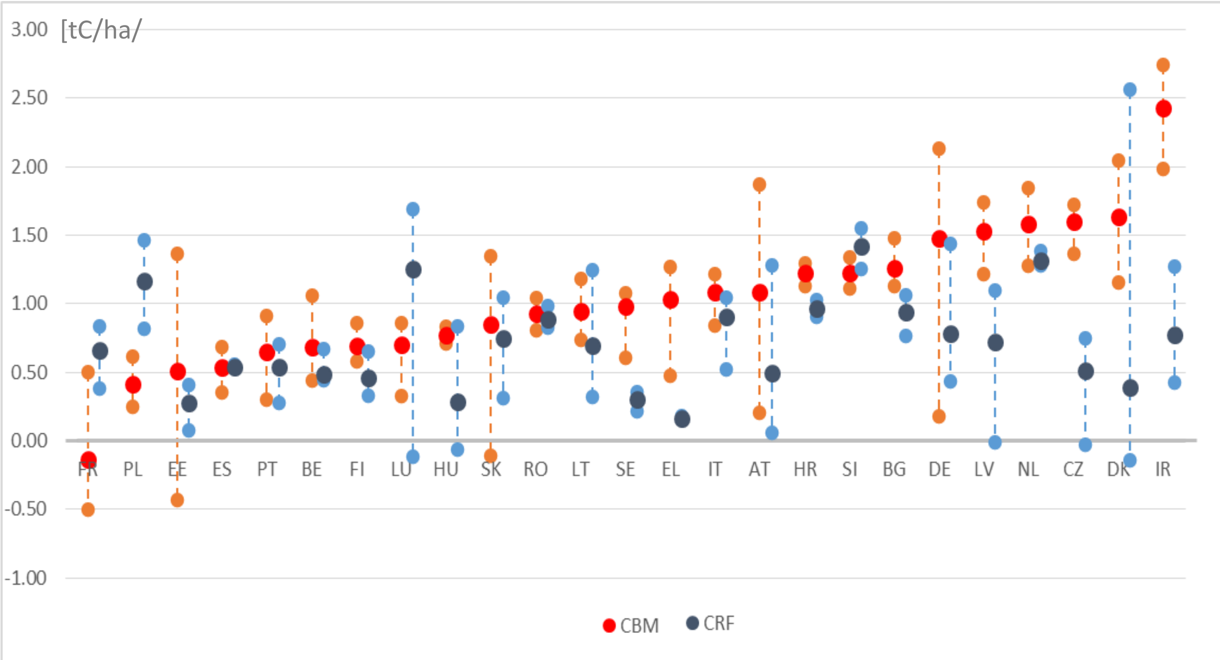
Table A6. Net primary production per hectare per year (NPP) and forest carbon stock (Soil, Litter, Dead wood) at constant harvest levels for three pools: examples of Denmark and Germany (2000-2030) estimated from CBM outputs

	Denmark				Germany			
		C Stock per ha t C ha-1				**C Stock per ha t C ha-1**		
	NPP per ha	Soil	Litter	Dead wood	NPP per ha	Soil	Litter	Dead wood
2000	4.50	61.82	5.71	10.72	7.36	69.58	21.93	21.36
2001	4.56	61.80	5.63	10.47	7.38	69.57	22.07	21.24
2002	4.62	61.78	5.57	10.23	7.41	69.57	22.22	21.13
2003	4.67	61.77	5.54	10.05	7.45	69.57	22.40	21.06
2004	4.72	61.75	5.49	9.84	7.47	69.57	22.62	21.13
2005	4.73	61.75	5.52	9.80	7.49	69.58	22.86	21.22
2006	4.74	61.73	5.53	9.69	7.51	69.58	23.10	21.33
2007	4.75	61.72	5.56	9.61	7.51	69.60	23.36	22.06
2008	4.76	61.70	5.61	9.57	7.53	69.60	23.53	22.00
2009	4.76	61.69	5.65	9.55	7.56	69.60	23.68	21.93
2010	4.75	61.67	5.67	9.51	7.58	69.61	23.84	21.92
2011	4.75	61.65	5.69	9.47	7.60	69.62	24.01	21.92
2012	4.73	61.63	5.72	9.43	7.62	69.62	24.16	21.95
2013	4.73	61.61	5.72	9.37	7.64	69.63	24.33	21.96
2014	4.72	61.59	5.74	9.32	7.66	69.64	24.48	21.97
2015	4.71	61.57	5.75	9.28	7.69	69.65	24.64	21.99
2016	4.69	61.55	5.76	9.25	7.72	69.66	24.79	21.99
2017	4.68	61.53	5.78	9.22	7.75	69.68	24.93	21.99
2018	4.66	61.51	5.80	9.20	7.78	69.69	25.07	22.00
2019	4.64	61.48	5.82	9.18	7.81	69.70	25.21	22.00
2020	4.62	61.46	5.84	9.17	7.84	69.72	25.35	22.00
2021	4.60	61.44	5.86	9.16	7.87	69.73	25.48	22.01
2022	4.58	61.41	5.88	9.16	7.90	69.75	25.61	22.02
2023	4.55	61.39	5.90	9.16	7.92	69.76	25.74	22.02
2024	4.53	61.36	5.91	9.16	7.94	69.78	25.87	22.04
2025	4.50	61.34	5.93	9.17	7.97	69.79	26.00	22.07
2026	4.47	61.31	5.94	9.17	8.00	69.81	26.14	22.11
2027	4.44	61.28	5.96	9.18	8.02	69.83	26.28	22.15
2028	4.41	61.26	5.97	9.19	8.05	69.85	26.39	22.16
2029	4.38	61.23	5.99	9.21	8.07	69.87	26.53	22.19
2030	4.35	61.20	6.00	9.22	8.09	69.89	26.67	22.24

Uncertainty associated to lookup table values

The CBM output transferred to C stocks changes of living biomass, of dead organic matter and in mineral soils, as applied in the UNFCCC National Inventory Submissions, are finally compared to the CRF data. CBM (Figure A8) and GHG Inventory experts rate the differences as acceptable.

Figure A8. Comparison of carbon stock changes between CBM and UNFCCC CRF tables for Member States



Additional to the major fact that the approach by a lookup table represent a simplification of forest ecosystem dynamics, there are additional elements to consider with regard to CBM model estimates. For instance, there values compared are processed (i.e. simple average for Implied emission factors (IEFs) from CRF tables and weighted average for carbon stock changes (CSC) from CBM), and uncertainty related to data used as input in the CBM or used to report in the CRF tables.

Overall, CBM provides estimates within a realistic range when considering the IEFs and CSC values contained in the CRF tables as the reference (see Figure A8 in Annex 2). Some differences can be explained by the quality of input data in the CBM modelling. Moreover, in almost all of the cases, the MS have access to more disaggregated and updated data than CBM. Identified differences so far, were investigated and resolved mainly for the living biomass, and as much as possible for other C pools. Given the national aggregation level for which estimates are compared ± 10-15% compared to historical values reported in the CRF tables are considered as acceptable (against the min or max of the entire available range). This acceptability threshold can be relaxed when the IEFs and CSC values for the gains or loss factors are very small, so that even the country data can be considered as highly uncertain.

Other differences may be irreconcilable as being related to the specific modelling framework, e.g. implementing average silvicultural practices, simplification of the uneven-age stands structures, etc. Here it is important to highlight that the conceptual approach behind the CBM model and the CRF tables is different. While CBM computes on yearly steeps, the CRF data is usually generated from 5-years remeasurements from National Forest Inventories (NFIs). The latter is obviously smoothing out occasional annual harvest peaks due to natural disturbances, so that effects are distributed over the years. Moreover, MS may apply corrections to the estimation of gains and loss factors (e.g. specific growth curves based on the health status of stands) while CBM uses a standard growth curve. In CBM the uncertainty is reduced as far as possible by trying to mimic as much as possible the approach taken by the MS (e.g. in terms of forest type stratification, forest standing stock and growth curves, biomass expansion factors/allocation).

Last but not least, the input data in CBM was subject to validation against country's official reporting to various organizations (i.e. UNFCCC, FAO, Eurostat, SoEF, see Pilli et al., 2016b). Additionally, such activity was complemented in some cases with checks performed together with MS national experts.

KJ-NA-30514-EN-N

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doi:10.2760/900305

ISBN 978-92-76-27386-8