ForestNavigator

D6.2 Next generation EU and National models at the service of EU forest policies

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Abstract

This deliverable describes the updates to member state and EU forest modelling frameworks for policy impact assessment. The report also details model recalibration efforts and methodologies that are crucial for national GHG inventory reporting, as well as for compliance with EU LULUCF regulations.

This deliverable provides a comprehensive overview of the EU-level model GLOBIOM/G4M-X and Member State models CBM-Czechia, CBM-Ireland, CBM-Italy, and the Heureka model for Sweden. Next, this report details model recalibration efforts to incorporate the newest national forest inventories, as well as include the occurrence of disturbance events and the implications of recalibration to regional forest sinks. Subsequently, the updates to the EU-level model GLOBIOM/G4M are described, including its coupling with biodiversity and local climate impact models, as well as recalibration of forest structure and management regimes. Finally, the description of the integration of climate change impacts on both EU and member state models is presented, with preliminary results on the development of the forest sink in the EU.

Keywords

Forest management, bioeconomy, policy impact assessment, biodiversity, modelling

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Abbreviations

AIDB	Archive Index Database
AR	Afforestation
BE	European beech
C	Carbon
CAI	Current annual increment
CBM	Carbon Budget Model
CBM-CF3	Carbon Budget Model of the Canadian Forest Sector
CFI	Czech Forestry Institute
CLU	Climate Unit
COSMC	Czech Office for Surveying, Mapping and Cadastre
CRF	Common Reporting Format
CzSO	Czech Statistical Office
D	Deforestation
DAGB	Change in aboveground biomass
DBH	Diameter at breast height
DOM	Dead Organic Matter
EC	European Commission
EEA	European Environmental Agency
EU	European Union
FAWS	Forest area available
FI	All firs including silver and douglas fir
FNAWS	Forest area not available
FMPG	Forest Management Plans and Guidelines
FT	Forest Type
GAI	Gross Annual Increment
GCM	General Circulation Models
GHG	Greenhouse Gas
GLOBIOM	Global Biosphere Management Model
INFC	Italian National Forest Inventory
IPCC	Intergovernmental Panel on Climate Change
LB	Long-lived broadleaved tree species including maple species, European hornbeam, European Ash and others
LULUCF	Land Use, Land Use Change and Forestry
MAT	Mean annual temperature
MS	Member State
MT	Management Type
NAI	Net Annual Increment
NEP	Net Ecosystem Production
NFI	National Forest Inventory
NID	National Inventory Document
NPP	Net Primary Production
OA	All oak species
PI	All pine species and European larch

SB	Short-lived tree species, including birch, alder, poplar and willow
SP	All spruce species, but notably Norway spruce
SPU	Spatial Processing Units
UNFCCC	United Nations Framework Convention on Climate Change
WD	Wood Density
WEM	With Existing Measures
WP	Work Package
YT	Yield Table

Executive summary

The EU's sustainability agenda places forests at the centre of its climate, biodiversity, and bioeconomy policies, with underlying climate mitigation and biodiversity protection targets. However, these functions are increasingly threatened by climate-driven disturbances, such as bark beetle outbreaks and droughts, which have reduced forest productivity and, in some cases, turned forests from carbon sinks into carbon sources, raising doubts about the forest sector's contribution to climate targets through carbon sink enhancements. These challenges also increase uncertainty in forests' capacity to deliver ecosystem services, support green growth, and meet the EU's climate neutrality goals.

This work advances forest sector modelling by integrating updated national data, climate change impacts, natural disturbances, and adaptive forest management strategies to improve the representation of the bio-based economy and strengthen policy guidance in the EU and its member states.

The primary objective was to recalibrate EU and country-level forest models using the most recent National Forest Inventory (NFI) data, refine growth and harvesting parameters, and explicitly incorporate climate and disturbance effects in modelling frameworks. The updated models include:

- GLOBIOM/G4M-X at the EU level
- CBM models for Czechia, Ireland, and Italy, and
- the Heureka model for Sweden.

The forest area, including afforestation and deforestation, forest productivity and removals for the member state models were updated, based on the latest NFI information. Additionally, impacts of recent disturbance events, such as the windstorm Ewoyn in Ireland and bark beetle outbreaks in Czechia, were accounted for in the model recalibration. This procedure led to alterations in the estimates of forest productivity, which also cascaded to the forecasted forest sink, highlighting the importance of continuous data-model fusion to monitor the progress of the forest sector toward the EU climate targets.

Similarly, the EU model GLOBIOM/G4M was updated with new datasets on the initial forest age class distribution, and the definition of forest management classes was refined based on bottom-up simulations of silvicultural regimes. GLOBIOM/G4M was also updated to represent carbon stocks in harvested wood forest products, and to endogenise the impacts of forest management and land use decisions on biodiversity and local climate effects, via coupling with iBIS.SDM and MESMER-L-X models, developed as part of the ForestNavigator work in WP4.

The EU and MS models were also updated to better account for climate change impacts on the forest sink and extend their thematic resolution, in terms of carbon pools and management approaches. Simulations of forest productivity under different climate change scenarios were conducted with the biophysical model i3PGmiX. Based on these simulations, forest growth shifters were computed at the resolution required by each modelling framework and used to shift the forest productivity in the internal model logic.

Preliminary results show that climate change impacts may exert a strong influence on the EU forest sink and wood markets. They also highlight the importance of adaptation and mitigation measures to attain the EU bioeconomy, climate, and biodiversity objectives, while maintaining healthy and resilient forests.

I. Introduction

Forest ecosystems are central to the EU's sustainability objectives, with policy targets requiring the joint consideration of biodiversity, climate, and bioeconomy concerns. As part of the Green Deal, the European Commission (EC) has committed to legally protecting and managing more effectively a minimum of 30% of the EU's land area for Nature, while restoring degraded and carbon-rich ecosystems and reducing anthropogenic pressures. Under the scope of the EU Green Deal, the Nature Restoration Law requires the implementation of restoration efforts on at least 20% of the EU's land and sea areas by 2030, to expand these efforts to all degraded ecosystems by 2050. In parallel, the LULUCF regulation and the Forest Strategy 2030 emphasise the critical role of forests in carbon sequestration, both in line with the Fit for 55 targets, compensating hard-to-abate sectors, and highlighting the need for detailed accounting and monitoring of emissions and removals. The contribution of the LULUCF sector, however, goes beyond climate mitigation, providing biodiversity-rich habitats and supporting rural economies, aiming to increase forest resilience towards climate change impacts and disturbances and improving forest management practices.

At the same time, European forests face emerging threats posed by climate change and biodiversity loss. The EU climate risk assessment (EEA, 2024) highlights that climate change is an important driver of biodiversity loss and ecosystem degradation in Europe, emphasising that the achievement of effective adaptation and mitigation in the region also depends on the maintenance of biodiversity and ecosystem resilience. Forests, grassland, and wetlands are particularly vulnerable to climate and disturbance impacts, affecting local livelihoods and policy targets. For example, drought has triggered unprecedented bark beetle outbreaks in the Czech Republic, which have temporarily transformed the forest sector from a carbon sink to a carbon source and shifted the forest age structure in the region. The 2018-2020 droughts have also been estimated to have caused a loss of forest production of up to 60% in Italy, France, and Spain.

These impacts add uncertainty to the capacity of European forests to fulfil their multifunctional objectives, providing ecosystem goods and services, and supporting green growth. Mauri et al. (2024) highlight that shifts in species composition can cause a loss in the provision of ecosystem services in EU forests. Recalculation of the forest sink provided by the latest national forest inventories (NFIs) shows that in the past years, natural and anthropogenic disturbances caused a decline in the forest sink in many member states, inducing uncertainties on the feasibility of achieving national climate targets, putting at risk the achievement of climate neutrality by 2050. These novel conditions ask for an update on the dynamics and processes included in forest modelling frameworks used in policy support from MS to the EU level, integrating the latest data and understanding of the carbon sink development in the region.

In this context, forward-looking models used in policy support need to address these emerging challenges when computing climate mitigation pathways and supporting forest planning and forest policies. This asks for the integration of climate change impacts, natural disturbances and adaptive forest management strategies as part of the portfolio of options in these models, aiming to sustain ecosystem functioning and the contribution to climate, biodiversity and bioeconomy targets. Still, the representation of these processes in EU and MS modelling tools has been limited.

The objective of this deliverable is to advance the modelling of EU and MS forest modelling tools by:

- recalibrating the EU (GLOBIOM/G4M-X) and MS models (CBM-CFS3 and Heureka) using the latest National Forest Inventory (NFI) data to update forest growth dynamics and fellings

- integrate climate change impacts on forest growth, productivity, and the overall forest sink, incorporate adaptive forest management strategies and consider biodiversity impacts, and integrate disturbance impact representation in these modelling tools

The ForestNavigator project covers four case study countries. For these member states, CBM-Czechia, CBM-Ireland, and CBM-Italy were applied, while the Heureka model was used for Sweden. The outputs of the recalibration were compared to the historical period. The rationale behind the three case studies was to demonstrate the approach to implement the disturbances, including the main disturbance agents in the EU. This approach equips the Member State models with the capability to ensure a consistent pathway computation in the scenarios to be implemented in WP7 and 8, where both EU and MS models will be deployed under alternative forest sector futures.

Chapter 2 describes the modelling frameworks applied, outlining their general functionalities, main functionalities and mechanisms implemented in simulating land-use and carbon dynamics. Chapter 3 details the approach to recalibrate the forest models using the latest NFI data and GHG reporting data to accurately reflect forest dynamics, including forest growth and fellings. Chapter 4 introduces a series of updates implemented into the GLOBIOM/G4M-X model and similar approaches in MS models to enhance their capability to represent climate change impacts and natural disturbances on forest dynamics. In Chapter 5, we present the main conclusions and the next steps to quantify EU climate mitigation pathways using the updated modelling frameworks.

2. Model description

2.1. GLOBIOM/G4M-X

The Global Biosphere Management Model (GLOBIOM) (IBF-IIASA 2023) is a global recursive dynamic partial equilibrium model of the forest and agricultural sectors (Figure 1). The model is based on a bottom-up approach where the supply side of the model is built up from the bottom (land cover, land use, management systems) to the top (production/markets). Agricultural and forest productivity are modelled at a spatially-explicit level through links to biophysical models (crop models, forest growth models, etc.) for different production systems. The model computes market equilibrium for agricultural and forest products by allocating land use among production activities to maximise the sum of producer and consumer surplus, subject to resource, technological, demand, and policy constraints. Demand and international trade are represented at the level of 59 world regions. The base year of the model is 2000, and the model is calibrated using FAOSTAT data and other data sources for the historical period.

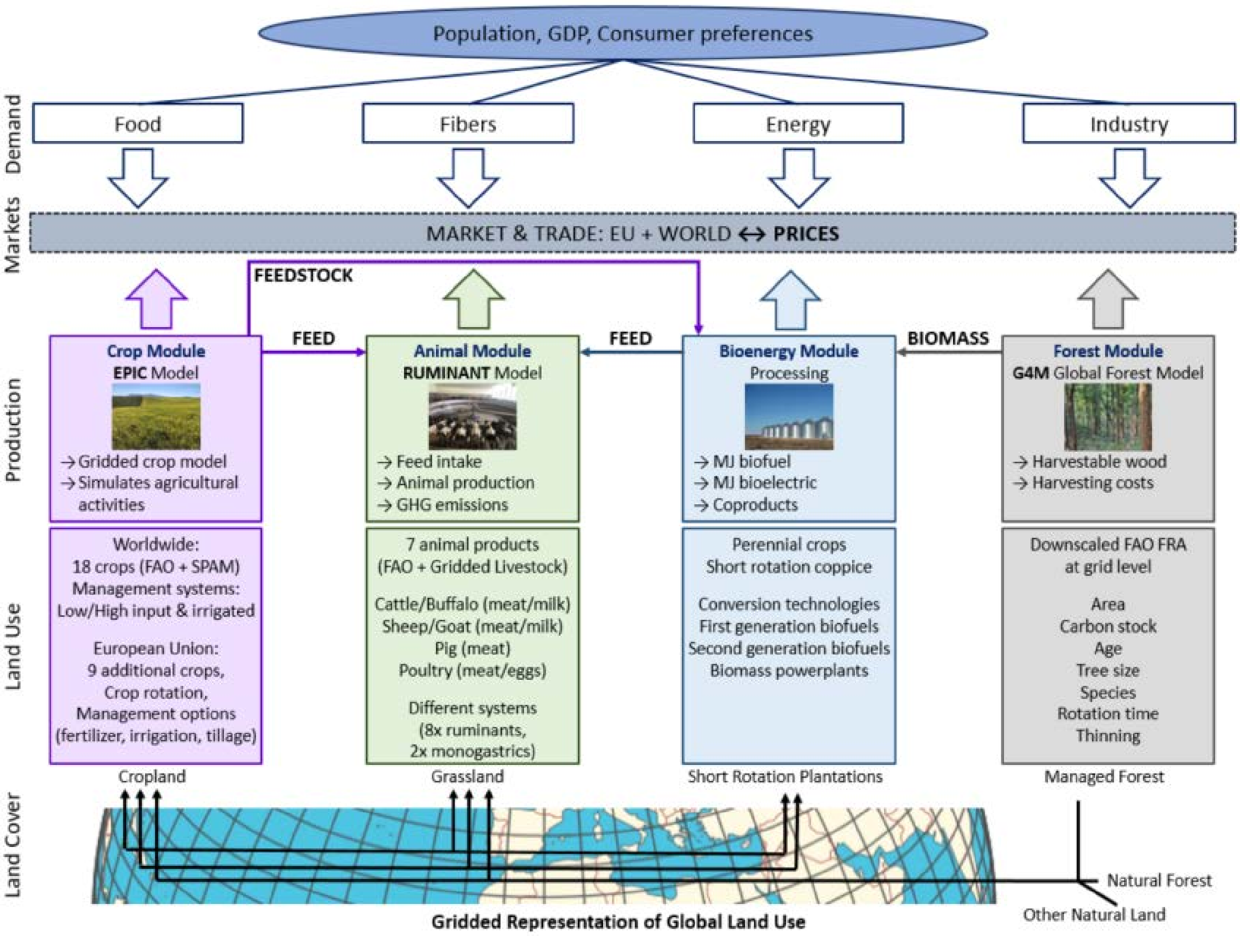

Figure 1. Global Biosphere Management Model (GLOBIOM) schematic representation. Source (IBF-IIASA 2023).

GLOBIOM includes a detailed representation of forest management, covering the following forest land-cover types: managed forests, primary forests, plantation forests, afforested forests, and deforested areas. Each forest land-cover type can have multiple management systems, which can vary in intensity. Managed forests have eight management systems: coniferous production forests, non-coniferous production forests, coniferous multifunctional forests, non-coniferous multifunctional forests, coniferous close-to-nature forests, non-coniferous close-to-nature forests, strictly protected secondary forests, and unprotected secondary forests. Plantation forests have two management systems: energy wood production and roundwood production (RW). Primary forests have one management type: primary forests. Afforested forests have one management type: afforested area for carbon sequestration/restoration.

The forest sector has about 50 different product categories, which can be divided into primary products, by-products, semifinished products, final products, recycled products, and aggregate products. The demand for aggregates of final products (i.e., construction, furniture, wood-packaging, different paper and paperboard grades, wood-based textiles, and bioplastic) is generated from FAOSTAT (2024) semifinished products data and aggregated to the final products using country-level shares from Mantau (2010).

G4M estimates the impact of forestry activities (afforestation, deforestation, residue harvest, and forest management) on biomass and carbon stocks. A decision on afforestation or deforestation is made after comparing the net present value of a managed forest (the difference between wood price and harvesting costs, and income from storing carbon in forests) with income from alternative land use in the same place. The model incorporates empirical forest growth functions for major tree species groups. G4M is spatially explicit and runs on a 0.5° x 0.5° resolution. Since the model does not represent either forest markets or other economic sectors, it must rely on information from other sources (i.e., GLOBIOM or other databases) for wood prices, land rents, urban sprawl, etc. Similarly, information about natural disturbances is used as an input to the model. As outputs, G4M produces estimates of forest area change, carbon sequestration, and emissions in forests, impacts of carbon incentives (e.g., avoided deforestation), and supply of biomass for bioenergy and timber.

GLOBIOM/G4M together cover all UNFCCC land use categories relevant for CO_2 emissions. Only wetlands and settlements are not endogenously modelled. G4M covers the forestry sector and delivers emissions/removals from biomass and soil carbon changes from afforestation, deforestation, and harvest residue collection activities, and emissions/removals from forest management. GLOBIOM supplies emissions/removals from cropland and grassland management, as well as the rewetting of drained peatland under agricultural use.

GLOBIOM/G4M has been extensively used for global and regional assessments of the land-based mitigation potential, incl. avoided deforestation, reforestation and afforestation, forest management, agricultural emissions reduction, and soil organic carbon sink enhancement. Several previous studies also assessed the impact of different land-based mitigation strategies and pathways on food security (e.g. Chang et al. 2021; Janssens et al. 2020).

2.2. Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3)

The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) is a dynamic, yield-driven simulation model that tracks carbon (C) dynamics in forest ecosystems under varying management practices, land-use changes, and natural disturbances (Figure 2). It operates on annual time steps to estimate C stocks in living biomass, mineral soil, and dead organic matter (DOM) along with transfers to the atmosphere and harvested wood products, and ecological indicators like net primary productivity and net ecosystem productivity (Kurz et al., 2009).

CBM-CFS3 follows the conceptual framework of IPCC Reporting Method 1 (Penman et al., 2003), using Spatial Processing Units (SPUs) that represent geographic areas in a non-spatially explicit way. Each forest stand is defined by age, area, and up to ten classifiers and is linked to a yield curve and associated SPU. SPUs provide region-specific data, including biomass allocation, turnover rates, DOM characteristics, climate, and disturbance regimes. Ideally, model users provide complementary data on forest succession, disturbance types, and management strategies, typically sourced from National Forest Inventories (NFIs) (Kurz et al., 2009).

Gross merchantable volume is described via growth curves for various species or forest types under undisturbed conditions. These curves form the basis for calculating biomass using species-specific, stand-level volume equations (Boudewyn et al., 2007; Canada's National Forest Inventory, 2016). Aboveground components include merchantable stems, bark, branches, foliage, and non-merchantable biomass. Belowground biomass and turnover are estimated using equations from Li et al. (2003). Annual foliage and deadwood inputs into DOM pools are calculated using turnover rates applied to standing biomass stocks. CBM-CFS3 also simulates a wide range of natural and anthropogenic disturbances, including fire, insect outbreaks, partial cuts, and clear-cut harvesting. Users define disturbance parameters for each time step, including eligibility criteria (e.g., stand type and age), the disturbance target (area, percent, or carbon), and its efficiency (Kull et al., 2016). Each disturbance's impact is modelled using a disturbance matrix (Kurz et al., 1992), which defines how carbon is redistributed among pools, the atmosphere, and the harvested wood product sector.

The model explicitly simulates C dynamics in ten live biomass pools and eleven DOM and soil pools (Kurz et al., 2009). Transitions among pools occur via litterfall, mortality, and decomposition. DOM and soil pools decay exponentially at rates influenced by temperature and pool type. A fraction of decayed material transfers to the soil, while the remainder is released to the atmosphere as CO_2. In the event of a disturbance, pool sizes are adjusted based on the defined disturbance matrix.

The CBM-CFS3 modelling framework (Kurz et al., 2009) is widely used to report forest GHG inventory data, as specified under the International Panel for Climate Change (IPCC) Good Practice Guidance for LULUCF. There are numerous examples of its use at the European scale by the EC's Joint Research Centre (Pilli et al., 2013, 2018) and for individual countries, e.g. the Czech Republic (Cienciala et al., 2024) and Ireland (EPA, 2024). The model was initially set up for use in Ireland in 2018 for GHG reporting to the UNFCCC using the European Archive Index Database (AIDB) (Pilli et al., 2018) and nationally derived forest growth and biomass equations from the 2006-2017 NFIs (EPA, 2024). The model integrates NFI data (e.g., stand age, area, species, productivity classes and soil types), merchantable volume increment curves, equations to convert volume to biomass components, data on disturbances and simulates transfers of C between pools and the atmosphere (Figure 1). The equations and parameter values for growth, biomass-to-volume conversions, biomass components, turnover and C transfers for each species, management and disturbance type are defined in an AIDB (Kull et al., 2016), with country-specific parameters (Black et al., 2025).

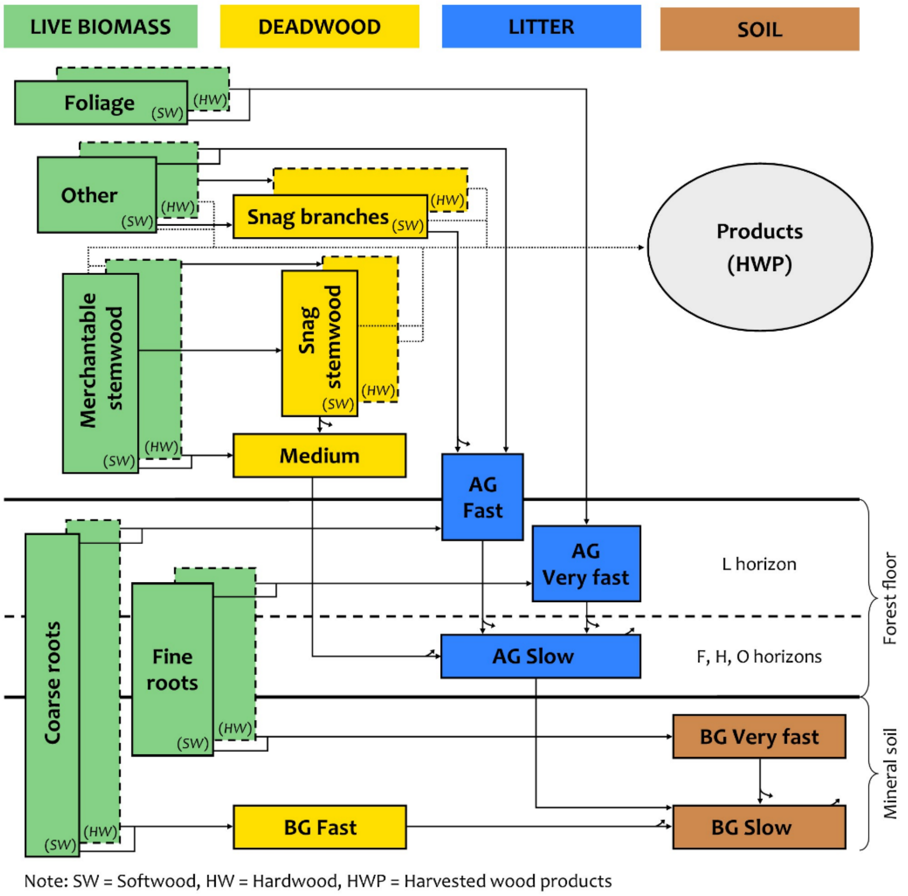

Figure 2 Schematic outline of the Carbon Budget Model framework (Modified form Kurz et al., 2009). HWP stands for harvested wood products, AG stands for aboveground biomass and BG for belowground biomass.

2.2.1. CBM Czechia

The modelling tool CBM-CFS3 (Kull et al., 2019; Kurz et al., 2009) was first introduced in the LULUCF sector of the national GHG inventory for the 2022 submission to UNFCCC (CHMI, 2022; Cienciala, 2022). This version includes all essential forest ecosystem carbon pools and allows assessing their changes due to both natural and management-driven disturbances. At the same time, the Canadian CBM-CFS3 author team generously made model software and its updates available for other applications elsewhere (specific thanks to Stephen Kull and Werner Kurz). Therefore, the tool was adopted to aid Czech national forestry reporting and accounting for both the UNFCCC Convention and Kyoto Protocol. The latter included accounting of the LULUCF activities at that time (2022), which included afforestation, deforestation and forest management, all for the period 2013-2020. Since then, CBM-CFS3 has been used in the Czech LULUCF inventory to aid assessment of category 4.A. Forest land and land-use conversions involving forest land, up to the latest submission of the National Inventory Document (NID) in 2025 (CHMI, 2025).

The Czech application of the CBM-CFS3 for GHG reporting used the customised AIDB for the European countries (Pilli et al., 2018) that was further calibrated using the national activity data, which naturally also served for driving the model. In line with the other international reporting on forest resources of the country, such as to FAO FRA and Forest Europe, the Czech model application to forestry used the information on national forest resources based on the database of the Forest Management Plans and Guidelines (FMPG). FMPG are centrally administered by the Czech Forestry Institute (CFI), formerly named the Forest Management Institute, Brandýs nad Labem. These data tightly link to the Czech cadastral system of land use, centrally administered by the Czech Office for Surveying, Mapping and Cadastre (COSMC). These resources were complemented by tree-level data from the Czech landscape inventory project CzechTerra (Černý et al., 2015; Cienciala et al., 2015, 2016). It primarily served for calibrating the national tree allometry according to the specific process for CBM-CFS3 as described by Boudewyn et al. (2007). Next, the CzechTerra results, combined with the early Czech National Forest Inventory (NFI) results (Kučera & Adolt, 2019), were used for calibrating the components of dead organic matter (deadwood, litter) and soil. The entire CBM modelling strategy for the Czech GHG inventory of the LULUCF sector closely followed the earlier Tier-2 GHG assessment methodology that was used until NIR (National GHG Inventory) 2021 submission covering the period 1990-2019. This used a robust grouping of tree species into four major species groups at the national level, which was retained for verification purposes in the early CBM model application from NIR 2022 UNFCCC onwards (CHMI, 2022; Cienciala, 2022).

This reporting practice is going to significantly change by adopting solely the data of the Czech National Forest Inventory (Kučera & Adolt, 2019; Máslo et al., 2023a, 2023c, 2023b, 2023d, 2024), in line with the coming national reports to FAO FRA (2025) and Forest Europe (2025), replacing the formerly used national information based on the FMPG data. It will include a more detailed spatial resolution at the regional (NUTS3 level) and a more detailed species grouping into seven species groups. This follows the earlier CBM model application based on FMPG data (Cienciala & Melichar, 2024). However, in contrast to that, it is going to be solely based on the Czech NFI data and for the coming Czech GHG inventory submissions (for NID 2027 at the latest) prepared in collaboration with the NFI expert team of CFI, Brandýs n. Labem. The very pilot CBM-CFS3 model calibration using the Czech NFI data is detailed in Chapter 2.4.

2.2.2. CBM Ireland

The Irish version of CBM was developed using calibration of the parameters set out in the AID, as done for other EU member states (Pilli et al., 2013). The CBM model calibrated using the 2006, 2012, 2017 and 2021 Irish NFI data (Black et al., 2025). In Ireland, only one administrative unit and one climatic unit are used (i.e. 1 SPU). This is because of the homogeneous nature of forests and climatic zones within the country. Forest stands are categorised by species cohorts and productivity strata with specific growth curves and biomass functions (Black et al., 2025). The state of the forest (i.e. the age class (5-year bins) structure and area breakdown of species cohorts) with defined management types and soil types is derived using NFI data. These age class-species distributions by forest area are redefined after the completion of each NFI cycle. For afforestation scenarios, a non-forest area matrix is defined, which specifies the areas available for afforestation since 1990 based on species and soil type (EPA, 2024). The age classes for defined species and management types are specified in an inventory table in the Simulation database.

Full details of the CBM-CFS3 set-up, control of harvests, and other disturbances for Ireland can be found in Black et al. (2025) and the Irish National Inventory report (EPA, 2024)

2.2.3. CBM Italy

In 2012, Italy was taken as a prototype for testing the application of the CBM, at the country level, for EU Member States (Pilli et al., 2013). Within the following years, the same model was repeatedly applied to the Italian case study (e.g., Pilli et al., 2016, 2021, 2022), but most of the input data and methodological assumptions have continued to be based on the first modelling assessment, as described in Pilli et al. (2013).

In the present study, like previous ones, most of the information used have been based on the Second Italian National Forest Inventory (Gasparini et al., 2011, hereafter defined as INFC 2005), but all input data were reassessed and, when possible, updated and revised according to new information made available in the literature and a critical assessment of previous methodological assumptions.

The general modelling framework includes seven classifiers and two growth curve libraries, plus the definition of the disturbance events, including transition rules and disturbance matrices, applied within the calibration period and within the following simulation period. The calibration period 2005 - 2023 was used for calibrating and validating the model output against other independent data sources, including the Third Italian National Forest Inventory (Gasparini et al., 2022, hereafter INFC 2015). The calibrated model will be applied within the simulation period 2024 - 2070 in order to test different model scenarios, as defined within the Integrated Modelling Toolbox.

The following subsections detail the classifiers applied within the current modelling framework, the methodological assumptions used to define the forest area at the beginning of the model run and land use change that occurred within the calibration period (i.e., afforestation and deforestation), the growth curves and the disturbance events as defined within the calibration period, and the updates and refinements applied to Dead Organic Matter (DOM) pools. The last subsection reports on some model outputs, focusing on the validation of model results against independent data sources.

Classifiers

The modelling framework includes seven parameters used to classify the forest area reported by INFC within different groups. Two classifiers (forest type and species group) distinguish the forest area according to the species composition. The forest structure and management system applied to each forest type are defined by the classifier's management type and management system. The spatial distribution of the forest area at the NUTS 2 level is defined by the classifier region, while the climatic conditions associated with each forest unit are defined by the classifier Climatic Unit. A specific classifier, named status, distinguishes the origin of the forest area and the area available for wood supply. Each classifier includes specific codes described below.

1. Status distinguishes the forest area existing in 2005 (i.e., time step 1 of the simulation period) between forest area available (FAWS) and not available (FNAWS) for wood supply. The same classifier is also used to allocate the non-forest area, i.e. the area to be afforested or deforested during the model run. The assessment of the share of FAWS and FNAWS was based on the information reported by INFC 2005.
2. Forest type (FT) distinguishes the forest area between 20 categories, directly inferred from the classification system applied by INFC 2005 (see Appendix). A detailed description of these categories is reported by the supplement material provided by INFC 2005 (Gasparini et al., 2011, Tavola 3.3 and Allegato A). Forest types were further distinguished, through a specific classifier, between coniferous and broadleaves, according to the leading species defined by the INFC.

Each FT is linked to a species-specific biomass allometric equation, derived by Boudewyn et al. (2007), and further defined within the AIDB associated with the CBM model. Each equation converts the merchantable standing volume reported by growth curves to different dry biomass components, distinguished between merchantable, non-merchantable, and sapling-sized trees (i.e., smallest, non-merchantable-sized trees). In order to improve the consistency of the model output with the estimates reported by the latest Italian NFI (INFC 2015, used for model validation), the default allometric equations reported within the EU AIDB and already used within previous studies (e.g., Pilli et al., 2013, 2021) were further revised. For this purpose, the goodness of each equation is assessed by comparing the expected biomass wood density (WD) reported by literature (WD_{exp} as derived by the Italian NIR) with the basic wood density, inferred by a preliminary model output (WD_{cbm}), estimated as:

$$WD_{cbm} = \frac{Merch\_bio_{cbm}}{Merch\_vol_{cbm}} \qquad \text{Eq. (1)}$$

where, $Merch\_bio_{cbm}$ is the merchantable C biomass reported by the model output, and $Merch\_vol_{cbm}$ is the corresponding merchantable volume estimated by the allometric equation associated with each FT. The following figure compares the biomass wood density expected by the literature and provided by the model output, according to the default EU AIDB (Pilli et al., 2017) and with the new equations selected within the present study (see figure below).

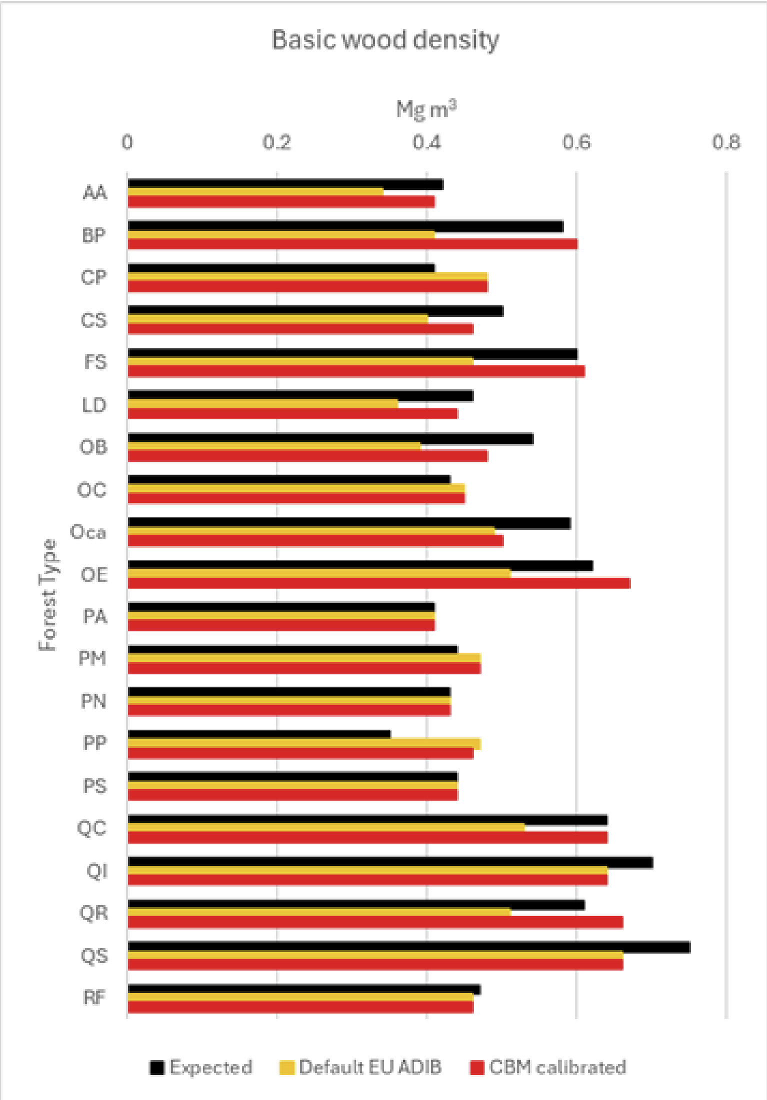

Figure 3. Comparison between the basic wood density reported by the Italian national Forest Inventory, and estimates from a preliminary model run, using the default equations reported by the EU Archive Index Database (AIDB) and the new calibrated equations from the Carbon Budget Model (CBM).

The same classifier assigned to the category FT also includes other ancillary classes used to define the area that will be afforested during the model run (defined as not-forested land (NF) preliminary associated with various FTs). Considering that in Italy afforestation is mostly due to natural expansion of the forest land due to abandonment of grasslands and other marginal areas, the not-forested land is preliminarily assigned to the land use category Grassland, with a default, average soil C stock equal to 81 Mg C ha^{-1}.

3. Regions classify the forest area between 21 administrative regions and autonomous provinces, in line with the classification system reported by INFC data (2005 and 2015). The CBM codes assigned to this classifier and the corresponding NUTS codes are reported in the Appendix.

4. Management type (MT) includes three categories: high forests (H), coppices (C), and special management type (S), further distinguished between six management systems (MS) described in the following table. This classification was directly inferred from the data reported by INFC 2005, also applied by INFC 2015.

Table 1. Management classes in CBM Italy

CBM Management Type	CBM Management System	Description
H	E	Even-aged high forests
H	U	Uneven-aged high forests
C	S	Simple coppice
C	M	Coppice with standards
C	H	Coppice with high forests
S	S	Special management type

H= high forest, C = coppice, S = special management type

5. Climatic Unit (CLU) distributes the forest area across 17 CLU, as defined by Pilli (2012). Each CLU was preliminarily associated with specific mean annual temperature (MAT) and total annual precipitation (P) values, already defined within the EU AIDB applied to this study (see Appendix).

Age class distribution: Forest area associated with even-aged forest management systems (even-aged high forests (HE) and coppice (C)) was further distributed across 14 age classes with a 10-year width, except for the age class AGEID0, which has been associated with a temporary unstocked area, as reported by the INFC. The areas attributed to AGEID1, AGEID2, AGEID3, and AGEID4 were directly inferred by the age class distribution reported by INFC. For the other age classes, where INFC age classes are 40-year wide, the original forest area was redistributed between the age classes used by CBM, according to an age correction factor (CF_{Age}), inversely proportional to the relative age (see Appendix).

The uneven-aged forest area was attributed to a single age class according to specific methodological assumptions described in section 3.3. The growth curves used within the model run include a larger age class interval, until AGEID20 (i.e. age >200 years old).

2.3. Heureka Sweden

The Heureka system is extensively presented in Lämås et al. (2023). In the following section, we provide a general overview of the software used for the Heureka system and models used in Heureka to project forest development (Lämås et al., 2023).

2.3.1. The Heureka system

The Heureka system consists of several software tools, three of which – StandWise, RegWise, and PlanWise – are used to project future forest development. StandWise is an interactive simulator for analysing individual stands, while RegWise and PlanWise work on multiple scales, from stand to national level. RegWise relies on rule-based simulations, whereas PlanWise applies optimisation techniques.

All three tools share a common set of mainly empirical tree- and plot-level growth and yield models that simulate forest development over time. A treatment unit—usually equivalent to a stand or sample plot—represents the smallest management level where actions such as thinning, final felling, or no intervention are applied. The software also includes ecological and economic models for scenario analysis and management planning, evaluating how silvicultural measures affect certain ecosystem services indicators. Additionally, PlanEval, based on Multicriteria Decision Analysis, supports systematic ranking and evaluation of scenarios, particularly those generated with RegWise and PlanWise.

2.3.2. Models projecting forest development

The Heureka decision support system integrates numerous interlinked models that simulate tree-layer dynamics, forming the basis for most other analyses. Users can often choose among different growth models.

For stand establishment on bare land or after final felling, species composition and height distributions are imported from a database of field plots (Elfving, 1982) or estimated using functions based on the same data. Seedling growth is modelled with height functions (Elfving, 1982, 2011a), and damage on young trees (2–6 m) is simulated following Näslund (1986), affecting mortality and height growth. Damage levels from moose, voles, snow-break, frost, and whipping can be individually adjusted.

Forest development is modelled in 5-year time steps and divided into two stages: stand establishment and development of established stands, separated at approximately 6–7 m stand height. Basal area growth in established stands is modelled using individual-tree models (Söderberg, 1986; Elfving, 2011b by default), combined with a stand-level basal area model (Elfving, 2011c). These functions apply to most Swedish tree species individually (e.g., Scots pine, Norway spruce, oak, beech, aspen) or in groups (birches, other deciduous), with exotic species like Lodgepole pine and larch treated as Scots pine. A complete species list is provided in Lämås et al. (2023).

When the stand-level model is applied, it projects total basal area growth, which is then distributed among individual trees. These models are derived from Swedish NFI data and validated against NFI and long-term field trials covering diverse treatment programs (Fahlvik et al., 2014; Aldea et al., 2023). They perform well under even-aged, single- or mixed-species management. However, uneven-aged management is less accurately represented due to limited Swedish data. In multi-layered stands, the models tend to underestimate basal area and volume growth, as evaluated over eight-year projections.

Height development in established stands is modelled by species-specific functions for Scots pine, lodgepole pine, Norway spruce, birch, aspen, beech, oak, and larch presented in five publications. Ingrowth of trees (DBH ≥ 4 cm) follows Wikberg (2004). Mortality in established stands can be modelled using Fridman & Ståhl (2001), Elfving (2014), or Siipilehto et al. (2020), the latter based on Nordic collaboration. Retention-tree mortality after final felling is modelled separately, with default settings from Roberge et al. (2015).

3. CBM-MS model recalibration

Leveraging the latest available NFI data, the CBM-MS models were recalibrated to reflect the latest trends in forest dynamics in the EU, in terms of forest growth, fellings, and disturbances. The recalibration is essential to recalculate the forest sink trajectories for the EU MS, and accounting for the effect of sudden changes in forest structure caused by utilisation or extreme events, which can affect, for example, the age class distribution and future carbon sequestration rates. In this section, we describe the model recalibration efforts per country. The Heureka model was already recalibrated and is therefore not covered here.

3.1. CBM Czechia

3.1.1. Introduction and input data for calibration

The GHG reporting for the LULUCF sector in the Czech Republic has been aided by the estimates of the locally calibrated modelling tool CBM-CFS3 (Kull et al., 2019; Kurz et al., 2009) since the 2022 national GHG inventory to UNFCCC (CHMI 2022; Cienciala 2022). In line with the other international reporting on forest resources of the country, such as to FAO FRA and Forest Europe, the Czech GHG inventory for the forestry used the information on forest resources based on database of the Forest Management Plans and Guidelines (FMPG), centrally administered by the Czech Forestry Institute (CFI), formerly named as Forest Management Institute, Brandýs nad Labem. These data are tightly linked to the Czech cadastral system of land use, centrally administered by the Czech Office for Surveying, Mapping and Cadastre (COSMC). Now, this reporting practice is going to significantly change. The two most important changes are:

- Overall progress in National Forest Inventory (NFI) implementation, data processing and readiness to provide relevant and timely information on forestry by CFI and its NFI team that permits use of these data for the coming national reports to FAO FRA (2025) and Forest Europe (2025), replacing the formerly used national information based on the FMPG data.
- Increasing demand for harmonised, objective, and timely information on forest resources required by domestic and international policies on environmental agendas.

Linked to this development, the coming national GHG inventory reports must become harmonised and respond to GHG-specific requirements set by the revised EU LULUCF regulation (European Parliament, 2018, 2023). They, among other things, specify emission reduction goals for the sector in the period 2021-2025 and 2026-2030. Reports are accompanied by specific technical requirements for the emission inventories of the LULUCF sector and emission accounting mechanisms. This sets the need for adequate changes in the Czech GHG inventory. It includes full implementation of the NFI data, recalibration of the national CBM-CFS3 modelling tool at adequate spatial detail and ensuring spatial coherence with the national land use data based on cadastral information. Methodologically, these changes must adhere to the mandatory IPCC requirements for emission inventories of the LULUCF sector (IPCC 2006, 2019).

The information provided in this deliverable represents the pilot calibration of the CBM-CFS3 to Czech conditions using NFI data, which will lead to changes in the coming national GHG reports, starting with the NID 2026 or 2027 submission at the latest. This pilot work utilised selected information from NFI2 and NFI3 campaigns, covering jointly the period 2011 to 2020 (Jan Máslo, personal information in 2025). Other complementary information from COSMC and the Czech Statistical Office (CzSO) was available for additional years until 2023. This pilot calibration should be considered preliminary and limited to the period 2011-2023, as it will undergo further refinement and changes in the coming months and years.

We acknowledge that this pilot work would not be possible without collegial support from the Czech Forestry Institute (CFI) and its NFI analytical team led by Jan Máslo. They kindly provided the essential NFI data in the required structure for the current calibration.

3.1.2. Forest Area

Data on land-use areas are a key input for compiling GHG inventories for the LULUCF sector. Land-use areas are classified according to IPCC land use categories, and any change (increase or decrease) in a specific category is mirrored by a corresponding change to the source or destination land use category (or categories).

To date, the Czech LULUCF inventory has been based entirely on the cadastral land-use system, centrally administered by COSMC. This institute provides annual, country-specific activity data attributed to IPCC land-use categories, including land-use conversions, at the level of individual cadastral units (over 13,000), which are linked to administrative regions (NUTS3 and finer). This allows for a geographically explicit tracking of land use for the mandatory reporting period beginning in 1990.

For forestry reporting, it is particularly important to monitor afforestation and deforestation, as these represent changes in forest resources and require mandatory estimates of ecosystem carbon stock changes. At the same time, LULUCF-related climate policies – starting with the early Kyoto commitments – introduced country-specific forest definitions (Schlamadinger et al., 2007; Ellison et al., 2013). These definitions are based on biological parameters similar to those used by the FAO, definition of forest (minimum area, tree height at maturity, canopy cover and width of forest formations). During the first Kyoto Protocol commitment period, parties were required to set national thresholds for these parameters, which soon raised concerns about harmonisation (Cienciala et al. 2008b; Ståhl et al. 2012).

More importantly, the link between these forest definitions and the mandatory land-use categories - and associated policies - remains missing. Understanding this gap is essential for both analytical consistency and policy interpretation.

In practice, the implementation of NFI data requires altering the overall concept of the land-use system based on cadastral data. Specifically, the Czech NFI data use the standard FAO forest definition (min. area of 0.5 ha, with trees higher than 5 meters and a canopy cover of more than 10%, or trees able to reach these thresholds in situ). It makes no distinction to cadastral land use, i.e., it may include forest formations on predominantly agricultural and urban land use. According to the NFI results (Máslo et al., 2023), the share of forest outside the cadastral forest land represents a substantial 10% of the overall forest area by FAO definition, with an increasing trend during the 2020s (Table 2).

Table 2. Forest area by forest land category – area and relative share is shown for NFI2 and NFI3 campaigns

	NFI2 (2011-2015)		NFI3 (2016-2020)	
Forest land category	Area (th. ha)	Share (%)	Area (th. ha)	Share (%)
Under FMPG	2,611	90.3	2,597	88.9
Outside FMPG	282	9.7	326	11.1
Forest land area total	2,893	100	2,923	100

Adapted from (Máslo et al., 2023a, NFI = National Forest Inventory, FMPG = Forest Management Plan and Guidelines.

Merging forest area information from NFI into the overall cadastral system of land use and land-use change identification required identification of cadastral land use category for the plot outside the cadastral forest land, or more specifically, outside forest covered by FMPG. Thereafter, the specific land use conversion events are guided by the general share of source/destination land use categories. Forest land identified by NFI outside FMPG takes precedence in the adopted system, while the areas of other IPCC land use categories correspondingly decreased. A similar system is adopted in GHG inventories of other countries with similar conditions, such as Austria, which recently introduced similar forest categories called forest in yield and forest not in yield (Austria, 2025).

3.1.3. Afforestation and deforestation

Estimating and reporting changes to forest land area is an integral component of the GHG inventory of the LULUCF sector, which allows building projection scenarios that capture land use changes. Therefore, the constructed system that integrates the full NFI information on forest land in the cadastral system of land use is designed to provide objective and coherent information of afforestation and deforestation events compatible with IPCC classification used for GHG reporting under UNFCCC. The illustrative results of attributed land use conversion, including forest land, i.e., afforestation and deforestation, based on the forest areas identified by the Czech NFI, are shown for two NUTS3 units in Figure 4 and Figure 5. It shows a historical period since 1970, which is required to meet the 20-year land transition period default as guided by the IPCC methodological guidance (2006). Note, however, that the pilot model calibration elaborated for this report includes only the period 2011-2023. Hence, the specific areas of afforestation and deforestation at NUTS3 regional resolution are taken for this period and are constrained by the areal information based on NFI2 and NFI3 results (Máslo et al., 2023a). As these results represent the period 2011-2020, the afforestation and deforestation areas follow a simple linear extrapolation of the observed data for the period 2021-2023. That information will be rectified once updated (i.e. NFI4 period 2021-2025) data become available.

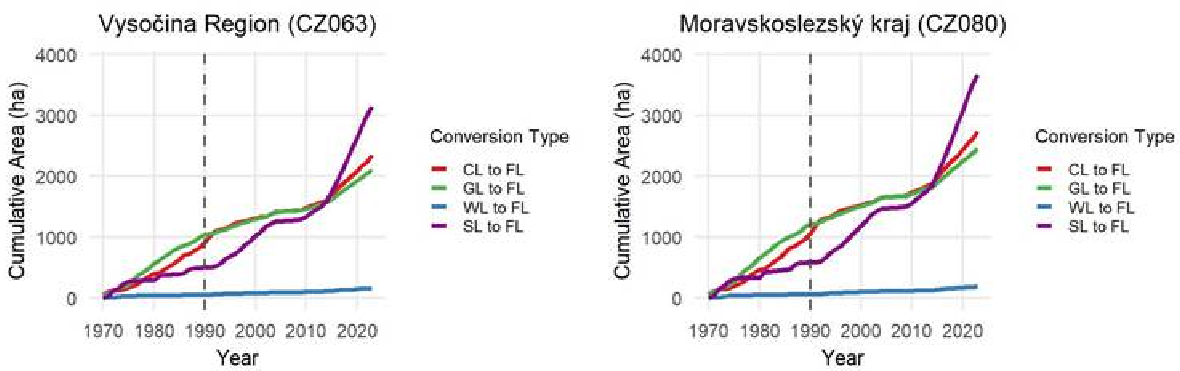

Figure 4. Estimation of cumulative afforestation areas from 1970 to 2023 using the cadastral information of the Czech Office for Surveying, Mapping and Cadastre and area estimates of the National Forest Inventory (Máslo et al., 2023a) – tentative results at example NUTS3 regions. CL = cropland, FL = forestland, GL = grassland, WL = wetland, and SL = settlements.

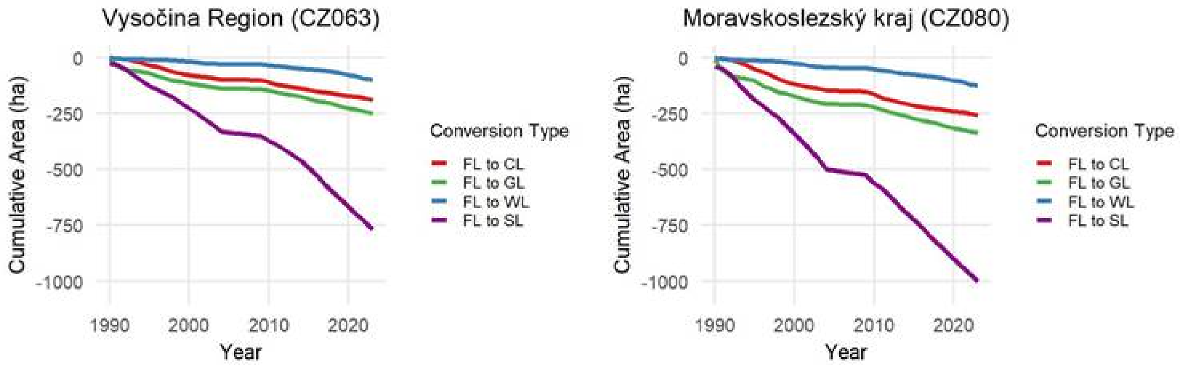

Figure 5. Estimation of cumulative deforestation areas from 1990 to 2023 using the cadastral information of the Czech Office for Surveying, Mapping and Cadastre and area estimates of the National Forest Inventory (Máslo et al., 2023a) – tentative results at example NUTS3 regions. CL = cropland, FL = forestland, GL = grassland, WL = wetland, and SL = settlements.

The specific data on areas respects the intended detail of the CBM-CFS3 application, as well as the emission reporting requirements. Hence, afforestation and deforestation events are classified at the level of NUTS3 regional units and the source/destination land use category (Figure 6, Figure 7).

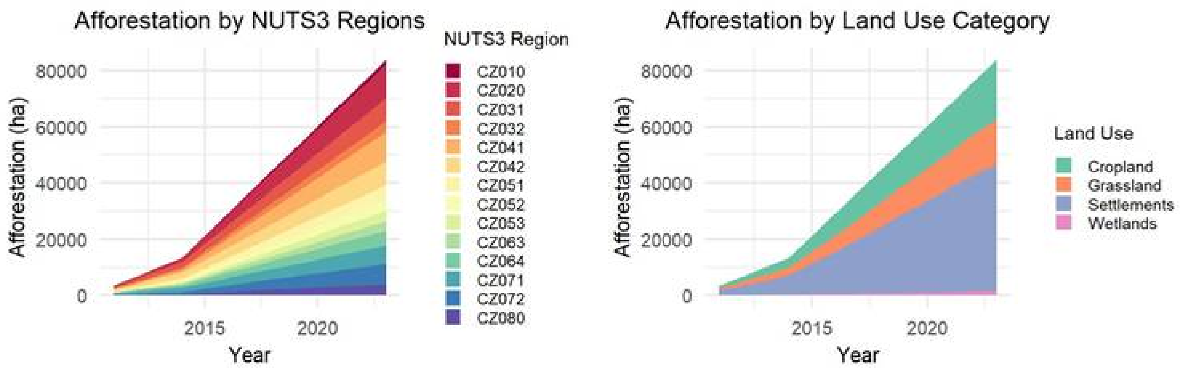

Figure 6. Cumulative afforestation areas at NUTS3 resolution (left) and by land use category (right) from 2011 to 2023 (based on National Forest Inventory and Czech Statistical Office estimates).

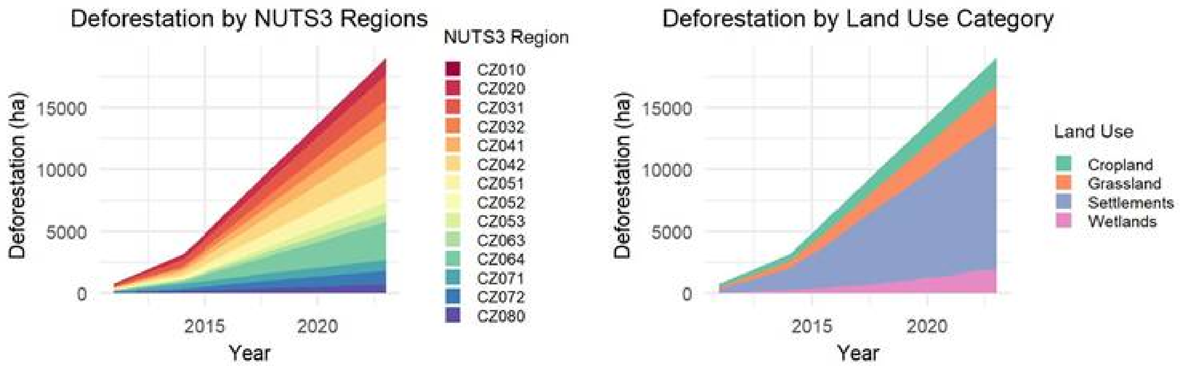

Figure 7. Cumulative deforestation areas at NUTS3 resolution (left) and by land use category (right) from 2011 to 2023 (based on National Forest inventory and Czech Statistical Office estimates).

Additionally, the model application allows controlling species composition and its development in time, as illustrated in Figure 8. The share of tree species shows a tentative approximation, which will be further refined at NUTS3 resolution.

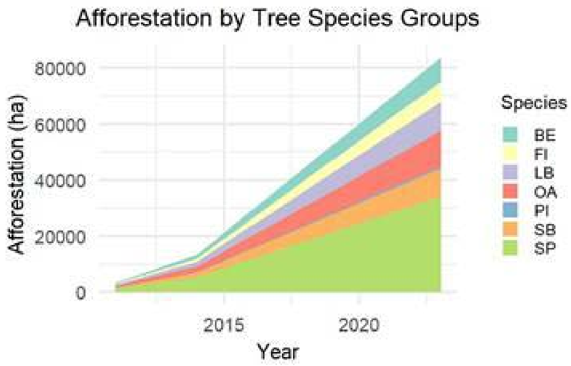

Figure 8. Cumulative afforestation areas by tree species groups for the period 2011 to 2023 (based on National Forest Inventory and Czech Statistical Office estimates). BE = European beech; FI = all firs, including Silver and Douglas fir; LB = long-lived broadleaved tree species, including maple species, European hornbeam, European Ash and others; OA = all oak species; PI = all pine species and European larch; SB = short-lived tree species, including birch, alder, poplar and willow; SP = spruce species.

3.1.4. Species aggregation – forest types

Aggregating tree species is essential to capture species-specific growth performance, management, and environmental policy preferences, specifically in terms of forest adaptation to progressing climate change. The aggregation should optimally utilise the available information from both the NFI program and available country statistics, specifically that on harvest. For this report, we retain the aggregation as adopted by our pilot CBM-CFS3 modelling study using FMPG data (Cienciala and Melichar, 2024). We distinguish seven forest types by species groups, which are summarised in Table 3 together with their share by area and volume as inferred from the NFI2 and NFI3 data campaigns.

Table 3. Forest types by tree species groups used for the CBM-CFS calibration and their share by area and volume as inferred from data of National Inventory cycles 2 and 3 - NFI2 and NFI3 (data source – Máslo et al. – personal communication 2025).

Forest type		NFI2 (2011-2015		NFI3 (2016-2020)	
	Abbr.	Area	Volume	Area	Volume
Beech	BE	10.03%	8.69%	11.1%	9.50%
Firs	FI	1.22%	1.85%	1.3%	2.04%
Long-lived broadleaved	LB	13.15%	7.00%	13.7%	7.22%
Oaks	OA	7.89%	6.46%	8.3%	6.79%
Pine and Larch	PI	13.20%	17.22%	13.1%	17.82%
Short-lived broadleaved	SB	11.41%	5.37%	12.0%	5.90%
Spruce	SP	43.10%	53.40%	40.5%	50.73%

The specific species groups include:

- BE – European beech;
- FI – all firs including Silver and Douglas fir;
- LB – long-lived broadleaved tree species including maple species, European hornbeam, European Ash and others;
- OA – all oak species,
- PI – all pine species and European larch,
- SB – short-lived tree species including birch, alder, poplar and willow;

- SP – all spruce species, but notably Norway spruce.

This grouping reflects the country-specific conditions, highlighting the traditional main production species (spruce, pine, beech, oak), important species groups for long-term adaptation (firs and long-lived broadleaves other than beech and oak) and mostly pioneer tree species with specific ecological relevance (short-lived broadleaves).

3.1.5. Allometric equations and model-specific parametrisations

The local parametrisation of tree biomass follows the CBM-CFS3-specific approach outlined by Boudewyn et al. (2007). The biomass component estimation using allometric equations concerns five primary biomass compartments: stem wood, bark, branches, foliage, and stem over bark. Input requirements include diameter at breast height (DBH) and total tree height, with stump height derived as one percent of total tree height for applicable equations. The following approaches and equation sets were used:

Coniferous species (Norway spruce, Scots pine) used Vonderach et al. (2018) additive models where the stem is divided into stump and coarse wood components with separately calculated bark. Fir species follow the same approach with a critical correction for silver fir bark estimation using Jagodziński et al. (2019) instead of the original Vonderach equations to provide realistic bark proportions.

- European beech combines Vonderach et al. (2018) for wood components with Wutzler et al. (2008) for foliage.
- Oak similarly uses Vonderach et al. (2018) for woody parts and Krejza et al. (2017) for foliage.
- Long-lived broadleaves (Ash, Hornbeam, Maple) apply species-specific Vonderach et al. (2018) equations with shared Krejza et al. (2017) foliage equations.
- Short-lived broadleaves (Alder, Birch) utilise Marklund (1988) equations with direct stem over bark estimation, combined with Repola (2008) for foliage.

Equation selection prioritises peer-reviewed sources with robust validation datasets. Vonderach et al. (2018) provide the methodological backbone due to its comprehensive additive framework and extensive calibration dataset from German and Central-European forests, which includes data from Czech forest sites (Cienciala et al., 2006, 2008a). Wutzler et al. (2008) similarly incorporate data from the Czech Republic (Cienciala et al., 2005) in addition to German sites, ensuring regional applicability. Supplementary equations from other sources (Marklund, 1988; Repola, 2008; Krejza et al., 2017; Jagodziński et al., 2019) were selected based on species-specific relevance for biomass components.

A key element of country-specific model calibration is the parametrisation of equations by Boudewyn et al. (2007). Eq. 1 relates stand-level merchantable volume (under bark in the case of the Czech Republic) to stem biomass (over bark), Eq. 2 estimates the share of nonmerchantable biomass fraction (NMF), Eqs. 4-7 provide forest type (species) specific shares of aboveground biomass components.

The fitted relations of Eq. 1 and Eq. 2 using the interim selection of NFI 2 and NFI3 data (Jan Máslo, personal communication, 2025) are graphically displayed in Figure 9. The fit of Eq. 1 was usually strong (coefficient of determination R^2 between 0.95-1) given the strong linearity of this relationship and extensive calibration material from NFI2 and NFI3 campaigns. In contrast, the fit for Eq. 2 describing the relation of the nonmerchantable factor (NMF) and total merchantable stem biomass mass per hectare and species groups, showed much larger uncertainty (explained variability between 41 to 73 %), which is due to the natural heterogeneity and can be addressed only by adequately large sample size for calibration (between n=118 to 4,519 qualifying plots for the least and most frequent species, FI and SP, respectively). The explained variability ranged between 40 to 70% for the individual species groups.

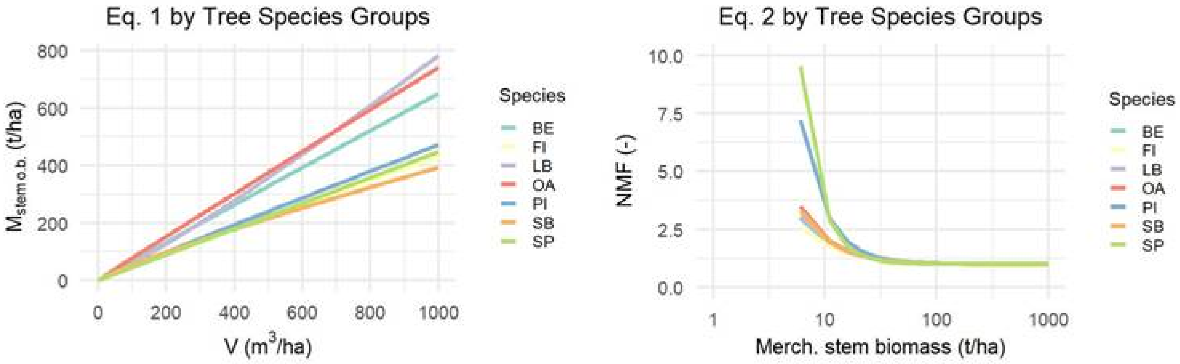

Figure 9. The parameterised relation of Eq. 1 relating stand-level merchantable volume (under bark) to stem biomass over bark ($M_{stemo.b.}$) (left) and Eq. 2 to share of nonmerchantable biomass fraction (NMF) (right) as in Boudewyn et al. (2007), for tree species groups (BE – European beech; FI – all firs including Silver and Douglas fir; LB – long-lived broadleaved tree species including maple species, European hornbeam, European Ash and others; OA – all oak species, PI – all pine species and European larch, SB – short-lived tree species including birch, alder, poplar and willow; SP –spruce species).

The set of Eqs. 4 to 7 as in Boudewyn et al. (2007) expresses the share of stem, bark, branches and foliage in relation to merchantable volume (Figure 10). The parameterised biomass components of Eqs. 4 to 7 for stemwood, bark, branch and foliage as in Boudewyn et al. (2007) for tree species groups were fitted using a multinominal model. The resulting RMSE varied from 0.016 to 0.033 for individual species. For the equation forms used and the related interpretation, see Boudewyn et al. (2007).

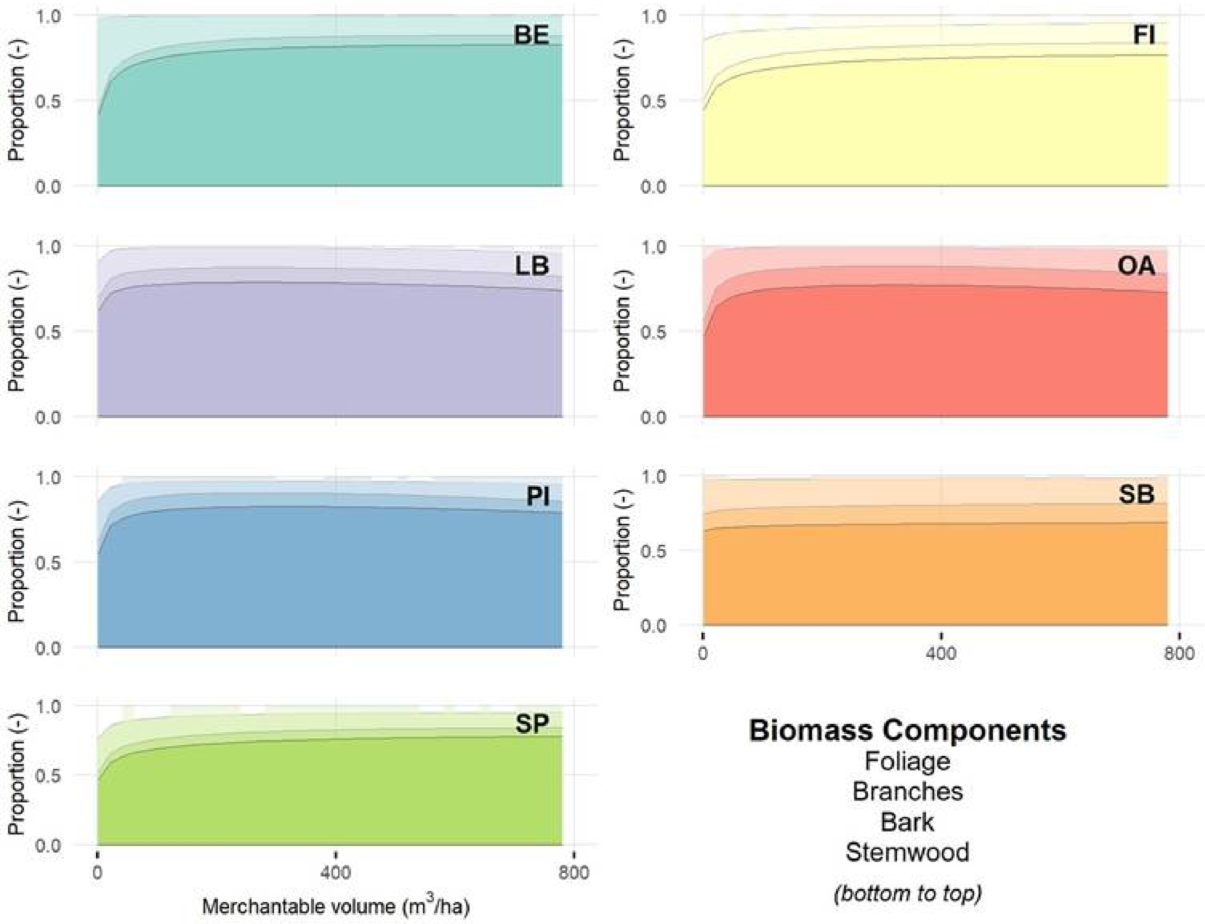

Figure 10. The parameterised biomass components of Eqs. 4 to 7 for stemwood, bark, branch and foliage as in Boudewyn et al. (2007) for tree species groups (BE – European beech; FI – all firs including Silver and Douglas fir; LB – long-lived broadleaved tree species including maple species, European hornbeam, European Ash and others; OA – all oak species, PI – all pine species and European larch, SB – short-lived tree species including birch, alder, poplar and willow; SP –spruce species).

3.1.6. Growth curves

CBM input data include two growth curves libraries: (i) initialization yield tables (YT), applied to assess the standing stock at the beginning of the model run and provide initialization of C stocks in each pool included in the model in the initial year of the simulation (consistently with NFI), and (ii) current YTs applied during the model run, to assess the expected annual increment in the absence of disturbances or management activities (Pilli et al., 2013). Calibration of growth curves is required for initialisation. YTs used aggregated data by species group type and NUTS3 regions, using the data of NFI2. The resulting fits using area-weighted nonlinear regression of the equation proposed by Pilli et al. (2013) were expectedly strong for initialisation YT (explained variability 87% to 99%), as they represent standing growing stock volume aggregated across all NUTS3 units.

Correspondingly, the current annual increment (CAI), which is used (together with natural mortality, see below) to derive the current YT based on the level of individual species groups and NUTS3 regions, used the estimation period covered by NFI2 and NFI3 campaigns (2011-2020). The variability in input data for approximation of the CAI function was larger, and the fits were generally weaker (R^2 adj. from 0.23 to 56 for individual species groups), using simple constraints to handle outliers (valid data entry 0 to 30 m^3/ha/y). The resulting fitted curves are visualised in Figure 11. It should be noted, however, that CAI estimates from the Czech NFI represent gross annual increment (GAI), as they include natural mortality. Conceptually, however, CBM-CFS3 requires input in the form of net annual increment (NAI) that excludes natural mortality. Hence, an additional set of NAI growth fits was prepared, using identical constraints as for CAI fits described above, with a similar range of explained variability (R^2 ranging from 0.32 to 0.61 for individual species groups). These sets of functions were used for the pilot model run and tentatively recalibrated by a single correction factor in one model iteration relative to the reported NFI estimates (Máslo et al., 2023b) for four species groups, European Beech, Oak species, Pine species, and Spruce species, and similarly for long-lived broadleaved tree species in the following iteration.

Based on the observed generic large increment variability, we solely used a country-level approximation of NUTS3 input data aggregated by age classes for this pilot parametrisation, which may later be replaced by more detailed fits, such as by climatic units (CLU) and/or NUTS3 regions used by the model application (see below).

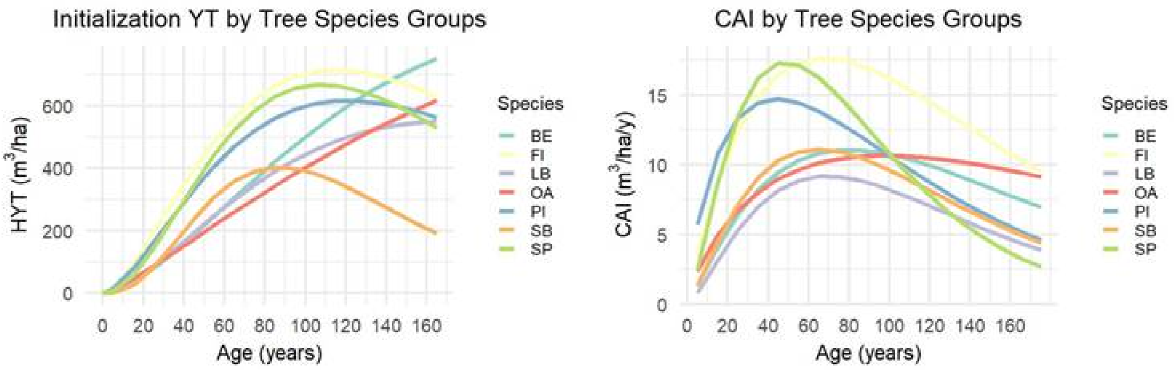

Figure 11. The parameterised growing stock (initialization HYT; left) and current annual increment (CAI) (right) curves by tree species groups BE – European beech; FI – all firs including Silver and Douglas fir; LB – long-lived broadleaved tree species including maple species, European hornbeam, European Ash and others; OA – all oak species, PI – all pine species and European larch, SB – short-lived tree species including birch, alder, poplar and willow; SP –spruce species).

3.1.7. Dead organic matter pools

Dead organic matter (DOM) pools include carbon in litter and dead wood, the changes of which are mandatory components of the national GHG emission inventory reports of the LULUCF sector. CBM-CFS3 covers these pools using nine specific components. For each annual time step, biomass is transferred from living biomass sub-pools (foliage, merchantable and other wood components, coarse and fine roots) to DOM pools, controlled by a set of annual turnover rates assigned to each living biomass component. The transfer from each DOM pool component is determined by specific annual decay rates. Finally, a fraction of biomass is released to the atmosphere from each DOM sub-pool, according to a specific temperature decay function (Kurz et al. 2009).

For this pilot calibration of CBM-CFS3, the tentative set of the adopted biomass turnover rates and DOM turnover rates included those specified in the original European Archive Index Database as customised by Pilli et al. (2018) and later altered by the country-specific model applications (Cienciala, 2022; Cienciala and Melichar, 2024). The following parameters were adjusted specifically for this report (incl. reference if not by personal expertise):

- AverageAge (150 to 125 years) by cross-checking NAI and soil carbon pool variables
- StemAnnualTurnOverRate (0.003 to 0.0029) by cross-checking NAI and GAI from the reference NFI data

- SoftwoodStemSnagToDOM (0.032 to 0.132) from a preliminary EU calibration of Viorel Blujdea (personal communication 2025)
- HardwoodStemSnagToDOM (0.032 to 0.174) from a preliminary EU calibration of Viorel Blujdea (personal communication 2025)
- OrganicMatterDecayRate for medium pool (0.0374 to 0.154) from a preliminary EU calibration of Viorel Blujdea (personal communication 2025)
- SoftwoodFoliageFallRate (0.11 to 0.18)

The DOM-specific outputs were tentatively crosschecked with the published literature (Máslo et al. 2024a) and relevant activity data used for the Czech GHG emission inventory of the LULUCF sector (CHMI 2025). It should be noted that the calibration of the DOM pools will certainly require further attention and cannot be considered conclusive.

3.1.8. Model output validation

The results of the pilot model calibration on the NFI data are demonstrated below on the examples of production indices (GAI, NAI) and DOM stocks (litter, standing and lying deadwood).

Production indices

Gross and net annual increment (GAI, NAI, respectively) are production indices that integrate several key ecosystem processes and provide elementary information on productivity specific to the studied forest types and regions. With the pilot model calibration described here, we attained reasonable correspondence to the published national NFI results as included in the recent harmonisation study of Gschwantner et al. 2024), which includes the reference average values of GAI, NAI and natural mortality in units of m3/ha/y (over bark).

As for the current annual increment, which basically resembles GAI as it includes natural mortality, the most recent publications of Máslo et al. 2023b estimated an annual mean between the NFI2 and NFI3 inventory cycles of 27.47 Mm3/year or 9.86 m3/ha/year (under bark). Another study using a harmonised definition of GAI and NAI for several European countries, including the Czech Republic, reported mean GAI and NAI as 9.53 and 7.91 m3/ha/year as over-bark values (Gschwantner et al. 2024). Our pilot GAI estimates using the calibrated model are 26.4 Mm3 or 9.34 m3/ha (under bark), suggesting an underestimation of 5 % with respect to the values of Máslo et al. (2023b), and minor overestimation relative to the values of Gschwantner et al. (2024), once compared to the over-bark version.

Complementarily, the reported mortality can either use the estimate of 4.01 Mm3/year or 1.44 m3 /ha/year representing stem mortality (under bark values), or mean total mortality derived from GAI and NAI estimates, which is reported as 1.62 m3/ha/year (over bark values) by Gschwantner et al. (2024). Relative to both references, the pilot estimates by CBM suggest a mortality rate of 4.94 Mm3/year or 1.75 m3/ha/year, which is somewhat (significantly) larger than the above references.

Finally, the productivity model outputs were also cross-checked together with the assessed changes in aboveground biomass (△AGB), which was also very recently published by the NFI team (Máslo et al. 2024b), both for the 5-year inventory intervals between the NFI2 and NFI3 campaign, and as the mean for the calibration period 2011-2020. These data are visualised together with the pilot CBM estimates for broadleaved and coniferous species in Figure 12. It should be noted that △AGB is the key variable for GHG inventory of the LULUCF sector, often representing quantitatively the largest component of ecosystem carbon stock change, and hence of CO_2 emissions and removals. The results shown in Figure 12 give confidence in model approximation: the mean discrepancy for the 10-year period is 0.10 Mt C/year, with means of 0.95 and 0.85 Mt C/year attributed to NFI and CBM, respectively. At the same time, it reveals calibration challenges, which should further address the pattern observed for broadleaved tree species, as well as the assessed mortality quantities. The promising solution that is to be implemented in the coming iterations of the calibration efforts will be using NUTS3-specific growth curves, including growth coefficients that can be derived from the observed data for the period 2011-2020. This, however, could not be implemented for the current pilot application due to time and capacity constraints.

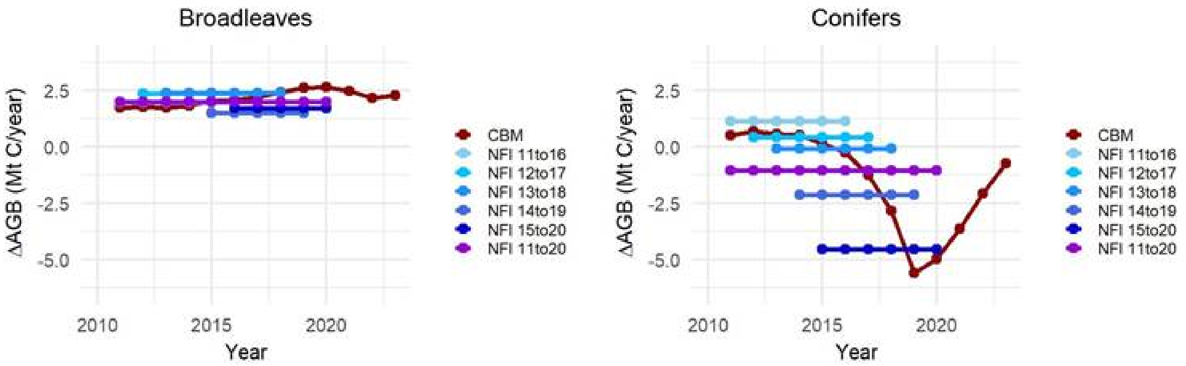

Figure 12. Carbon change in aboveground biomass (DAGB) as assessed by National Forest Inventory (NFI) for 5-year periods and mean for 2011-2020, together with the pilot CBM estimate (annual values for the period 2011-2023) for broadleaved (left) and coniferous (right) species.

Dead organic matter (DOM) stocks

The DOM stocks include most prominently litter and deadwood, the changes of which are mandatory components of GHG emission inventory reporting.

CBM-CFS3 includes three specific litter pools, the sum of which can be compared to litter as estimated by ground inventories. The available reference material for litter was published based on NFI2 estimates (Kučera and Adolt, 2019). For this report, however, we used a derived product from a processed mapped product based on NFI and other available observations (M. Vašát, L. Borůvka – personal communication 2025). It shows a mean value attributed to forest areas in 14 NUTS3 regions as 17.0 t C/ha, whereas the CBM estimate gave 16.8 t C/ha. A paired test of the NUTS3 means between the two estimates confirmed no significant differences with respect to regional variability (paired t-test p-value 0.916, n=14).

Of the four categories of deadwood represented by CBM, a comparison of standing and lying deadwood offers a straightforward assessment of how these pools compare to the NFI observations. For standing deadwood, the report of Máslo et al. (2024a) gives volumes of 4.4 and 8.0 m3 for NFI2 and NFI3 campaigns, which correspond to about 0.88 and 1.6 t C/ha (CHMI, 2025). The mean estimate of CBM for the period 2011-2020 is 1.5 t C/ha. Similarly, lying deadwood (merchantable size) was reported as 8.5 and 7.8 m3/ha by NFI (Máslo et al., 2024a), which corresponds to about 1.7 and 1.6 t C/ha (CHMI, 2025). Relative to that, the mean estimate of CBM for the period 2011-2020 was 2.3 t C/ha. These values were considered grossly correct and robust enough for pilot model runs with the tentatively calibrated CBM-CFS3.

Complementarily, we also assessed the quantities of mean mineral soil carbon pools at the regional (NUTS3) level using the map product of Vašát and Borůvka (2025, personal communication). For a reference soil depth of 30 cm, the map and CBM estimates gave regional (NUTS3) mean values of 67.7 and 72.5 t C/ha, respectively. Although these estimates differ by 7 % when tested by a paired t-test (p=0.010), they were considered satisfactory for the pilot calibration.

3.1.9. Recalibration summary

This pilot recalibration of the CBM-CFS3 model for the Czech Republic represents a fundamental shift from Forest Management Plans and Guidelines (FMPG) data to NFI data for GHG reporting in the LULUCF sector. The work utilised data from NFI2 and NFI3 campaigns covering 2011-2023 and establishes the tentative methodological foundation for upcoming national GHG inventory reports starting with NID 2026 or 2027 submissions.

Key calibration components included: Forest area integration using NFI-based estimates with FAO forest definition, incorporating forest land both within and outside cadastral boundaries. Afforestation and deforestation tracking was established at NUTS3 resolution using historical cadastral data and NFI-based area changes. Seven forest types were defined based on ecological and management characteristics, with growth curves calibrated using NFI data. Allometric parametrisation utilises peer-reviewed Central European equations with species-specific adaptations for biomass estimation. The model integrated various disturbance events, including harvest operations and spruce-specific drought/bark beetle mortality, with harvest data harmonised between NFI and official statistics. Dead organic matter pool parameters were adjusted using European database values modified by country-specific observations.

Model validation demonstrated reasonable correspondence with published NFI results for key variables, including annual increment, aboveground biomass changes, and dead organic matter stocks. However, some discrepancies were identified, particularly in mortality estimation.

This pilot calibration provides a working framework sufficient for immediate application but should be considered preliminary. Further refinement is needed, particularly regarding NUTS3-specific growth parameterisation, mortality estimation accuracy, and integration of additional NFI campaigns as they become available. The current calibration represents an essential first step toward harmonised, objective forest carbon accounting using comprehensive NFI data.

3.2. CBM Ireland

The currently used version of CBM-CFS3 for GHG inventories was calibrated using only three repeat inventory cycles over the period 2006 to 2017. The limited amount of forest growth data meant that the model, at the time, did not represent all major forest species and management strata. In particular, thin (intermediate harvest at a marginal thinning intensity of 70%, followed by clearfelling) and no thin (clearfelling only) stands are not differentiated. This is important given that thin and no thin management practices have very different GHG profiles (Ameray et al., 2021; Duffy et al., 2020).

Following the completion of the 4th NFI in 2022, the CBM-CFS3 modelling framework was recalibrated using a more detailed stratification of forest types, increasing from 12 to 18 species strata to better represent forest growth, particularly in thinned and non-thinned stands (Black et al., 2025).

3.2.1. Recalibration procedure

Net (or current) annual increment and standing volume curves for each species stratum were derived from NFI plot data (see Black et al., 2025). The volume-to-biomass equations for spruce were also modified by the inclusion of the NFI 2022 data in the training dataset (Black et al., 2025). No changes were made to the volume-to-biomass conversion equations for non-spruce stands initially used to implement the Irish CBM-CFS3 model (EPA, 2024).

The deadwood C pool was calibrated using NFI information. Changes include an increase in the transfer rate from dead trees (snags) to the medium deadwood pool (lying deadwood) and revision of dead organic matter model parameters (Black et al., 2025).

Validation of CBM-CFS3 outputs for the period 2006-2022 was performed by comparing the biomass, standing deadwood (stem snags), and lying deadwood (medium DOM) C stocks derived from each NFI inventory cycle. For the afforestation since 1990 (AR) subcategory, the CBM-CFS3 model was initiated in 1990 using afforestation disturbances for the species and soil strata defined from the NFI (EPA, 2024). The methods used to derive aboveground and belowground biomass, stem snag and medium C pools for each NFI plot are outlined by the Department of Agriculture, Food and the Marine (DAFM, 2022). The NFI plot C stock estimates for each inventory cycle were aggregated into different forest categories and species strata for comparison with the CBM-CFS3 outputs.

For the simulation of harvest, thinning and clearfell harvest targets (merchantable C over bark) were derived from NFI plot data. Stand replacement after clearfelling was assumed to have occurred 1 year after harvest with the same species unless NFI data indicated that the species changed after replanting. Deforestation and wildfire disturbance events for each species stratum were derived from the NFI and implemented using a target merchantable C target at each time step. Validations of all remaining forest lands, afforested before 1990 (FM), were performed by initiating the CBM-CFS3 simulation using the first NFI cycle data (i.e., 2006) with species strata age class distributions in 5-year classes and standing stock equations for each species strata (Black et al., 2025). Thinning, clearfell, deforestation and fire disturbances were implemented in FM simulations in the same way that AR harvest disturbances were implemented. Simulations were run to 2021 and compared to the 4 NFI inventory cycle data.

3.2.2. Recalibration results

Cross-validation of the simulated aboveground and belowground biomass stocks with NFI data revealed that the CBM-CFS3 model was sufficiently calibrated for both the forest management (FM) and afforested land (AR) forest categories (see Black et al., 2025). We show that biomass increment is accurately simulated over a period of 32 years for the AR forest and 16 years for the FM category (Black et al., 2025).

A comparison of the net annual increment (NAI) and harvest rate data from the model output and NFI data also suggested a good agreement (DAFM, 2022). Using a conversion factor of 1.1 to convert timber volume from under- to over-bark, the CBM-CFS3-derived NAI is 10.9 compared with 11.5 $m^3 ha^{-1} yr^{-1}$ for the NFI for the year 2006. The harvest rates, expressed as a percentage of NAI, derived from the NFI are 47-57%, whereas those derived from the CBM-CFS3 are 50-57% for the period 2006-2022.

The NFI-derived snag stem turnover rate to the medium DOM pool of 9.1% is significantly higher than the default value (3%) for CBM (Kurz et al., 2009) and slightly higher than the more recent estimates derived from the Canadian NFI, where a confidence interval range of 5.5 to 8.2% is reported using Bayesian inversion techniques (Hararuk et al., 2017). Although adjustment of the DOM parameters resulted in a much-improved estimate of deadwood stocks and stock changes (Black et al., 2025), the model still overestimates deadwood C stocks compared with the NFI data. The only national-derived DOM parameters are for spruce-dominated forests (Black et al., 2025), so improvements to the DOM model require more work, particularly with respect to deadwood dynamics in other conifer and broadleaf stands. The model could also be improved by defining species strata-specific stem turnover rates and snag C transfer rates. Some consideration could be given to the CBM model architecture to better characterise DOM dynamics. In particular, there is no physical transfer from the medium pool to represent the fragmentation of decomposing lying deadwood to the litter pool. New model developments, however, are underway to represent turnover rates and decay rates at the forest type level and other classifiers, improving the DOM dynamics. The advantage of using CBM-CFS3 is that it was developed for full accounting of C pools because it provides a mass balance of all C flows from merchantable volume to the DOM pool. In contrast, NFI adopts a size threshold (e.g., 7 cm diameter snags for Ireland), so field measurements may not capture all C flows from biomass to snags and from snags to the medium DOM pool.

The projections presented in Figure 13 represent the current forest policy, without additional climate change abatement action (WEM), as identified in the Irish climate change action plan (CAP24, 2024). The impact of the recalibrated model, compared to the originally calibrated models used for national reporting and projections (EPA, 2024; Lanigan et al, 2023), shows some important differences (Black et al., 2025, Figure 2).

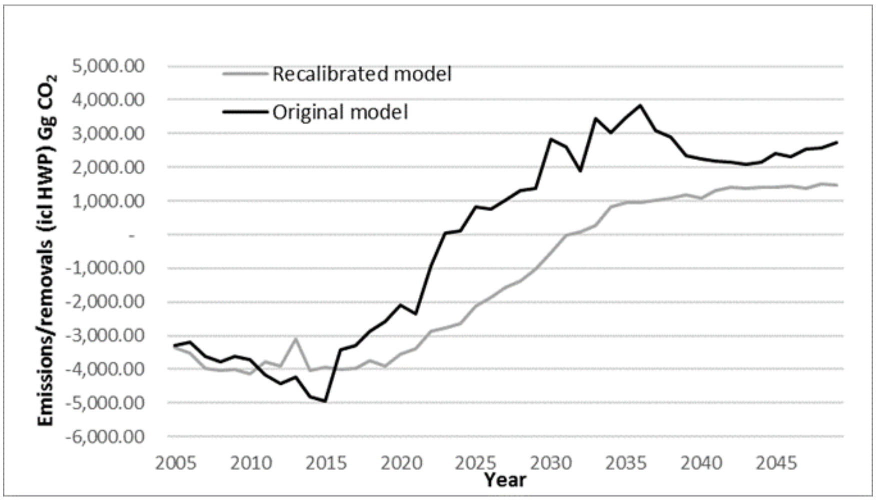

Figure 13. A comparison of the historic (2006-2023) and business-as-usual policy projection (with existing measures - WEM) total GHG (incl. harvested wood products - HWP) profiles derived from the previous version (original model) and the recalibrated version of CBM-CFS3 (Recalibrated model).

There are small differences for model outputs over the historic time series up to 2017, but from 2017 to 2022, the total GHG sink is -569 to -1,028 Gg CO2 per year higher for the WEM scenario derived using the recalibrated model in this study (Figure 13). The previously calibrated CBM-CFS3 model for Ireland also projects a faster transition to a net emission over the period 2022-2035. For this period, net emissions are 1,028 to 2,951 Gg CO^2 per year higher when the previous version of the model is used.

Recalibration of biomass stocks and stock changes had the largest impact on the overall GHG balance when compared to the previous version of the model. These differences are due to a combination of the new species stratification, differentiation of thin and no-thin growth curves for spruce, recalibration of growth curves, and the new biomass to volume equation for spruce (Black et al., 2025).

The recalibrated model will now be used by the Irish GHG inventory for future submissions to the UNFCCC and for national projections. The model framework has also been modified to run simulations for different scenarios specified in WP 6 of the Forest Navigator project.

3.3. CBM Italy

3.3.1. Forest area

Input data used for defining the area at the beginning of the model run (i.e., the inventory table) were derived from INFC 2005. We preliminarily distinguished the following categories, which were treated separately: even-aged high forests, uneven-aged high forests, coppices, plantations, special management systems, forest area not attributed by INFC to any management category, and temporary unstocked forest area. A summary of these categories is reported below.

Table 4. Forest area categories in CBM Italy.

INFC 2005 classification system			CBM manag. type/system	Area (kha)
Management type	**Management system**	**Age class distribution**		
High forests (H)	Even-aged[1]	Reported	**HE**	1,270
		Not classified by age class		238
		TOTAL even-aged considered by CBM		**1,485[2]**
	Uneven-aged	Not reported	**HU**	1,156
	Irregular	Not reported		493
	Not defined	Not reported		889
	From even-aged[2]	Not classified by age class		23
	TOTAL uneven-aged considered by CBM			**2,560**
Coppices (C)	Simple	Reported for overall coppices management type (3,313 kha)	**CS**	872
	With standards		**CM**	2,408
	With high forests		**CH**	383
	TOTAL coppices considered by CBM			**3,663**
Special		Not reported – assumed as uneven-aged	**SE**	118
Not classified		Not reported - distributed between HE-HU-coppices		757
Plantations		Reported, but without details at FT level[3]	HE	122
Temporary unstocked area		Not reported – assigned to age class 0 under even-aged high forests and coppices		54
			Total forest area	**8,759**

[1] Even-aged high forest data reported by INFC include 151 kha classified as coppices in transition to high forests, distinguished by FT and region, without any specific age class distribution.
[2] Excluding 23 ka reassigned to uneven-aged high forests.
[3] Proportionally distributed between PP, BP and CP

For each category, we applied the following methodological assumptions to distribute the INFC 2005 forest area between various management types/systems:

1. Even-aged high forests (HE) include the area already classified as even-aged and distributed by age classes (1,270 kha), plus the area not classified by age classes (238 kha), but reported as undetermined even-aged high forests and assigned to various regions and FT. Moreover, INFC data include under this category the area covered by coppices in transition to high forests (equal to 151 kha). The area not classified by age classes was proportionally distributed between the area classified by age classes, within each region and FT. A residual unclassified forest area, equal to 23 kha, reported as even-aged, but assigned to FT/regions without any age-class distribution, was attributed to uneven-aged high forests. The total area assigned to HE is equal to 1,485 kha, also including coppices in transition to high forests.
2. Uneven-aged high forests (HU) include the forest area already assigned to uneven-aged forests (1,156 kha), plus the area classified as "irregular" forests (492 kha) and the area "not defined" for the forest management system (888 kha). The total area assigned to HU is equal to 2,560 kha, also including 23 kha moved from the previous category HE.
3. Coppices include three management systems, simple coppices (872 kha), coppices with standards (2,408 kha) and coppices with high forests (383 kha), distinguished by regions and FT, but not classified by age classes. INFC 2005, however, also reports the overall age class distribution assigned to coppices, distinguished by regions and FT, but without further details on the specific management system. These data (including 3,313 kha) were used to infer the share of area assigned to each age class within each region and FT[i]. The area assigned to each management system, as reported by INFC, was proportionally distributed between various age classes according to the share defined on the overall coppice area. The total forest area assigned to coppices is equal to 3,663 kha.
4. Forest plantations include poplar, broadleaves and coniferous plantations, distributed by regions. Since the age class distribution is only available for each region, for the overall category "plantations", the forest area attributed to each FT/region was proportionally distributed between various age classes according to the general age class distribution attributed to plantations, within each region. Also in this case, the forest area that was not assigned to any age class was proportionally redistributed between the other age classes. The total forest area classified as plantations is equal to 122 kha.
5. The area classified as "special" management system (high forests with special management type, only including the forest types chestnut and cork oak) was considered uneven-aged.
6. The area "not classified" within any of the previous groups, equal to 757 kha, but already distinguished by regions and FT, was proportionally redistributed between the previous categories and age classes, at least for even-aged forests.
7. The "temporary unstocked area" (54 kha), distinguished by regions and FT, was proportionally distributed between even-aged high forests (HE) and coppices (CE) and assigned to the age class 0 (AgeID0).

[i] An additional forest area, including 349 kha classified as coppices on various regions and FT, but without a specific age class attribution, was proportionally distributed between the other age classes. When, for some region/FT, no age class distribution was reported (18 kha), the forest area was assigned to the age class 3 (AGEID3).

Based on this assessment, the final forest area, equal to 8,759 kha, perfectly matches the total forest area reported by INFC 2005 (including forests, plantations and temporarily unstocked area).

The area assigned to each FT, MT, MS, region and age class (for even-aged forests) was proportionally distributed between 17 CLUs. The relative proportion of forest area assigned to each CLU, further scaled at the regional level, and distinguished between broadleaves and coniferous species, was derived by the spatial intersection between a forest biomass map (Avitabile et al., 2020) distinguishing the forest area covered by broadleaves and coniferous species, and a specific map reporting the spatial distribution of each CLU at European level.

The forest area distributed between different forest categories and CLUs was finally distinguished between the area available and not available for wood supply (defined within the classifier "Status") using as a proxy the area not available for wood supply reported by INFC 2005 (Tab. 6.5, INFC 2005 data). We first defined, for each region and FT, the share of forest area not available for wood supply, and then we proportionally distributed the previous data set according to this share. The remaining fraction was considered as available for wood supply.

3.3.2. Afforestation and deforestation

The area available for afforestation during the calibration period (i.e., until 2023) was directly derived from the area assigned to even-aged high forests categories, and it was proportionally distributed between different FTs, regions and CLUs. Within the CBM inventory table, this area was assigned to the land use category "grassland remaining grassland," and each record was identified from species-specific soil types uniformly attributed to the CBM soil type "average" (Kull et al., 2019).

The total afforestation (AR) and deforestation (D) rate occurred between 2005 and 2015 were determined by the difference between the forest area reported, for each region and FT, by INFC 2015 ($A^{2015}_{reg,FT}$) and the corresponding forest area reported, for the same categories, by INFC 2005 ($A^{2005}_{reg,FT}$). INFC 2015 data were preliminarily harmonised to INFC 2005, and the area not classified by FT was proportionally distributed between the remaining categories. When, for each region and FT, the difference between $A^{2015}_{reg,FT}$ and $A^{2005}_{reg,FT}$ was positive, the area was assumed as afforested land (Eq. 2) and assigned to the corresponding disturbance event (DISTID 8); when the difference was negative, the area was assumed as deforested land (Eq. 3) and assigned to DISTID 7 (see § 2.5 for further details).

$$if\ \Delta\ (A^{2015}_{reg,FT} - A^{2005}_{reg,FT}) > 0 \rightarrow AR = (A^{2015}_{reg,FT} - A^{2005}_{reg,FT}) \qquad \text{Eq. (2)}$$

$$if\ \Delta\ (A^{2015}_{reg,FT} - A^{2005}_{reg,FT}) < 0 \rightarrow D = (A^{2015}_{reg,FT} - A^{2005}_{reg,FT}) \qquad \text{Eq. (3)}$$

The final dataset was proportionally distributed between FAWS and FNAWS, according to the relative share assigned to each category within the INFC 2005 data. The annual rate of afforestation and deforestation occurred between 2005 and 2015 was determined by dividing by 11 years the area assigned to AR and D on Eq. (2) and Eq. (3), respectively. The total net difference between AR and D, equal to 322 kha (Table 10), is in line with the absolute difference between the total forest area reported by INFC 2005 (8,759 kha) and INFC 2015 (9,085 kha). Since 2016 onward, the annual afforestation rate was inferred from the data reported by the latest Italian National Inventory Document (NID, 2025), taking into account also the expected impact of deforestation.

Table 5. Afforestation and deforestation dynamics.

Year	Expected Deforestation	Expected Afforestation
2005	11,050	40,363
2006	11,050	40,363
2007	11,050	40,363
2008	11,050	40,363
2009	11,050	40,363
2010	11,050	40,363
2011	11,050	40,363
2012	11,050	40,363
2013	11,050	40,363
2014	11,050	40,363
2015	11,050	40,363
2016	11,050	202,379
2017	11,050	202,379
2018	11,050	202,379
2019	11,050	202,379
2020	11,050	202,379
2021	11,050	202,379
2022	11,050	258,079
2023	11,050	258,079

3.3.3. Growth curves

CBM input data includes two growth curves libraries: (i) initialisation YT, applied to assess the standing stock at the beginning of the model run, and (ii) current YTs applied during the model run, to assess the expected annual increment in the absence of disturbances or management activities. Growth curves were derived from volume and increment data reported both as aggregated values (from INFC 2005) and as plot-level data (from INFC 2015). NFI data reports the stem volume over bark, including large branches with a minimum diameter of 5 cm and the corresponding current annual increment, derived by the annual increment of the stem radius, determined through the cores' sampling technique (Gasparini et al., 2011, 2022). For this reason, the increment data reported by INFC represent the gross annual volume increment, equal to net annual increment (NAI) plus annual natural losses (Avitabile et al., 2024).

Input data were preliminarily harmonised to the CBM model requirements by applying the following correction factors (CF):

- To exclude bark and large branches from volume data (at least for coniferous species) and trees with DBH ≤ 7 cm, we applied an overall CF equal to 0.96 for coniferous species and 0.89 for broadleaves.
- To exclude annual natural losses from the current annual increment values reported by NFI and other components such as large branches and small trees, we applied a CF equal to 0.76 for broadleaves species and 0.86 for coniferous species.

Correction factors applied to increment data were inferred by comparing the Italian NFI increment data with comparable data harmonised according to a common increment definition, excluding trees with a DBH ≤ 7.5 cm, branches for coniferous species, and annual natural losses from increment data. This information, summarised in the following table, was mostly derived from the data reported by Gschwantner et al. (2024). After a preliminary model assessment, we concluded that these CFs factor out most of the differences between the NFI data and the expected model's definitions.

Table 6. Comparison between the volume and increment components considered by INFC, the harmonised increment definition reported by Gschwanter et al. (2024), and the volume and increment components expected by CBM.

	INFC definition	Harmonized definition Avitabile et al. 2024	CBM definition	Correction Factor
Min Dbh	Dbh > 4.5 cm	Dbh ≥7.5	Dbh ≥9.0	
Stem components	Stem above stump height to top diameter of 5 cm + large branches with minimum diameter 5 cm	Stem over-bark from stump height to top diameter of 7 cm + large branches with minimum diameter of 7 cm for broadleaves.	Volume and NAI for merchantable stem under bark	
Annual Nat Losses	Included	Excluded	Excluded	
GAI conif.	5.8 m^3 ha^{-1} yr^{-1}	5.6 m^3 ha^{-1} yr^{-1}	5.6/5.8 = **0.96**	Vol conif.
GAI broad.	3.7 m^3 ha^{-1} yr^{-1}	3.3 m^3 ha^{-1} yr^{-1}	3.3/3.7 = **0.89**	Vol broad.
NAI conif.	Not available	5.0 m^3 ha^{-1} yr^{-1}	5.0/5.8 = **0.86**	GAI conif.
NAI broad.	Not available	2.8 m^3 ha^{-1} yr^{-1}	2.8/3.7 = **0.76**	GAI broad.

Note: Dbh = Diameter at breast height, GAI and NAI = gross and net annual increment, conif = conifers, broad. = broadleaves

Growth curves applied to even-aged stands were derived from volume and increment data reported by INFC 2005 for even-aged high forests, coppices, and plantations (Gasparini et al., 2011). Forest stands classified as special MT were considered as uneven-aged. Volume data were used to derive the initialization YT and increment data were used for deriving the current YT applied during the model run. In both cases, we started by using, if available, volume and increment data distributed by FT, MT (distinguishing high forests and coppices), regions and age classes. Original volume and increment data were preliminarily corrected, and they were interpolated through a combined exponential and power function (Sit, 1994), using the SAS© PROC NLIN procedure.

When the number of records (i.e. volume or increment data) reported by INFC for each FT, MT, and region were considered as representative of different age classes (i.e., INFC 2005 reports at least 4 age classes for each FT, MT, and region), we defined species-specific growth curves, parametrised at regional level.

When the number of records reported by INFC was not representative or the growth curves derived by the previous analysis were not consistent with original input data (each growth curve was further validated by an expert assessment) or PROC NLIN failed to converge, we derived a second, generic, dataset only distinguished by FT and MT. These generic growth curves were further scaled at regional level by comparing, for each FT and MT, the average volume and increment reported by INFC for each region, FT and MT, and within the same range of age classes reported by INFC, with the corresponding average volume and increment derived by the generic growth curves dataset.

This way, volume and increment data derived by the generic growth curves were also rescaled at regional level according to the specific values reported by INFC for each FT and MT.

Volume growth curves were directly used as initialisation yield tables, deriving the theoretical volume evolution util age class corresponding to 210 years. Increment growth curves were preliminarily converted to current YTs by deriving the cumulate increment volume associated to each age class, until a volume age class corresponded to 210 years.

Within the final initialization library, for even-aged forests, species-specific growth curves were assigned to 15% of high forest stands and 50% of coppices stands. Within the current library, species-specific growth curves were assigned to 13% of high forest stands and 48% of coppices stands. All growth curves were also validated through a final expert assessment.

For plantations, including poplars, broadleaves, and coniferous plantations, INFC 2005 reports a generic data series of volume and increment data by age classes, distributed by regions, but not distinguished by forest types. We considered these data as mostly referred to broadleaves and we applied the corresponding correction factors. Because data available for single regions were not sufficient to derive specific growth curves at the regional level, we first derived a generic volume and increment growth curve, and then scaled the generic growth curve at both the regional level and forest type, according to the same approach applied before.

Growth curves applied to uneven-aged stands were derived from NFI plot level data collected within the Third Italian NFI (INFC, 2015). From the original database, we selected 6,993 plots and the following parameters:

- *Vapv_m*: volume per hectare of living trees (stem + large branches) in m^3 ha^{-1} yr^{-1}.
- *ICVapv_m*: current annual volume increment per hectare of living trees in m^3 ha^{-1} yr^{-1}.
- *cod_istat*: administrative region code associated with the CBM regions.
- *codcfor*: forest category code associated with the CBM forest types.

Volume and increment data were preliminarily corrected using the same CF applied to even-aged stands. Growth curves were defined at FT and regional level through the following steps:

1. We preliminarily excluded from the original database all the groups of FTs and regions with a number of plots < 10.
2. We derived the percentage annual increment (ICP) associated to each plot, calculated as follows:

$$ICP = \frac{ICVapv\_m}{\mathrm{Vapv\_m}} * 100 \quad \text{Eq. (4)}$$

3. Possible outliers, defined as observations with a distance greater than 3 interquartile ranges from the median of each group (SAS Institute Inc., 1990), were excluded from the database using SAS© PROC UNIVARIATE procedure. We first identified and excluded volume's outliers (*Vapv_m*), then increment's outliers (*ICVapv_m*) and, finally, we excluded the percentage annual increment's outliers (*ICP*). The remaining observations in the *Clean_database* were considered for the following steps.
4. For each FT and region, we derived from the *Clean_database* a quadratic regression model defined by the following equation:

$$y = \alpha x + \beta \mathrm{x}^2 \quad \text{Eq. (5)}$$

where y = *ICVapv_m*, x = *Vapv_m* and parameters *α* and *β* were estimated using the SAS© PROC REG procedure. An example of the regression model application for the forest type LD and region Tn is reported in the following figure.

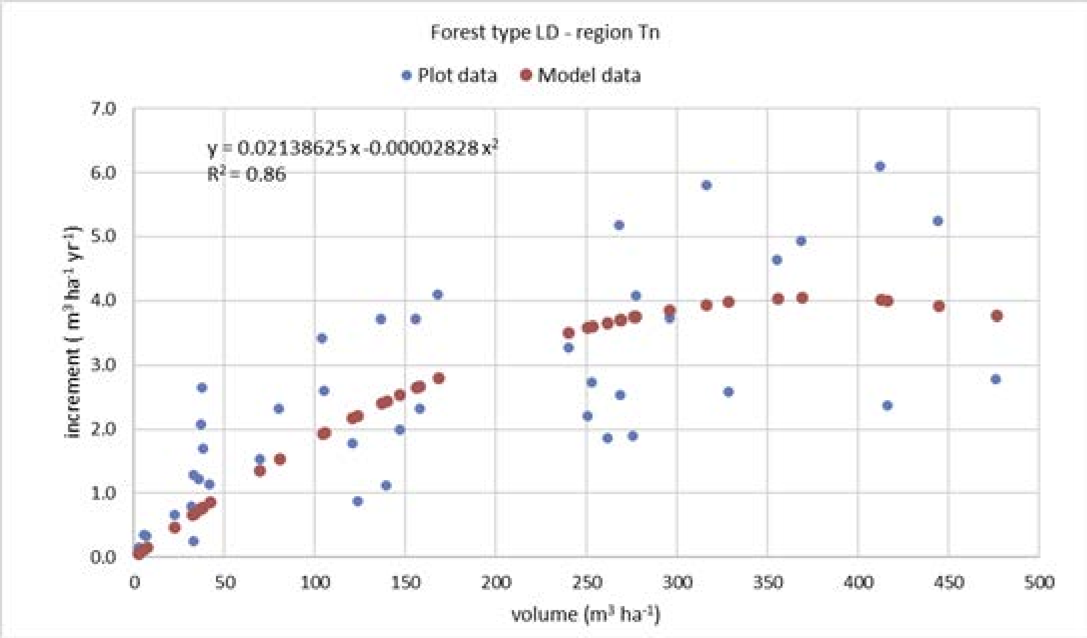

Figure 14. Observed and modelled productivity, relating the current increment (increment) to the standing volume (volume per ha).

For each equation, the regression model accuracy was evaluated using the adjusted R^2 calculated by the PROC REG procedure (e.g., for the example reported in Figure 14 R^2 = 0.86). All equations with an error degree of freedom < 10 were excluded from the following steps.

5. For each FT and region, we identified the minimum (V_{min}) and maximum (V_{max}) volume per ha reported within the *Clean_database* and we preliminarily distributed the corresponding volume range between 21 volume classes, with a constant volume range (V_{range}) equal to:

$$V_{range} = \frac{(V_{max} - V_{min})}{20} \qquad \text{Eq. (6)}$$

6. For each volume class, we estimated the annual increment (i_{Cl}) according to the regression models defined, for each FT and region, with Eq. (5) (see the example in Figure 15).

7. For each FT and region, the resulting increment values were used to derive species-specific uneven-aged growth curves including 21 volume classes (*cl*), with the volume of each class *n* (V_C^n) defined as follow (see Figure 16):

$$V_{Cl}^{n} = V_{Cl}^{n-1} + 10 * cai_{Cl}^{n-1} \qquad \text{Eq. (7)}$$

Where cai_{CL} is the annual increment estimated on the previous step.

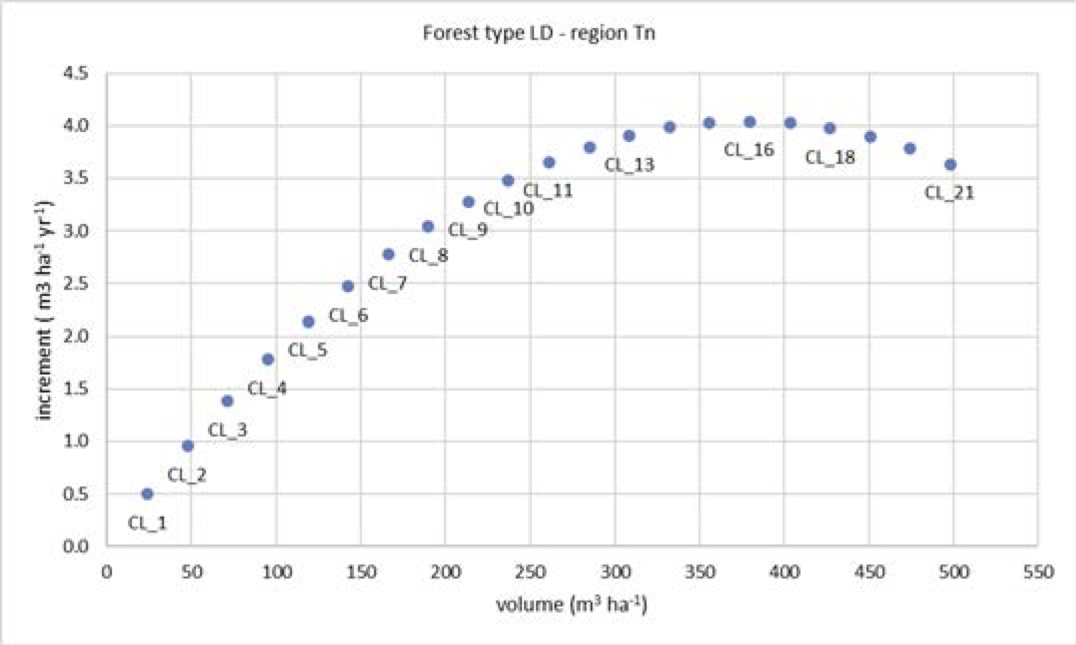

Figure 15. Annual increment by volume class in terms of standing volume per ha.

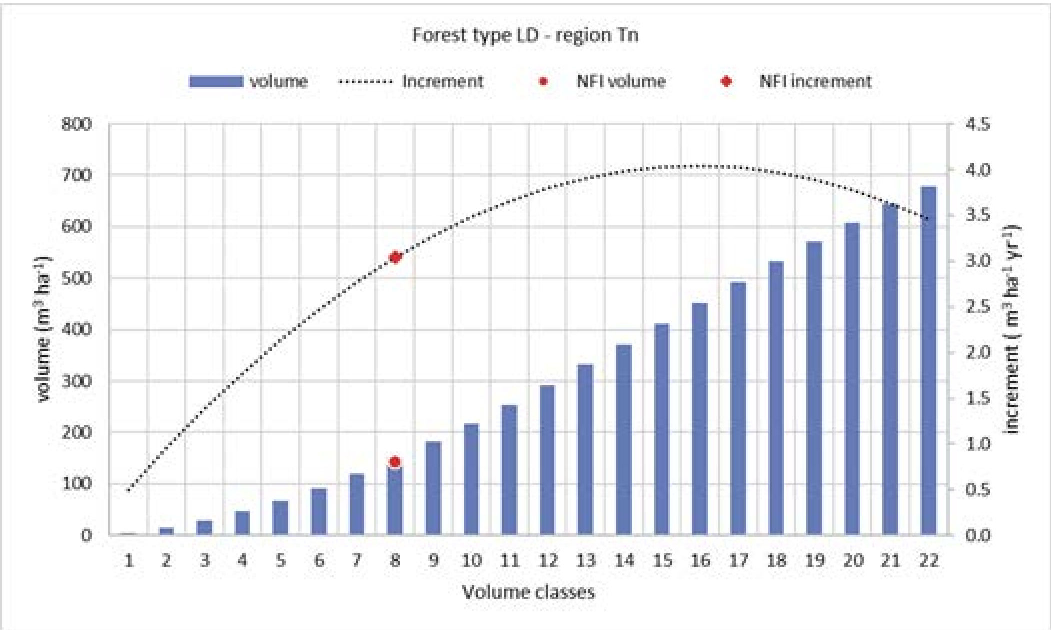

Figure 16. Example of cumulated volume per ha (left y-axis) derived from the annual increment values (right y-axis) associated to each volume class (x-axis) defined for the forest type LD – larch and mountain pines and region Tn - Provincia Autonoma di Trento. Red points highlight the volume and increment values derived by the Italian National Forest Inventory input data (preliminarily corrected), for uneven-aged forest stands within the same forest type and region.

8. Regression models defined in step (4) do not include all the uneven-aged forest stands reported by INFC input data, because some stands were excluded from the analysis (e.g., outliers or stands with fewer than 10 plots). Therefore, for each FT, a second set of generic growth curves were defined, to be applied only where species-specific growth curves were missing. This second set of growth curves was defined, for each FT and excluded extreme volume data, by the mean volume derived, for each age class, by the species-specific growth curves defined in step (6).

9. Combining the species-specific growth curves defined by Eq. (7) with the generic growth curves defined in step 8 we provided, for all FT and regions considered within the inventory table, a set of growth curves suited for uneven-aged forest stands. These curves can be directly used both as initialization yield tables and current yield tables.

When uneven-aged YTs were implemented within the CBM modelling framework, each volume class was considered as equivalent to an age class and the area assigned to each uneven-aged FT and region, was allocated within a unique “volume class”, following the same principle described by Pilli et al., 2013. To correctly simulate the initial standing volume at the beginning of the model run (time step 0), we assigned to each uneven-aged stand the volume-class corresponding to the standing volume reported by the input data used for CBM initialization (i.e., the standing volume reported by INFC 2005). For this purpose, for each FT and region, each uneven-aged stand reported within the CBM inventory input data was first associated to the volume reported by the corresponding uneven-aged growth curve, and then to the equivalent volume-class, assumed, within the CBM modelling framework, as a "virtual" age class (see the example reported above). Therefore, the initial age classes assigned to uneven-aged stands within the CBM inventory input data vary by region and FT, depending on the corresponding growth curve. The same assumptions were also applied to the special management type assigned to the forest types chestnut and cork oak, where no age class distribution is reported by INFC data.

3.3.4. Calibration of Dead Organic Matter pools

Dead Organic Matter (DOM) pools include deadwood, litter and soil, as defined by IPCC. Within the CBM modelling framework these pools are further distributed across nine different sub pools. For each annual time step, biomass moves from five living biomass sub pools (i.e., merchantable, other wood components, coarse and fine roots, and foliage) to seven DOM sub pools, according to a series of predetermined annual turnover rates assigned to each living biomass sub pool. The outflow from each DOM sub pool is determined by a physical transfer to other more stable sub pools (e.g., from the snag stems to the medium sub pool), driven by the annual decay rate assigned to each sub pool. A further fraction of biomass is released to the atmosphere from each DOM sub pool, according to specific temperature decay functions (see Kurz et al., 2009 for details).

The original EU AIDB used within the present study includes a set of predetermined biomass annual turnover and decay rates, mostly based on the default parameters provided by the Canadian Forest Sector. Within the present study, some of these parameters were modified with more recent information reported in the literature and to an ex-post assessment of the model output (see Table 7). In particular, the default biomass annual turnover rates were generally increased, using studies focusing on the Italian forests (e.g., Bertini et al., 2019), or other temperate and Mediterranean forests (e.g., Rock et al., 2008; Brunner et al., 2013).

Table 7. Adjusted biomass turnover rates for each component.

	Parameters	EU AIDB	AIDB updates	Source
BIOMASS TURNOVER RATES	AverageAge	Vary	90 yrs.	Calibrated by present study
	StemAnnualTurnOverRate	0.003	0.0048	[1]
	HardwoodBranchTurnOverRate	0.04	0.0425	[2]
	SoftwoodBranchTurnOverRate	0.04	0.0425	[2]

	HardwoodFoliageFallRate	0.11	0.95	-
	SoftwoodFoliageFallRate	0.11	0.95	-
	HardwoodCoarseRootsTurnOverRate	0.02	0.38	[3]
	SoftwoodCoarseRootsTurnOverRate	0.02	0.38	[3]
	HardwoodFineRootsTurnOverRate	0.64	1.11	[4]
	SoftwoodwoodFineRootsTurnOverRate	0.64	1.11	[4]
DOM TURNOVER & DECAY RATES	HardwoodStemSnagToDOM (to Medium)	0.032	0.0009 – 0.3239*	[5]
	SoftwoodStemSnagToDOM (to Medium)	0.032	0.0009 – 0.3239*	[5]
	HardwoodBranchSnagToDOM (to AG Fast)	0.10	0.001 – 0.25*	[6]
	SoftwoodBranchSnagToDOM (to AG Fast)	0.10	0.001 – 0.25*	[6]
	Medium decay rate	0.0374	0.0350	[7]
	BG slow decay rate	0.0033	0.0066	[7]
	BG slow Q10	1.0	2.65	[8]
	Medium Q10	2.0	1.0	Calibrated by present study
	Medium Proportion to atmosphere	0.83	0.90	[9]

Note: AIDB = Archive Index Database, AG = aboveground biomass, BG = belowground biomass, DOM = dead organic matter

[1] Bertini et al., 2019: average volume mortality rate determined at country level excluding Douglas Fir (see Tab. 1)

[2] Rock et al., 2008: mean coarse woody debris, as reported on Table 5

[3] Zhang & Wang, 2015: average coarse roots decomposition rate suggested for middle latitude areas.

[4] Brunner et al., 2013: revised fine-roots turnover rates suggested for *Fagus sylvatica* and *Picea abies*, applied to broadleaves and coniferous species, respectively.

[5] Climate-dependent decay rates derived from data compilation of decay constants of Fagus sylvatica and other deciduous trees occurring in temperate climates, as reported by Fravolini et al., 2018 (Table 6).

[6] Climate-dependent CBM decay rates modified proportionally to the decay rates attributed to Stem Snags

[7] Calibration on present study according to parameters reported by White et al., 2008 (Table 1)

[8] Increase default Q10 according to Hararuk et al., 2017

[9] Maximum proportion to atmosphere (0.70 – 0.90) suggested by White et al., 2008 for medium soil pool

DOM turnover rates were revised and modified using a temperature and precipitation gradient factor, derived from a large data compilation of decay constants of *Fagus sylvatica* and other deciduous trees occurring in temperate climates as reported by Fravolini et al. (2018). Based on these parameters, we defined a general precipitation-dependent turnover function, used to estimate the mean annual stem turnover rate (k) associated with different climatic units, defined according to the total annual precipitation (P) associated with each CLU:

$$k = 0.2486 * \ln(P) - 1.5179 \qquad \text{Eq. (12)}$$

This equation explicitly links the decay rate with environmental conditions, particularly with the precipitation gradient. Various studies highlight that the decay rate is largely influenced by soil moisture (Fravolini et al., 2018; Mackensen & Bauhus, 2003).

Default CBM decay rates associated to snag branches were also proportionally modified, according to the relative variation attributed to the same parameters for stem snags.

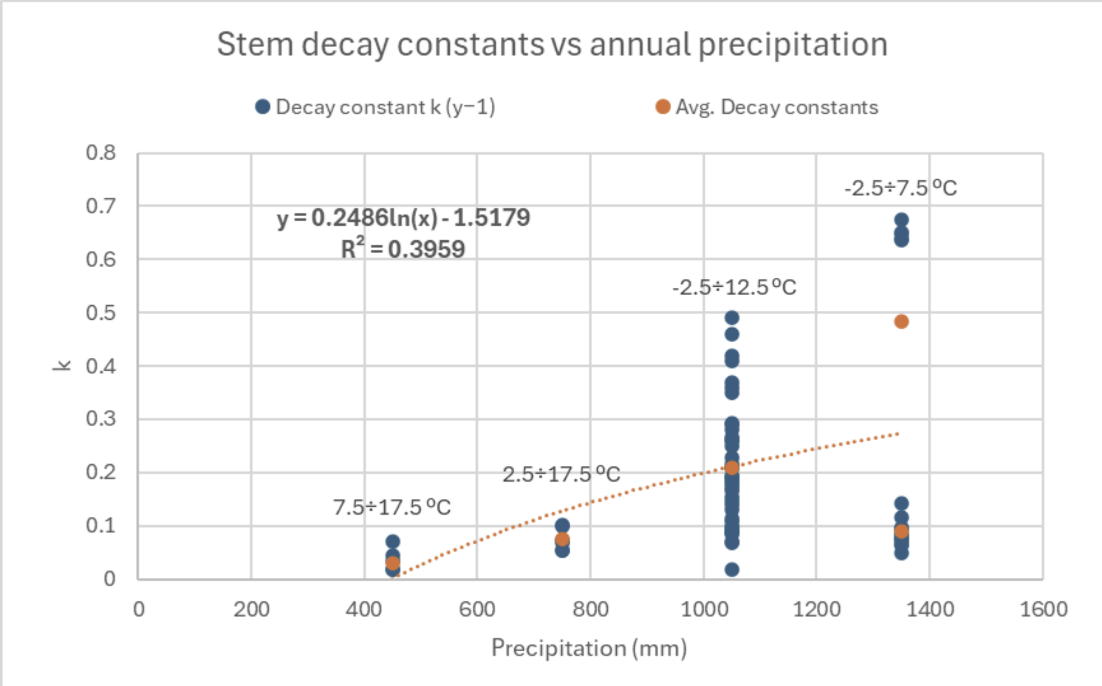

Figure 17. Decay rates, including (i) the stem annual decay rates (k (y−1)) reported by Fravolini et al. (2018), associated with CBM precipitation classes defined by our climate units; and (ii) the average decay rates inferred from previous data. Plot labels report the Mean Annual Temperature range associated with each precipitation level, within the Climate Units defined for Italy''s model run.

3.3.5. Model output validation

For the calibration period 2005 – 2023, the model output was compared with the INFC 2005 and INFC 2015 data, and other ancillary information, such as the 2025 National Inventory Document (NID) submitted by Italy to UNFCCC (Italy, 2025). Since INFC 2015 was not directly used as an input (except for deriving uneven-aged growth curves from plot-level data), the comparison with this data, when possible, can be considered as an independent validation of the model output.

Forest area

In this study, the forest area increased from 8,783 kha in 2005 to 9,035 kha in 2015, corresponding to a constant net afforestation rate of about 36 kha yr^{-1}. These values are consistent with INFC data, which report a total forest area of 8,759 kha in 2005 (−0.27%) and 9,085 kha in 2015 (+0.55%). However, the forest area reported by INFC for 2015 is lower (−128 kha) than the total forest land reported in the CRF tables for the same year (9,213 kha). From 2016 onward, assuming an increasing afforestation rate averaging about 180 kha yr^{-1}, the total forest area reached 10,389 kha in 2023, which aligns with the total forest land reported in Italy's 2025 CRF tables for the same year (10,848 kha).

Volume and Carbon stock

At the country level, aboveground biomass stocks estimated by CBM were 112.1 Mg ha^{-1} in 2005 and 123.2 Mg ha^{-1} in 2015. These values are slightly higher than those reported by INFC 2005, which were 99.8 Mg ha^{-1} in 2005 and 114.9 Mg ha^{-1} in 2015. However, the merchantable volume per hectare derived from the model output—using the same allometric equations applied in the AIDB—is closely aligned with INFC estimates (see figure below). Specifically, in 2005, the volumes were 144.3 m^3 ha^{-1} (CBM) and 144.9 m^3 ha^{-1} (INFC), while in 2015 they were 161.7 m^3 ha^{-1} (CBM) and 165.4 m^3 ha^{-1} (INFC). Differences emerge only when the estimates are disaggregated by forest type, where CBM shows some discrepancies compared to INFC, particularly for minor species, such as broadleaves (BP), coniferous plantations (CP), and other conifers (OC).

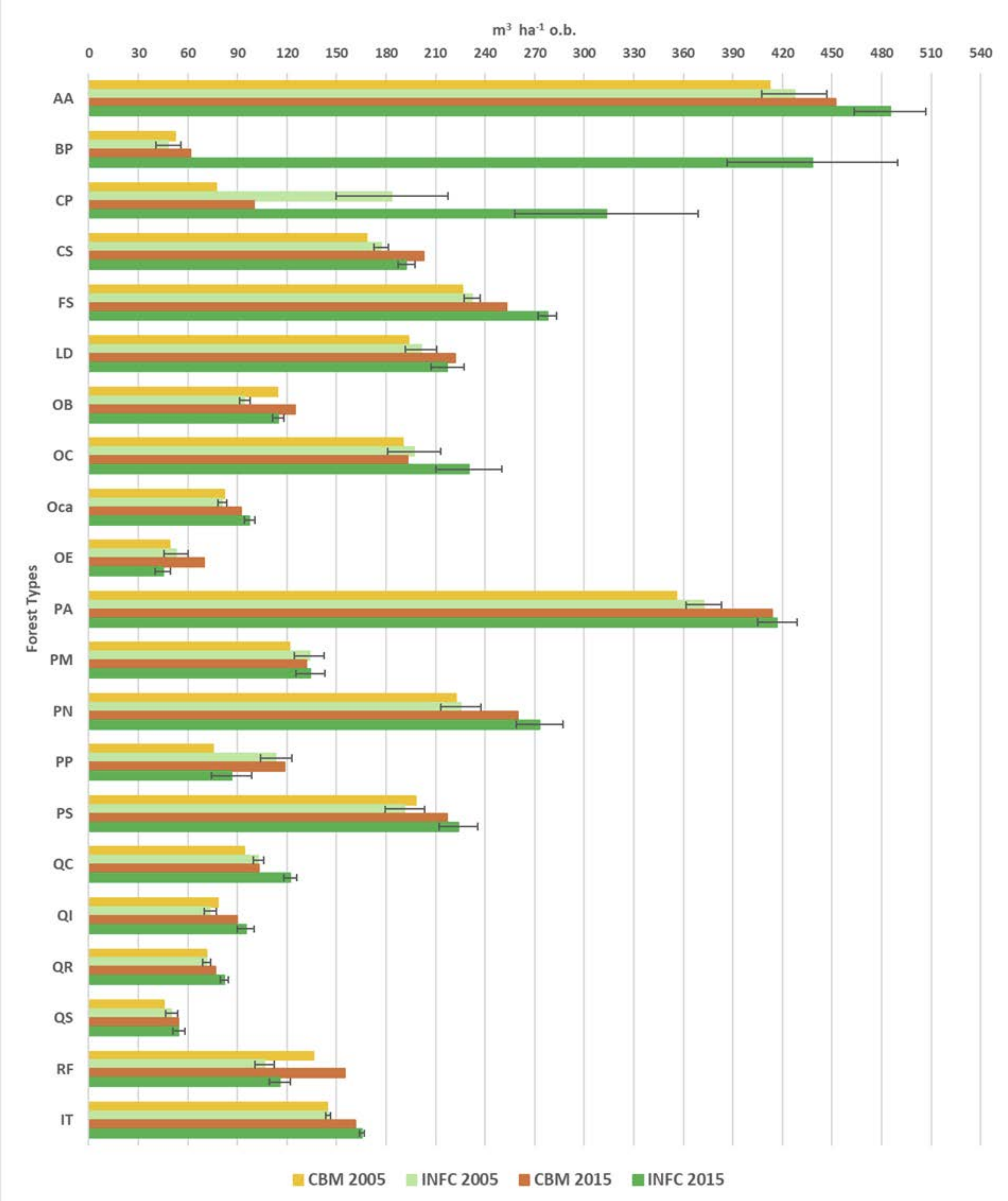

Figure 18. Comparison between the merchantable volume by Forest Type estimated by CBM for 2005 and 2015 and the corresponding merchantable volume (including branches), reported by Italian National Forest Inventory (INFC) 2005 and 2015. Forest Types codes are reported in Table 1 (last row refers to Italy). Bars associated with INFC values correspond to the percentage error reported by INFC data for each forest type.

Based on the model output, we provide a detailed analysis of the major increment components. Between 2005 and 2023, the average NAI and GAI were 2.97 m^3 ha^{-1} yr^{-1} and 3.85 m^3 ha^{-1} yr^{-1}, respectively. The difference is explained by annual natural losses (ANL), which averaged 0.88 m^3 ha^{-1} yr^{-1} and accounted for 23% of the GAI over the calibration period. During the same period, roughly 30% of NAI was removed through fellings, while the remaining fraction, about 2.09 m^3 ha^{-1} yr^{-1}, represented the average net C sink of the merchantable biomass stock.

Based on data from INFC 2005, harmonised according to a common 2005 EU-level reference definition, the GAI and NAI were 3.73 (±0.03) and 3.19 (±0.04) $m^3\ ha^{-1}\ yr^{-1}$, respectively (Gschwantner et al., 2024). For the same year, our model estimated GAI at 3.87 $m^3\ ha^{-1}\ yr^{-1}$ and NAI at 3.17 $m^3\ ha^{-1}\ yr^{-1}$. While the model's NAI is well aligned with the INFC-based value, its GAI estimate is slightly higher (+3.7%). This difference is largely explained by ANL: according to NFI data, ANL represented about 14% of the GAI, whereas our model estimated natural losses at about 18% of the GAI in 2005. Although this share is somewhat higher than the NFI estimate, it remains consistent with findings from other studies. For example, Bertini et al. (2019) reported that tree mortality losses in Italian forests account for about 20% of GAI, while Magnani & Raddi (2014), based on literature, suggested mortality losses could reach 31–36% of gross annual increment.

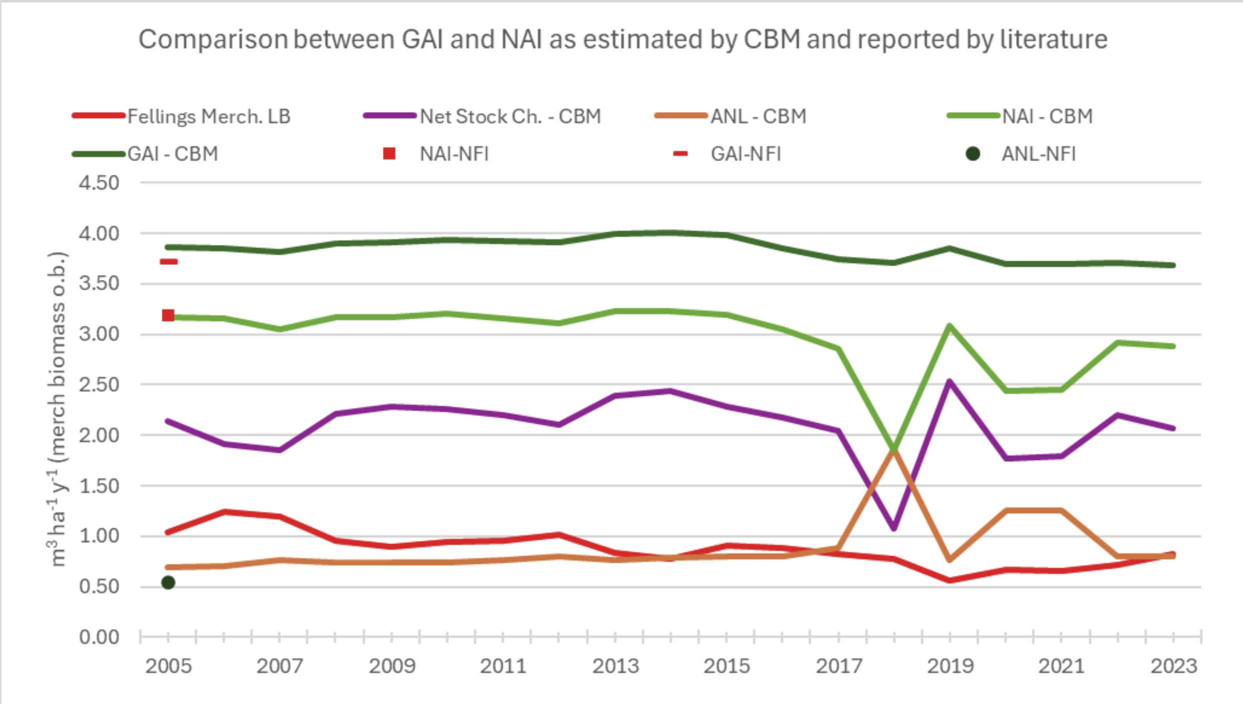

Figure 19. Net and Gross Annual Increment (NAI and GAI) estimated by CBM and inferred from National Forest inventory (NFI) data (Gschwantner et al., 2024), and different increment sub-compartments estimated by model, including: (i) annual amount of fellings provided by merchantable living biomass; (ii) net annual stock change of the merchantable biomass pool; (iii) annual natural losses, as estimated by CBM (ANL-CBM) and reported by literature (ANL-NFI, derived from Gschwantner et al., 2024). All data refers to the merchantable stock. Data reported from Gschwantner et al. (2024) are based on data collected by INFC 2005.

The total aboveground C stock estimated by our model for 2015, equal to 61.3 Mg C ha-1, is consistent with the C stock reported by INFC 2015, equal to 59.4± 0.9 Mg C ha-1 (including small trees and shrubs). For litter and soil pools, INFC does not report any data, but the average soil C stock estimated by CBM, equal to about 88 Mg ha-1 within the entire calibration period, is in line with data reported by Caddeo et al. (2019), based on a large literature review of various studies.

INFC 2015 provides detailed information on volume and carbon stored in trees' dead wood pool, further distinguished between standing dead trees, lying trees and stumps. Within the CBM model, the deadwood pool is distributed between four sub-pools. The carbon stored on snag stems and medium DOM pools considered by CBM (see Figure 20) can be compared with INFC pools, and converted to volume, using country-specific basic wood density values provided by literature (Morelli et al., 2007; Paletto & Tosi, 2010). At this purpose, we associated snag stems to the WD values assigned to the first decay class ("recently dead trees") reported by Morelli et al. (2007) and

Paletto & Tosi (2010), and we associated the medium CBM sub-pool to the WD assigned to the medium decay class (fragments of bark only) as reported by the same authors (see Supplementary Materials for further details). Table 15 compares the average volume and C stock reported by INFC 2015 and estimated by CBM, for the same year, for different dead wood pools. The average C stock attributed to standing dead trees by CBM, equal to 1.3 m^3 ha^{-1}, is quite aligned with the corresponding value reported by INFC (1.9 m^3 ha^{-1}), but the corresponding volume derived by CBM, equal to 4.9 m^3 ha^{-1}, is lower than the INFC data (7.4 m^3 ha^{-1}).

On the other hand, the C stock and volume allocated to the medium pool by CBM are about three times higher than the corresponding values reported by INFC for lying dead wood trees. This can be due to the inherent differences between data derived by direct field measurements, as collected by INFC, according to a specific protocol, and the modelling approach. In this last case, apart from the fraction released to the atmosphere, the amount of C associated with stem snags is transferred to the medium pool, independently of any size threshold. Indeed, while field measurements have some minimum dimension threshold, within the modelling approach, there is no minimum threshold to account for the C transferred to the medium pool. For this reason, apart from possible inconsistencies linked to the calibration process (including the CBM initialisation stage), we can reasonably expect that the amount of biomass assigned by the model to the medium pool is larger than the one reported by INFC data.

Deadwood component	**INFC 2015***				**CBM (2015)**		
	Standing dead trees	**Lying deadwood**	**Stumps**	**Total**	**Snag steam pool**	**Medium DOM pool**	**Total**
Definition	diameter and length ≥ 9.5 cm		diameter ≥ 10 cm	Including stumps	Dead standing stemwood of merchantable size, with bark	Coarse woody debris on the ground, excluding stumps and small trees	Excluding stumps*
Avg. volume (m^3 ha^{-1})	7.4	5.7	1.5	14.6	4.9	17.9	22.8
Avg. C stock (Mg C ha^{-1})	1.9 (57.5%)	1.09 (33.2%)	0.31 (9.3%)	3.3	1.3	3.9	5.2
* See section 4.3.10, Tab. 12.7, Fig. 12.3 INFC, 2015					* allocated to snags branches		

Figure 20. Comparison between the average volume and C stock reported by the Italian National Forest Inventory 2015 and estimated by CBM for different dead wood pools. All values refer to 2015. DOM stands for dead organic matter.

Within the calibration period, the carbon and biomass stock estimated by the model increase for all biomass pools (see figure below). The relative share of biomass assigned to the aboveground living pool is slightly increasing from 29% of the total stock in 2005 to 30% in 2023. The share assigned to belowground living biomass, dead wood and litter is stable, while the share of biomass covered by soil is slightly decreasing. This is due to the increasing living biomass stock, not to a decreasing absolute biomass stock assigned to the soil pool.

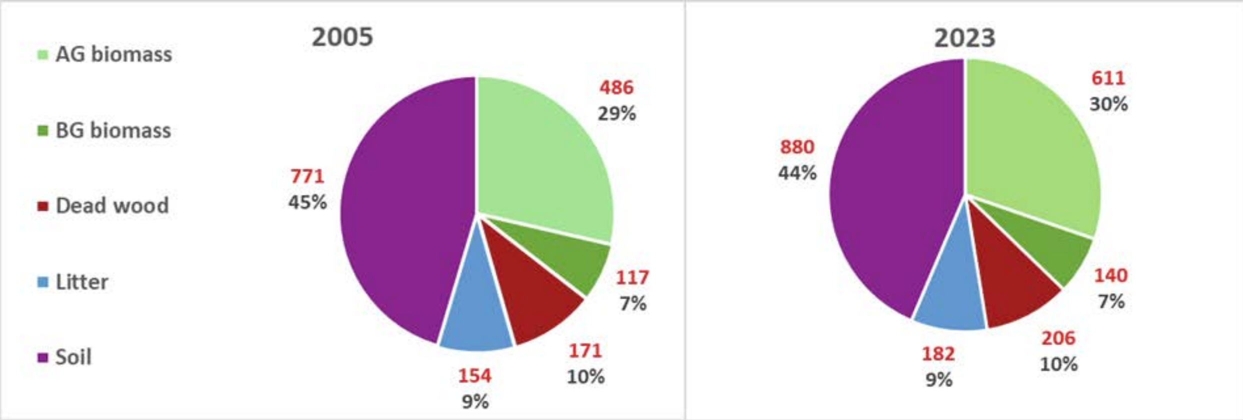

Figure 21. Carbon and biomass stocks in 2005 and 2023. Ag stands for aboveground and BG for belowground.

C sink

The following figure reports the net forest C sink estimated by CBM, further compared against the total, DOM and biomass C sink reported by the Italian NID (Italy, 2025), and the net stock change derived by INFC 2015 for the aboveground living biomass pool.

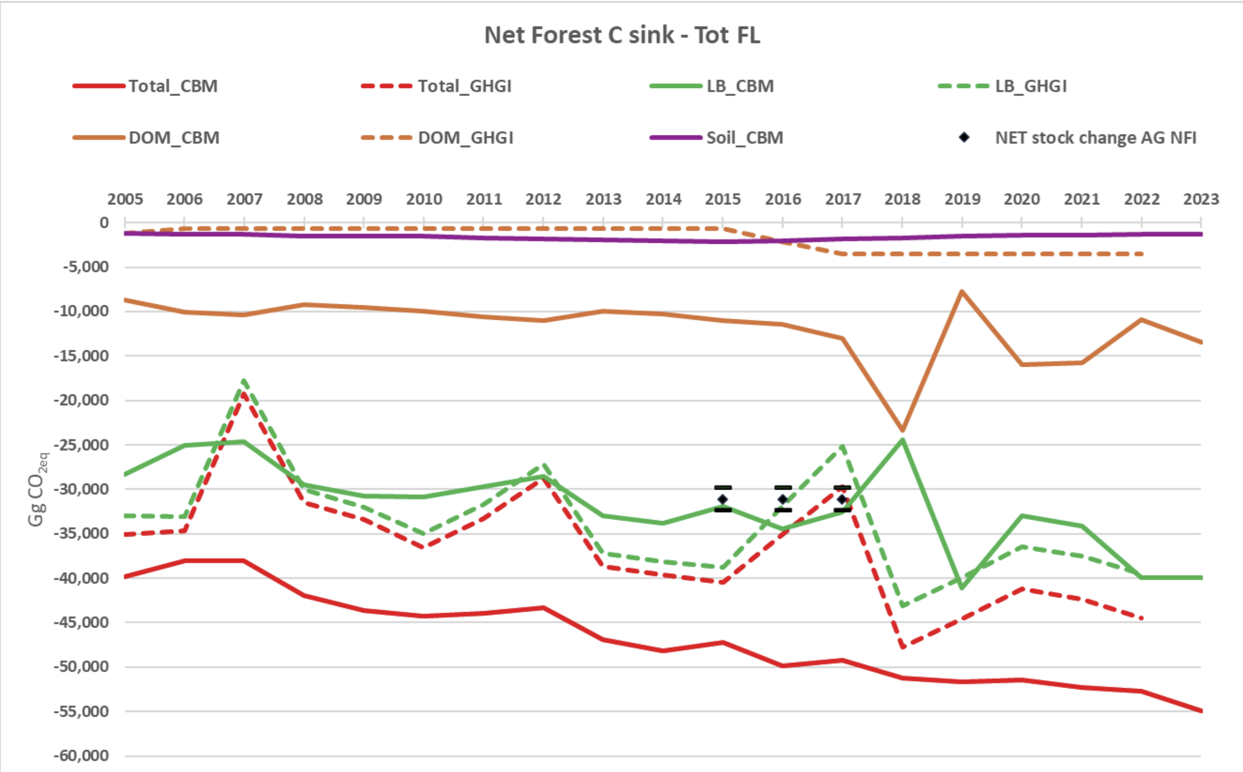

Figure 22. Net forest sink estimated by CBM, further distinguished between living biomass (LB), DOM (dead wood plus litter) and soil, compared against (i) the total (Total_GHGI) and living biomass (LB_GHGI, referred to Managed forest land) C sink reported by the Italian Greenhouse Gas Inventory (Italy, 2025), and (ii) the net stock change derived by Italian National Forest Inventory 2015. For these latest data, referred to the aboveground biomass stock, the figure also highlights the expected confidence interval, as inferred from INFC 2015 (red upper and lower bars).

During the calibration period, the living biomass carbon sink increased from about −28 Tg CO_2eq yr^{-1} in 2005 to −40 Tg CO_2eq yr^{-1} in 2023, following the same trend reported by the Italian NID. This increase is mainly driven by the decline in harvests up to 2018, combined with the rise in afforestation rates since 2016. The model estimate for 2015 (−31 Tg CO_2eq yr^{-1}) closely matches the net stock change in the aboveground biomass pool reported by INFC 2015 (−31 ± 1 Tg CO_2eq yr^{-1}; see table below). However, attributing this value to a specific year is challenging, given the long time span of NFI field measurements, which were mostly carried out between 2017 and 2020 (Pilli et al., submitted). On one hand, the annual volume increment in INFC 2015 is based on stem radius growth, calculated as the average of the five outermost rings (Gasparini et al., 2022). On the other hand, fellings are largely attributed to the period 2017 to 2019. For this reason, we assume that the average carbon stock change inferred from NFI data can be broadly attributed to the period 2015 to 2017. Within this period, the net stock change derived from NFI data is consistent with both our estimates and the values reported by Italy, at least for 2016 (−32 Tg CO_2eq yr^{-1}).

Table 8. Net forest carbon stock change derived by INFC 2015, taking into account the gross annual increment (GAI) and the amount of fellings estimated by Italian National Forest Inventory and the corresponding confidence intervals, and the annual natural losses as derived, from Gschwantner et al. (2024).

INFC 2015	Unit	Note	INFC data	INFC % error	Confidence interval	
GAI	Mg C	see Fig 12.9, INFC 2015	13,548,919	± 1%	13,413,430	13,684,408
FELLINGS	Mg C	see Fig 12.9, INFC 2015	3,164,519	± 15%	2,677,183	3,651,855
ANNUAL NATURAL LOSSES	Mg C	14% of GAI, Gschwantner et al. 2024	1,896,849	not available	1,896,849	1,896,849
NET STOCK CHANGE	Mg C	Sum	8,487,551	Sum	8,839,398	8,135,705
	Gg CO2	Sum *-44/12*1/1000	-31,121		-32,411	-29,831

INFC = Italian National Forest Inventory

Assuming that all living biomass stock has been completely lost (i.e. oxidised with direct GHG emissions to the atmosphere) on the area affected by wildfires, the Italian NID reports strong interannual variations in the living biomass pool within the years affected by major fire events (i.e. 2007, 2012 and 2017). On the opposite, CBM does not report similar interannual variations on living biomass or DOM pools, because, based on the ancillary information reported by INFC, the area affected by wildfires has been primarily distributed between underwood fires, mostly affecting DOM pools and only 20% of the merchantable living biomass, and crown fires, affecting 80% of the living biomass pool. This mitigates the impact of large wildfires on the forest C sink estimated by our model.

The minimum living biomass sink estimated by CBM occurred in 2018, reaching −25 Tg CO_2eq yr^{-1}, mainly due to the windstorm that occurred that year. By contrast, the Italian NID shows an opposite trend: the sink declined to −25 Tg CO_2eq yr^{-1} in 2017 (primarily due to wildfire events) and then increased to −43 Tg CO_2eq yr^{-1} in 2018, without reflecting any apparent impact of the Vaia windstorm on the living biomass or DOM pools. In subsequent years, the CBM-estimated sink was influenced by a combination of interannual harvest variations—largely driven by salvage logging—and additional carbon losses from living biomass caused by insect outbreaks since 2020. From 2020 onward, despite possible methodological differences, including in the estimated total harvest, our model's biomass carbon sink remains broadly consistent with the Italian NID.

The DOM carbon sink increased steadily from about −9 Tg CO_2eq yr^{-1} in 2005 to −13 Tg CO_2eq yr^{-1} in 2017, mainly driven by turnover associated with the growing living biomass stock. In 2018, the abrupt transfer of living biomass to deadwood and litter pools further increased the carbon sink attributed to the DOM pool. From 2019 onward, however, salvage logging redirected part of this stock from deadwood to product pools, thereby reducing the carbon sink attributed to DOM pool.

At the same time, the living biomass sink increased, reflecting the reduced intensity of ordinary silvicultural treatments in the three regions most affected by the windstorm and subsequent bark beetle outbreaks. No comparable effect is reported in the Italian NID, where carbon stocks on DOM pool are calculated using constant, linear accumulation rates based on NFI field measurements (NID, 2025). This methodological difference may also explain the considerably lower carbon sink reported by Italy (on average −1.7 Tg CO_2eq yr^{-1}), compared with our model estimates (about −11 Tg CO_2eq yr^{-1} over the entire calibration period).

Carbon stock changes in mineral soils are not accounted for by Italy, at least within the category *Forest Land Remaining Forest Land*. In CBM, however, mineral soil is treated as a stable pool, contributing a net sink of about −1 Tg CO_2eq yr^{-1} over the entire calibration period.

The total carbon sink estimated by CBM increased steadily from about −40 Tg CO_2eq yr^{-1} in 2005 to −55 Tg CO_2eq yr^{-1} in 2023. This trend is mainly driven by the growing sinks in living biomass and DOM pools, which contribute on average about 68% and 25% of the total sink, respectively. These shares are consistent with values reported in other countries (e.g., the Czech Republic) that use similar approaches. By contrast, the lower sink reported in the Italian NID is largely due to the DOM pool, which contributes only about 5% of the total sink over the calibration period. Additional discrepancies arise from interannual variations in the living biomass pool, primarily linked to wildfires.

In general, we can conclude that the living biomass sink estimated by CBM, is mostly driven by (i) harvest demand, (ii) natural disturbances and consequent salvage logging, above all after the 2018 windstorm, and (iii) the increasing contribution of afforested lands, above all since 2016 onward when, according to the latest Italian NID, the annual afforestation rate has abruptly increased from about 40 to over 180 kha yr^{-1}.

It is important to emphasise that, although our estimates for the living biomass pool are broadly consistent with the data reported by Italy, they remain inherently affected by uncertainty regarding the total amount of harvest that occurred in Italy over the entire calibration period. In this study, we used the average harvest volumes derived from an integrated analysis of statistics based on remote sensing, NFI data, and administrative surveys (Pilli et al., submitted). However, according to the same study, the uncertainty associated with these values is approximately ±50%.

3.4. Disturbance impacts in MS models

3.4.1. CBM Czechia

In CBM-CFS3, disturbance events represent land use and forest management interventions, and natural disturbances to forest ecosystems. The current country-specific model application for this pilot recalibration includes the following types of disturbances:

- afforestation and deforestation, both in the detail of source and destination land use category, are coherent with the GHG inventory requirements for the LULUCF sector (IPCC 2006). In practice, this allows discerning cropland, grassland, wetlands, and settlement land use categories as a specific source of afforestation and destination for deforestation events on an annual basis.

- harvest disturbances including a) thinning, b) salvage felling, c) final (planned) cut, d) harvest of dead standing trees (snags) – applicable only to spruce.
- conversion of dying living trees to standing dead trees because of integrated drought and bark-beetle infestation (with insufficient harvest capacities to conduct sanitary harvest in the current year) – applicable only to spruce

Each disturbance type is defined by a specific matrix that determines changes among ecosystem carbon pools and transfers to specific products and/or fluxes. The key disturbance types applied were like those described in detail earlier (Cienciala 2022; Cienciala and Melichar 2024). The specific transfer of living to dead spruce trees and the postponed salvage harvest of snags was implemented due to the observed situation with the recent extreme calamity experienced in the Czech forestry (Brázdil et al., 2022; Cienciala et al., 2024) in recent years, evidently initiated by the unprecedented climate extreme (Büntgen et al., 2021). The current set of disturbances covers the major events affecting carbon stock changes in forestry except wildfires. The effect of these is estimated separately for the national GHG emission inventory using Tier 2 methods, and while it has not been included in this pilot application yet, noting that the emission contribution of wildfires remains small, see e.g. CHMI (2025).

The key task related to harvest disturbances was integrating NFI harvest estimates based on the NFI2-NFI3 results. Although annual harvest data reported by CzSO are reliable and improving, the NFI estimates provide an independent and objective source of information. They cover not only land under FMPG but also include harvests from forests outside the cadastral forest land (see Table 1). For the period 2011-2020, the absolute difference between CzSO and NFI was 1.97 Mm^3/year, or about 9.5%, with the somewhat lower CzSO values due to the exclusion of land outside FMPG.

To harmonise both data sources, the annualization retained the available information from CzSO, while the absolute harvest quantity was retained from NFI. The recalculation was made at the level of NUTS3 regions and functional categories broadleaves and conifers as inferred from data in Figure 23. The figure shows that the relative difference between NFI-derived harvest estimates and those of CzSO are larger for broadleaved, which is mainly attributed to the fact that the forest not in yield (outside cadastral forest area, not covered by FMPG) is mostly composed of broadleaves – NFI2 results showed a broadleaved share of 80.5% in that category, in contrast to 38.7% share on cadastral forest land (Kučera and Adolt, 2019). Although the harvest intensity is estimated to be much lower on land outside FMPGL (Máslo et al., 2023c), it contributes to the observed higher harvest estimates for broadleaves in all NUTS3 units except Prague relative to CzSO reports by a factor 1.73 (Figure 23). In contrast – and correspondingly, the harvest of conifers differs only by a factor of 1.04, which is a good match of these totally independent estimates.

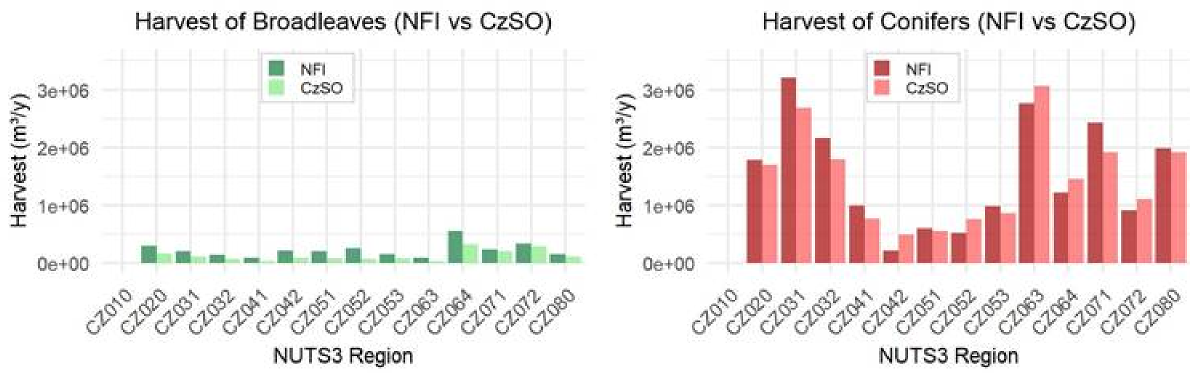

Figure 23. Harvest data (m^3 under bark) reported by the Czech Statistical Office (CzSO) and estimated by the National Forest Inventory (NFI) (Máslo et al., 2023c)– annualised amount applicable for the period 2011-2022, by NUTS3 regions.

The annualisation process applied to harvest data is illustrated in Figure 24 for four sample NUTS3 regions. Looking at conifers, NFI estimates may be smaller (CZ064, CZ072), larger (CZ071) or have a very good match (CZ080) relative to the independent data of CzSO.

Apart from merchantable wood harvest, CBM-CFS3 can track the prescribed extraction of harvest residues. For this report, the extraction intensity of wood residues was set to 20% for all sanitary harvest operations and final planned cuts. This is a consistent though slightly conservative estimate of the likely extraction of harvest residues in the country reported by CzSO in recent years.

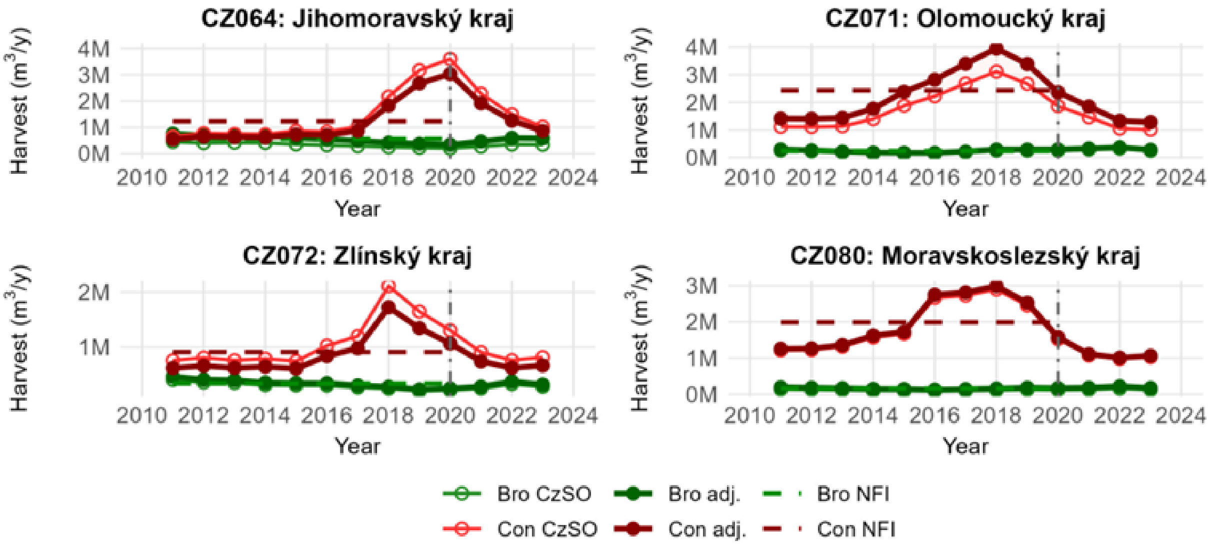

Figure 24. Example of adjustment and annualisation procedure retaining annual information of harvest from the Czech Statistical Office (CzSO), while using the reference absolute quantity from National Forest Inventory (NFI) estimates for different NUTS3 regions. The period 2021-2023 used identical ratios to obtain a reference harvest.

3.4.2. CBM Ireland

Damage to trees by strong winds is the most important abiotic hazard in Irish Forestry (Ní Dhubháin et al., 2001). The first well-documented effect of storm damage to private estate forests was in 1839, famously referred to as the "Night of the Big Wind" (Shields and Fitzgerald, 1989). However, the economic and forest productivity impact of wind damage was not documented until the 1970s, when the forest sector was more developed. Over the period 1971 to 1993, an average of 85,000 m^3 of timber was windthrown annually (Dhubháin et al., 2001), representing about 5% of the annual timber harvest.

Since the 1990s, wind damage has been expected to increase as stands in the "young" forest estate approached tree heights susceptible to windthrow. In 2014, storm Darwin affected ca. 8,000 ha of the national forest area, resulting in an additional 1Mm^3 of timber being salvage logged (EPA, 2024). In January 2025, Ireland experienced storm Éowyn, where record-breaking speeds were recorded. Recent estimates suggest that 26,000 ha of the Irish forest estate was windblown, providing an additional 10Mm^3 of timber now available for salvage logging. This is more than double the current annual timber harvest rate of 4.5Mm^3 per year and 7% of the national growing stock (142Mm^3, DAFM, 2022). As a result, it is now common silvicultural practice to manage forests to reduce windthrow risk by clearfelling at premature rotation ages, which has an adverse climate change mitigation impact (Black et al., 2025).

The current CBM-CFS3 model includes the direct and indirect impacts of forest wildfires in Ireland, which vary from 50 ha to 1,500 ha per year (EPA, 2024). The average wildfire area (169 ha per year) on the GHG profile is already included in CBM-CFS3 inventory and projection estimates.

The Irish version of CBM-CFS3 traditionally deals with windthrow impacts by including additional salvage logging as part of normal clearfell events in the year storm damage occurs. However, it is unlikely that the forest sector has the capacity to salvage log 10Mm^3 of timber from storm Éowyn, in addition to the already scheduled 5Mm^3 in 2025. Therefore, new disturbance matrices and a modelling capacity are needed to simulate windthrow with and without salvage logging, delayed salvage logging of windthrown areas and secondary impacts such as the increase in mortality due to pests and diseases because of large windthrow events (Palm-Hellenurm et al., 2024).

The objective of this work was to develop more detailed simulations of windthrow damage in CBM-CFS3 and to provide an early assessment of the GHG impact due to large storms before official UNFCCC inventory submissions are published. Developed tools will allow policy makers and managers to plan and assess the impact of different salvage logging operations on the forest GHG balance.

Figure 25 outlines the CBM-CFS3 workflow developed to simulate the short- and long-term GHG impacts of storm Éowyn. Recent work conducted by the DAFM and Coillte identified NFI plots, which were subject to storm damage, using intersects of plot sample points and remote sensing products (DAFM, 2025; Figure 5). Identified plot locations provided information on species strata and age when wind damage occurred to inform the scheduled salvage operation in CBM-CFS3.

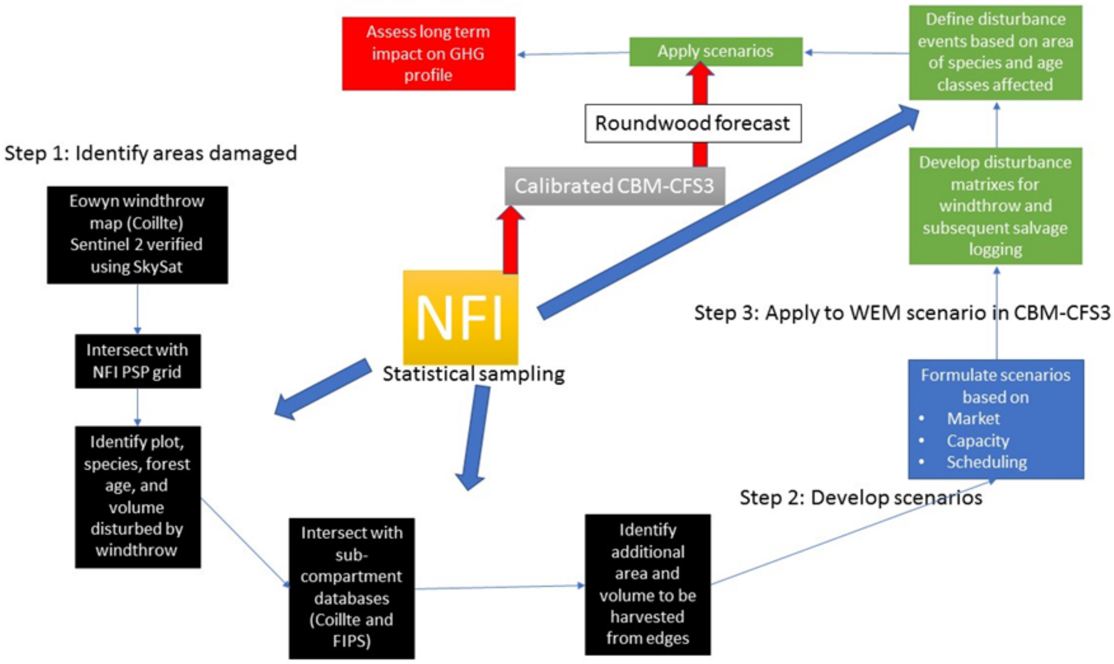

Figure 25:The CBM-CFS3 Ireland workflow for generating GHG profiles for storm Éowyn. NFI = National Forest Inventory, PSP = sample plot

Harvest targets for scheduled timber are taken from the baseline projection (WEM, Black et al., 2025). Scenarios for the salvage logging were developed based on an analysis of current market demand, harvesting capacity in Ireland, and salvage harvest scheduling information from the state forestry company (Coillte). Four basic scenarios were developed (Table 9) in addition to the WEM scenario (i.e. the recalibrated model WEM, Black et al., 2025).

Table 9. Strom Éowyn salvage logging and scheduled forest harvest scenarios.

Scenario	Scheduled forecast (WEM) harvest (% of volume)				Storm Éowyn salvage logging (% of windthrown area)			
	2025	2026	2027	2028/9	2025	2026	2027	2028/9
A	100%	100%	100%	100%	45%	45%	4%	6%
B	50%	50%	100%	100%	45%	45%	4%	6%
C	25%	25%	100%	100%	45%	45%	4%	6%
D	25%	25%	100%	100%	45%	45%	0%	0%

Source: Forest Service and Coillte (2025). WEM includes existing measures

Due to current national harvest capacity constraints, it is assumed that salvage logging will be carried out over 5 years, but with 90% of the windblow area harvested within 2 years to reduce the risk of pests and diseases and to minimise economic losses. This involves harvesting 45% of the windblown area in 2025, 45% in 2026, and the remaining salvage logging to be carried out from 2027 to 2029 (Table 9).

Scenario A, the worst-case impact scenario, assumes that all of the already scheduled harvests in the WEM projection (Black et al., 2025) will be carried out in addition to the salvage harvest. Scenario B and C assume that 50% or 25% of the scheduled forecast is harvested in 2025 and 2026, respectively (Table 9). Scenario D assumes the same harvest levels as scenario C, but with 10% not salvage-logged in 2027-2029. It also incorporates an increased risk of pests and diseases, resulting in an average annual mortality rate of 2% (derived from Palm-Hellenurm et al., 2024), modelled as 20% mortality every 10 years affecting 20% of the spruce areas (around 90,000 ha) from 2040 to 2070. This potentially represents a more cautious, likely outcome.

Additional assumptions include:

- The harvest capacity of the forest sector, including contractors from the EU and UK, is expected not to exceed 6.5Mm^3 per year in 2025 and 2026.
- Ten per cent of the salvage harvest is to be exported as roundwood, based on recent market trends. This timber is excluded from harvested wood products (HWP) inflows because the accounting rules under the EU LULUCF Regulation are for domestic production of HWP.
- An extra 10 to 20% of the windthrow areas, depending on ownership and stand age, were clearfelled as part of salvage logging operations, to account for blocking an adjacency of stand edges which are not windthrown.
- There is no pest and disease risk for scenarios A to C.
- No windthrow adaptation measures are considered except for the current silviculture practice, which is reflected in the WEM scenario.
- Inflows into HWP assume the same allocation to semi-finished products as outlined for the WEM scenario (Black et al., 2025). Besides the 10% of exported roundwood, there is no change to the allocation of roundwood to semi-finished products.
- No harvest residues or dead wood pools are used for bioenergy from firewood in Ireland.

Bespoke disturbance event matrices were developed to facilitate carbon flows between biomass, dead organic matter pools, and HWP inflows for windthrow within the CBM-CFS3 model framework (Table 10).

Table 10. Bespoke disturbance events and matrices developed for windthrow modelling in CBM-CFS3.

Disturbance ID (DISTID)	Function	Description
DISTID10	Windthrow without salvage	Facilitates windthrow with no harvest. Allocates all merchantable timber to the deadwood snag pool. Foliage and fine roots to the litter pool and coarse roots and branches to deadwood (50%) and litter (50%).
DISTID11	Salvage logging of windthrown areas after DISTID10	Harvests all snag timber created in DISTID10. A 10% harvest residue from snags to the medium pool is assumed. All other allocations are the same as clearfell carbon flows.
DISTID13	Salvage logging of windthrown areas in 2025 only	Assumes a conventional clearfell with an additional 7% of merchantable timber allocated to residues (i.e. the medium deadwood pool).
DISTID14	20% mortality	Simulates 20% mortality for Spruce stands due to potential pests and diseases following storm damage. The disturbance is a default CBM-CFS3 event. 20% of biomass pools are allocated to the deadwood and litter pools.

Source: Forest Navigator WP 6

Additional transition events are scheduled in CBM-CFS3 to allocate windthrown areas after DISTID10 to a "Windthrow"-species strata, which have a zero-growth increment curve. Once Windthrown stands are harvested, another transition facilitates the replanting of the stands with a species of choice. For scenarios A-D, the same pre-existing species before windthrow were replanted.

The historical time series shows a small increase in GHG removal and a harvest spike in 2014, associated with storm Darwin (Figure 26). According to GHG inventory data, storm Darwin (affecting 8,000 ha) resulted in an additional 1Mm^3 of harvested wood in 2014, corresponding to an estimated reduction of about 1,000 Gg CO_2 per year in forest and HWP removals. All salvage logging related to storm Darwin was simulated in a single year as standard clearfell events.

Storm Éowyn is projected to have a significant short-term impact on the GHG balance between 2025 and 2030 (Figure 26). In Scenario A, which assumes no capacity or market constraints, annual harvests exceed 10 Mm^3 in 2025 and 2026, leading to net emissions of approximately 1,200 Gg CO_2eq per year in those two years. Over the 2025–2030 period, this represents a reduction of forest and HWP sink capacity by 11,730 Gg CO_2eq compared to the WEM scenario.

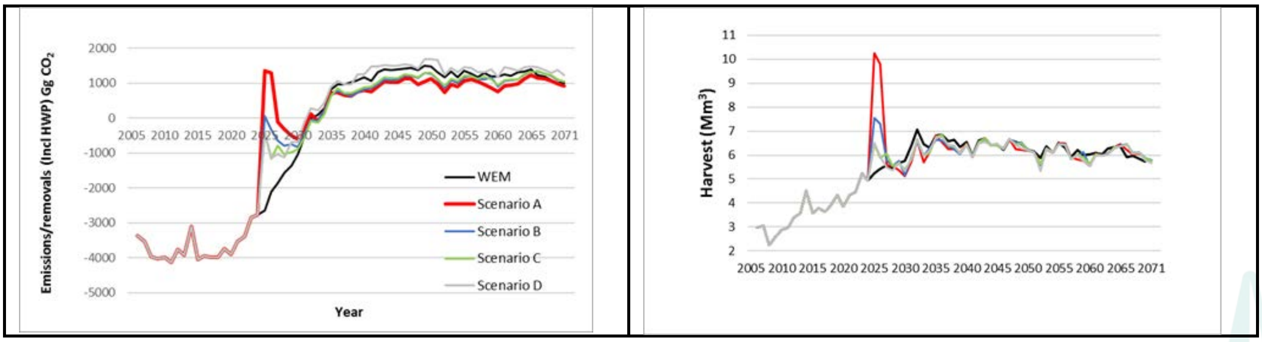

Figure 26. Windthrow impact on the forest sink in Ireland. Effects are shown for storm Darwin in 2014 and the GHG net removal/emission profiles for the WEM and four windthrow scenarios following storm Éowyn in 2025.

In the longer term (2031–2070), however, model results suggest that emissions under Scenario A are lower than under WEM. This is because less scheduled timber remains available for harvest after the salvage logging, and the NAI of the forest estate increases after 2045 due to forest regeneration and shifts in age-class structure (data not shown). Nevertheless, Scenario A is the least likely outcome, since the sector lacks the capacity to harvest 10 Mm^3 per year and export markets may be insufficient to absorb the additional timber without negatively affecting prices.

Scenario B also appears unlikely, as analyses by DAFM and Coillte indicate that even with additional harvesting contractors from the UK and Europe, national capacity in 2025 would be limited to 6.5 Mm^3. Scenario C, by contrast, seems the most plausible outcome, since it stays within this harvest capacity threshold (Figure 26). In this scenario, 75% of the currently scheduled harvest would need to be deferred to ensure sufficient capacity for salvage logging.

Under Scenario C, forests and HWPs remain a slight sink of −94 Gg CO_2eq in 2025. However, compared with the WEM scenario, this represents a reduction of 5,294 Gg CO_2eq in sink strength over 2025–2030 (Figure 26). In the long term (2031–2070), total emissions are also lower under Scenario C, by 5,406 Gg CO_2eq relative to the WEM scenario. This outcome is again linked to reduced timber availability for harvest and higher NAI resulting from forest regeneration after storm Éowyn. When scenarios D and C are compared, there is not much of a difference in removals or harvest in the short term (up to 2030), but scenario D has a higher emission profile after 2040 due to pest and disease mortality assumptions.

Our results suggest that the most likely impact of storm Éowyn (Scenarios C or D) will significantly reduce the Irish national forest sink. Under scenario C, Storm Éowyn is expected to add approximately 5,000 Gg CO_2 to the estimated EU LULUCF target deficit of 4,756 Gg CO_2 for the 2026-2030 compliance period (Black et al., 2025). Under the EU LULUCF regulation, flexibility mechanisms do not account for natural disturbances if salvage logging is carried out. Therefore, it is now highly unlikely that Ireland will meet its allocated 2030 target under Regulation (EU) 841/2023.

3.4.3. CBM Italy

This section describes the assessment and simulation of various disturbance events in Italy between 2000 and 2023.

Disturbance events include harvesting, natural disturbances, and land-use change activities. Harvesting includes ordinary silvicultural activities and salvage logging after natural disturbances. In Italy, natural disturbances include wildfires, windstorms, and biotic disturbance events, such as bark beetle outbreaks. Land-use change activities include afforestation (AR), deforestation (D).

Determining the annual harvest amount in Italy is a challenge due to the lack of official national statistics and the uncertainty in various data sources (Pra & Pettenella, 2016; Mariano & Seri, 2018; Pettenella et al., 2021; Pilli et al., 2021). For this reason, we performed an ad hoc assessment of the harvest amount in Italy between 2000 and 2023. This analysis was based on the integration of National Forest Inventory data with yearly time series derived from remote sensing data (Pilli et al., submitted). Starting from the total amount of fellings estimated at the national and regional levels, we inferred the total amount of removals used to define the input data expected by the model, assuming a constant correction factor equal to 0.85, to account for logging residues (Table 11).

Table 11. Removals definition for Italy.

Year	Tot Fellings (m3 103)	Removals = Fellings * 0.85
2005	13,701	11,646
2006	16,390	13,931
2007	15,663	13,314
2008	12,583	10,696
2009	11,807	10,036
2010	12,467	10,597
2011	12,786	10,868
2012	13,486	11,463
2013	11,161	9,487
2014	10,450	8,882
2015	12,151	10,328
2016	11,762	9,998
2017	11,131	9,461
2018	11,013	9,361
2019	11,638	9,892
2020	12,624	10,731
2021	11,222	9,539
2022	13,313	11,316
2023	13,143	11,171

Total removals scaled at the regional level were further distributed between various FT, MT, MS and disturbance events, based on the following steps:

1. The annual amount of harvest (H_y) was distributed between coniferous (C_y) and broadleaves (B_y) species according to the relative share of coniferous (FAO_C) and non-coniferous (FAO_{NC}) roundwood removals reported, for each year (y) and FAOSTAT series:

$$C_y = H_y * FAO_C \quad \text{Eq. (8)}$$

$$B_y = H_y * FAO_{NC} \quad \text{Eq. (9)}$$

2. We estimated the harvest share for each region (r) in 2005 (P^r_{2005}) and 2015 (P^r_{2015}) using the total fellings reported by INFC 2005 and 2015 (see tab. 1.11.1, INFC data, excluding plantations). The distribution within the intermediate period 2006 – 2014 was inferred as a linear interpolation between 2005 and 2015. Between 2016 and 2018, we applied the share reported by INFC 2015. Since 2019, the harvest shares were modified according to the specific assumptions linked to salvage logging activities carried out after the windstorm occurred in autumn 2018.
3. We estimated the share of harvest provided by plantations in 2005 and 2015 (PL_{2005} and PL_{2015}) by comparing the total fellings reported by INFC 2005 and 2015 for plantations with the amount of fellings assigned to the total forest area. The data series was not scaled to the regional level due to the high uncertainties of INFC data for this forest category. The distribution within the period 2006 – 2014 was inferred as a linear interpolation between 2005 and 2015 (see Figure 6, last group). From 2016 onward, we applied the share reported by INFC 2015.

4. We estimated the absolute amount of expected harvest by species' group (Hb_y^r and Hc_y^r for coniferous and broadleaves species, respectively), year (*y*), and region (*r*), excluding the amount of harvest assigned to plantations for the same year (PL_y) by combining the amount of harvest assigned to broadleaves and coniferous species as determined on point 1 (C_y and B_y), with the annual share of fellings assigned to each region (P_y^r), :

$$Hb_y^r = B_y * P_y^r * (1 - PL_y) \quad \text{Eq. (10)}$$

$$Hc_y^r = C_y * P_y^r * (1 - PL_y) \quad \text{Eq. (11)}$$

5. Based on the forest area available for wood supply (i.e., excluding FNAWS) as defined within the inventory table, we estimated the share of area assigned to each FT, MT and MS, within each region and species' group ($Prop_{FT\_MT\_MS}$), excluding poplar, broadleaves and coniferous plantations as far as the "special" MT.
6. The amount of harvest defined on point 4 was proportionally distributed between each FT, MT and MS according to the share defined on point 5.
7. We defined a preliminary dataset with about 100 potential silvicultural treatments and different harvest intensities for each combination of FT, MT and MS within different age class intervals.
8. The amount of harvest assigned to each region/FT/MT/MS on point 6, was further distributed between different disturbance events (i.e., essentially thinnings and final cuts for even-aged forest stands), according to the relative proportion of area available, at the beginning of the model run (i.e., time step 0, as reported within the inventory tables), under (for thinnings disturbance events) and over (for final-cuts) the minimum rotation length associated to each FT.
9. The amount of harvest assigned to each region/FT/MT/MS/disturbance event on step 8, was further converted to merchantable carbon (expected as input within the disturbance event table) by using species-specific WD values, taking into account also of the extra amount of harvest associated, for each disturbance event, to removals of stem snags and other wood components (i.e. branches, as quantified within the disturbance matrix associated to each disturbance event). These amounts were computed through a preliminary model run.
10. Harvest assigned to plantations was computed with a similar approach and added to the previous data set, providing a preliminary disturbance event table, including the total amount of harvest (in t of C) expected within the calibration period, distributed between various region/FT/MT/MS/disturbance events. These data were used for a preliminary model run.
11. The output of the preliminary model run was further compared with the amount of harvest expected by the input data defined on step 10 and, if needed, further corrected for each time step, redistributing to other groups (i.e., coniferous and broadleaves groups) the harvest not provided by some region/FT/MT/MS/disturbance events. The resulting database was finally used as a disturbance event table for the calibration period.

In autumn 2018, an extra-tropical windstorm Vaia felled about 9.5 million m^3 of merchantable wood in Northern Italy. Vaia is regarded as the most severe windstorm to hit Italy since World War II (Motta et al., 2018). Although there is uncertainty about the total volume of roundwood removed in Italy in recent years, we can speculate that the merchantable stock directly damaged by Vaia accounted for at least 60% of the total roundwood removed in 2018. Based on the most recent data reported by the three regions most affected by the storm (i.e., AA, Tn, and Ve), together with additional information from the literature, Vaia damaged approximately 52 kha of forest (Pilli et al., submitted). The storm primarily affected pure Norway spruce stands, and mixed Norway spruce – Silver fir and Norway spruce – European beech stands.

The effect of Vaia was simulated through four different disturbance events, with an increasing share of living biomass moving to DOM pools (Table 12), further distributed between different administrative units and FTs according to the general assumptions already suggested by Pilli et al. (2021). Within the present study, the area and minimum merchantable C stock affected by each disturbance class were recalibrated to match the total area and volume affected by Vaia within each region, using the latest data available from the literature, mostly reported at the regional level.

Table 12. Disturbance event definition. DOM stands for dead organic matter.

Disturbance event	Share of biomass moved to other pool	Applied to
Damage class I	15% from merch. biomass to DOM	2018 & 2020/21
Damage class II	40% from merch. biomass to DOM	2018 & 2020/21
Damage class III	70% from merch. biomass to DOM	2018 & 2020/21
Damage class IV	95% from merch. biomass to DOM	2018 & 2020/21
Salvage logging after a windstorm	90% from snag stems (DOM) to product pool	2019 – 2023

Salvage logging carried out in 2019 and 2020 was simulated with a specific silvicultural treatment, moving to the products pool 90% of the merchantable standing dead-biomass (snag stems) made available on the area affected by Vaia. The area affected by this event was calibrated in order to match the amount of salvage logging reported by literature for each region and FT within the simulation period 2019-2020.

For the administrative units Tn and AA, we mostly used data directly provided by local authorities. For other administrative regions, we assumed that the damaged forest area distribution by FT and damage intensity classes follow the same pattern as reported for the Tn region. See Pilli et al. (2021) for more information.

For the Ve, Tn, and AA regions, we assumed that after salvage logging, 30% of the forest area originally covered by spruce stands (PA) and fir stands (AA) in the Ve region was replaced by beech forest stands (FS), while 15% in the AA and Tn regions was replaced.

We introduced additional disturbance events for the period 2020-2023, along with salvage logging in the same regions affected by Vaia. According to recent studies (Battisti, 2024), since 2020 the regions affected by Vaia have also experienced a bark beetle outbreak, driven by the large volume of dead wood material and favorable climatic conditions, the same regions affected by Vaia were also affected by a bark beetle outbreak, mostly concentrated within the period 2021 - 2023 (Nardi et al., 2022), and the overall volume affected by this event was similar to the one affected by Vaia.

Wildfires are the main disturbance event affecting Italian forests, mostly within the Mediterranean and Pre-Alpine regions. The forest area affected by wildfire was estimated from the Forest Information System for Europe (FISE) data reported for each administrative region. This area, which also includes the land use categories *Other Wooded Land* and *Grasslands*, was scaled against the total area affected by fire, as reported by the Italian Country Report Format (CRF) tables for the category Forest Land (Italy CRF Tables, 2023). This way, we preliminarily excluded wildfires occurring on non-forest lands.

Because FISE does not report data after 2015, from 2016 onwards, we proportionally distributed the burned area reported by the CRF tables across administrative regions over the derived average burned area, for each region, for the period 2010-2015. The total forest area affected by wildfires within the calibration period 2005 – 2023 was further distributed between two disturbance events, representing crown fires and underwood fires, as defined by INFC 2005. For this purpose, we directly inferred from INFC 2005 the proportion of area affected by crown fires and underwood fires within each administrative region, and we assumed this proportion to be constant for the entire simulation period. Crown fires were associated with a stand-replacing disturbance event affecting 80% of living biomass pool, including 5% of salvage logging on merchantable standing stock. Underwood fires were associated with a disturbance event, mostly affecting dead wood and litter pools, and only 20% of merchantable living biomass. Within each region, the forest area assigned to crown and underwood fires was finally distributed, for each time step, proportionally to the forest area available and not available for wood supply, further distinguished between broadleaves and coniferous FTs, as inferred from the inventory database.

4. Model developments

4.1. GLOBIOM/G4M-X

A series of updates has been implemented into the GLOBIOM/G4M model to enhance its capability to represent climate change impacts, adaptive forest management, biodiversity considerations and carbon storage outside forests. We refer to the updated model as GLOBIOM/G4M-X hereafter.

4.1.1. Age class distribution and forest management

Forest age-class dynamics have been recently implemented into GLOBIOM (HEU CLEVER – D7.2), which improves the integration of climate impacts and disturbance occurrence into the model. In this context, for each grid cell, GLOBIOM employs an initial distribution derived from Besnard et al. (2021). Each grid consists of multiple even-aged stands, which are divided into different age cohorts according to these datasets. If the stand area is harvested or damaged by natural mortality, the stand area is moved to the first age cohort. After 2020, the age-class distribution evolves endogenously based on periodic harvest volumes, growth curves, mortality and forest area changes (deforestation/afforestation). To maintain the sustainability of harvest volumes over time in the recursive dynamics, the model includes two additional constraints: i) harvested volume must be lower than the biomass increment, and ii) cohorts younger than the optimal rotation time are not harvested. Hence, sustainable forest management is enforced for each grid cell, ranging from 0.5° to 2.5° (approximately 50x50km to 250x250km around the equator).

The data from Besnard et al. (2021), however, has an age class distribution inconsistent with the EU forest inventory data, with missing areas in the youngest cohorts. An initial correction was made to rebalance the age classes and increase the area of the youngest cohorts. We have recalibrated the model with an NFI-based age class map for the EU (Pucher et al., 2022). Figure 27 compares the original data from Besnard et al. (2021) with the new dataset employed (updated).

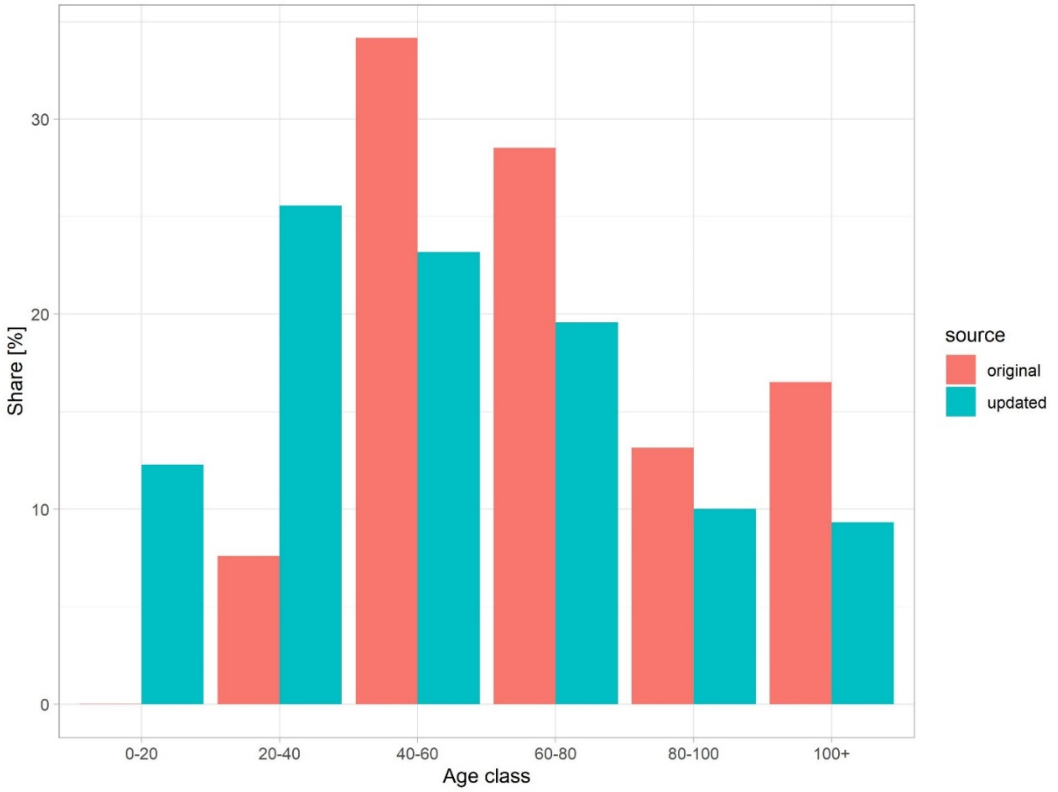

Figure 27. Comparison of age class distributions from Besnard et al. (2021)- original and Pucher et al. (2022) - updated.

Figure 28 displays changes in the age class distribution affected forest dynamics and the total forest sink in the EU27. Using the updated dataset, the forest sink increases up to 9 MtCO²eq by 2040, due to the larger share in younger and faster-growing forests in the updated dataset, which is more consistent with NFI observations. After 2040, differences decreased due to the effect of forest management and harvesting, which brought the age class distribution closer together.

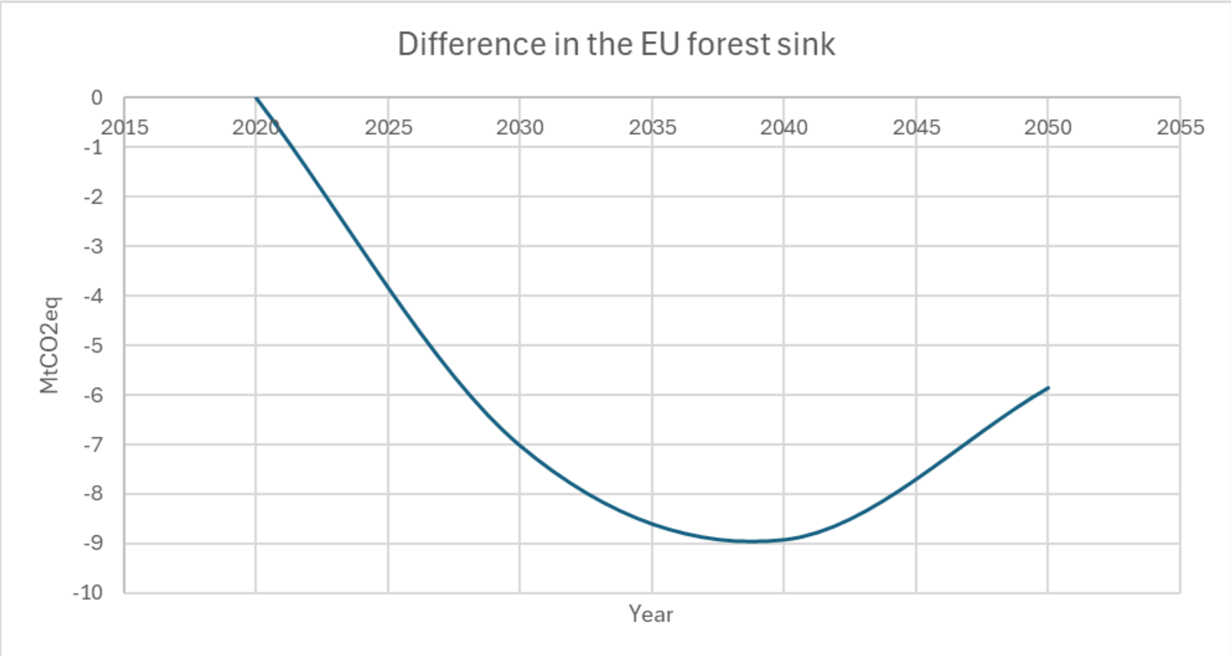

Figure 28. Differences in the EU forest sink.

4.1.2. Climate change impacts

Incorporating the impacts of climate change into forest management decisions is essential to guide policy impact assessments and the development of the forest sector in the future. Forest ecosystems are sensitive to changes in temperature, precipitation patterns, and the frequency and intensity of extreme weather events—all of which are projected to intensify with ongoing climate change in Europe and globally. These shifts directly affect tree growth rates, which cascade to wood availability, as well as the contribution of forest ecosystems to climate and biodiversity conservation targets. Moreover, climate change influences not only the biophysical aspects of forests but also the socioeconomic dynamics of the forest sector. Hence, climate change has important implications for global wood markets and may cause shifts in production, consumption and trade patterns. By integrating climate scenarios and adaptive responses, we can evaluate the effectiveness of different management strategies to cope with climate impacts. This allows policymakers, landowners, and industry stakeholders to make informed, risk-aware decisions and fulfil environmental objectives like climate mitigation and ecosystem services.

To account for the impacts of climate change in GLOBIOM, we expand the approach developed in Augustynczik et al. (2025) and Pilli et al. (2022), based on the application of forest growth shifters. We start by simulating biophysical impacts of climate change on forest growth, using different General Circulation Models (GCM) and Representative Concentration Pathways (RCP) combinations from ISIMIP3b (Table 13). We simulate forest dynamics for each climate scenario and under alternative forest management scenarios for the EU, with varying management intensity using the i3PGmiX model (see https://www.forestnavigator.eu/wp-content/uploads/FN_D3.2_ModelPrototype_corrected-typos.pdf).

Table 13.Climate change scenarios.

Scenario	GCM	RCP
Historical	-	-
RCP26_GFDL-ESM4	GFDL-ESM4	RCP2.6
RCP26_IPSL-CM6A-LR	IPSL-CM6A-LR	
RCP26_MPI-ESM1-2-HR	MPI-ESM1-2-HR	
RCP26_UKESMM1-0-LL	UKESMM1-0-LL	
RCP45_GFDL-ESM4	GFDL-ESM4	RCP4.5
RCP45_IPSL-CM6A-LR	IPSL-CM6A-LR	
RCP45_MPI-ESM1-2-HR	MPI-ESM1-2-HR	
RCP46_UKESMM1-0-LL	UKESMM1-0-LL	
RCP70_GFDL-ESM4	GFDL-ESM4	RCP7.0
RCP70_IPSL-CM6A-LR	IPSL-CM6A-LR	
RCP70_MPI-ESM1-2-HR	MPI-ESM1-2-HR	
RCP70_UKESMM1-0-LL	UKESMM1-0-LL	
RCP85_GFDL-ESM4	GFDL-ESM4	RCP8.5
RCP85_IPSL-CM6A-LR	IPSL-CM6A-LR	
RCP85_MPI-ESM1-2-HR	MPI-ESM1-2-HR	
RCP85_UKESMM1-0-LL	UKESMM1-0-LL	

Note: GCM = General Circulation Model, RCP = Representative Concentration Pathways

Based on the simulation outputs, we create forest growth shifters by comparing the forest increment of a certain climate scenario and management with the corresponding increment under the historical climate (Figure 29).

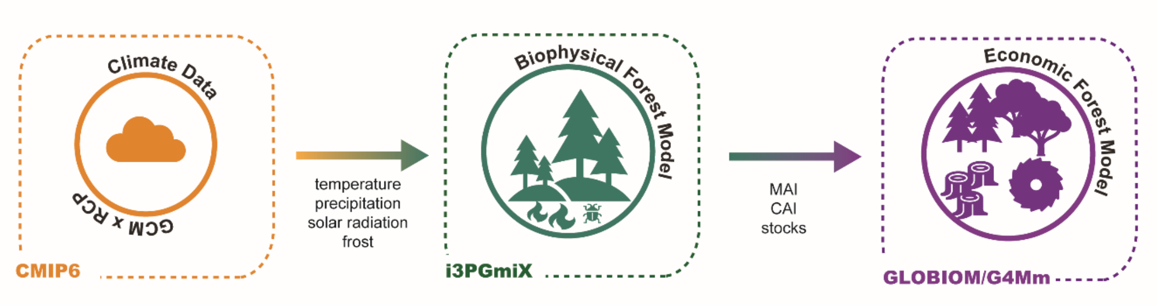

Figure 29. Schematic representation of the inclusion of climate change impacts in GLOBIOM/G4M. Source: Augustynczik et al. (2025).

At the global level, the climate change shifters are derived from the ORCHIDEE-MICT model (https://www.isimip.org/impactmodels/details/280/), based on the ISIMIP3b simulation round, for the same climate change scenarios, using the forest net primary productivity as a productivity indicator.

These climate shifters are then subsequently used in GLOBIOM/G4M to correct the underlying increment estimates in each grid cell of the models. Furthermore, the standing stocks of each forest cohort are also dynamically updated in order to reflect changes in productivity and mortality rates due to climate change impacts. The latter constraint is the timber availability for harvesting in each time period. Both the standing stock and increment changes due to climate change cascade to wood markets and forest management decisions in GLOBIOM/G4M.

Figure 30 and Figure 31 show the preliminary results of integrating climate change impacts computed by the biophysical models into GLOBIOM. Changes in forest productivity due to climate change cascaded to management intensity in the EU, as well as changes in the management portfolio in the region. The harvested volume increased until midcentury in the EU, with a stable trend until 2070. Higher biomass demand under RCP1.9 led to an increase in harvesting intensity and removals. Changes in productivity due to climate change led to a variation in the total harvested volume of approximately 7% by 2070 for the low bioenergy demand scenario. Under high mitigation ambition, however, differences in harvested volume due to climate change impacts amounted to nearly 100 million m^3. In general, scenarios with increased productivity in the EU, such as in GFDL-ESM4_RCP70, resulted in increased harvests and reduced harvesting intensity compared to the historical climate baseline.

In addition to alterations in the management intensity and removals, climate change impacts caused a shift in the regional allocation of production. In the EU, climate change impacts on productivity vary regionally, where productivity increases were observed in the biophysical model simulations in the boreal zone and higher elevations in Central Europe. Conversely, areas in the Mediterranean and Southeastern Europe displayed a decrease in productivity, especially in more intense climate change scenarios. In this context, production shifted towards areas with increased productivity in Fennoscandia, while a lower production was observed in areas with more negative climate impacts in the Mediterranean (Figure 31). This was also reflected in wood prices, which increased in those areas, especially for non-coniferous sawlogs, while pulplogs showed a price decrease generally, due to the higher disturbance activity and availability of lower quality wood.

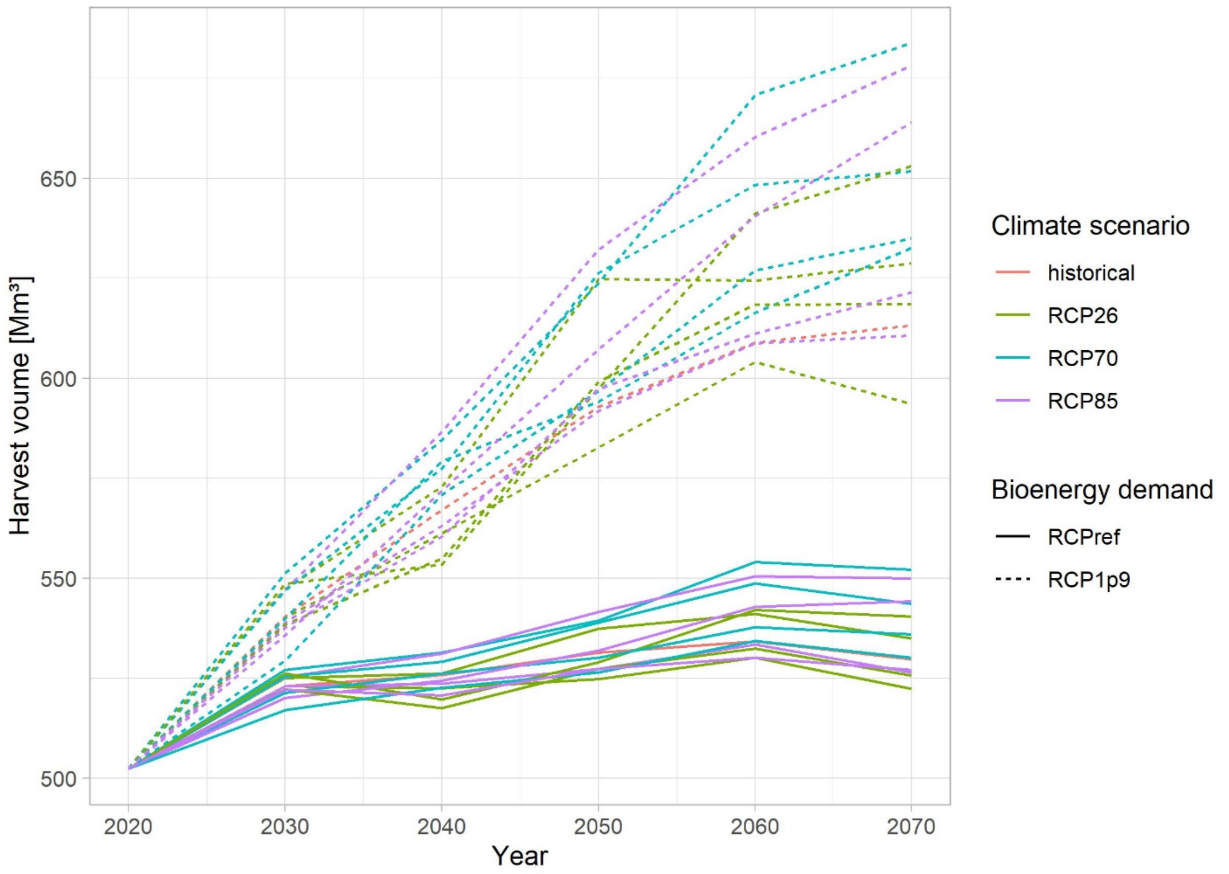

Figure 30. Climate change impacts on the EU harvest volume.

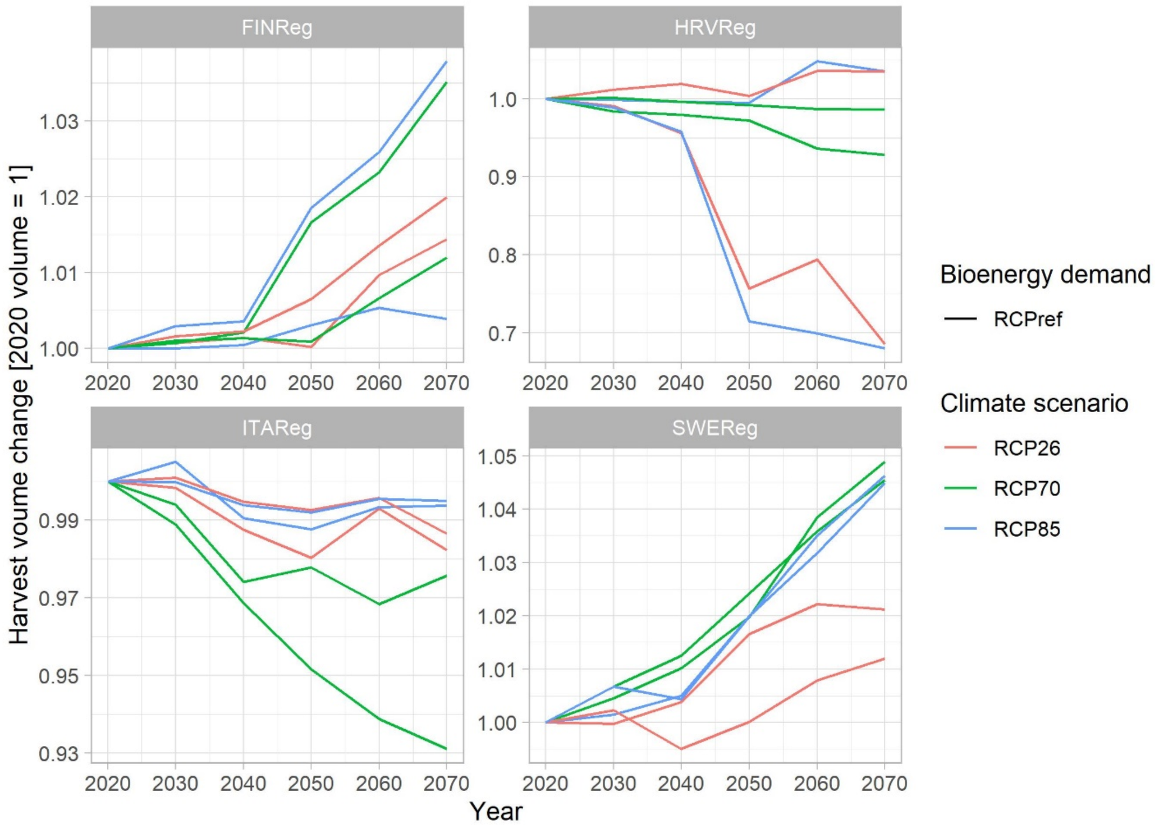

Figure 31. Climate change impacts on selected EU member harvest volume. FINRed=Finland, HRVReg = Croatia, ITAReg=Italy, SWEReg=Sweden).

4.1.3. Calibration of management intensities

Similarly, the thematic resolution of forest management has been expanded in GLOBIOM (HEU CLEVER – D7.2) to include different forest management intensity classes. In this context, forests are divided into three types: plantation forests, seminatural forests, and natural forests, which are also subdivided into coniferous and broadleaved forests. Within each forest class, seven management systems are available:

- PriFor: primary forests
- Cur0: unprotected secondary forest
- CurS: protected secondary forest
- CurC/CurNC: business-as-usual (BAU) management for coniferous/broadleaved
- CurC_M/CurNC_M: multifunctional management for coniferous/broadleaved
- CurC_L/CurNC_L: close-to-nature management for coniferous/broadleaved
- CurC_H/CurNC_H: plantation forestry for coniferous/broadleaved

The harvesting intensity for each management class is computed based on a fixed share of the BAU harvesting intensity for the EU. Here we have recalibrated the harvesting intensity shares for each country based on biophysical simulations conducted with the i3PGmiX model described in the previous section, modifying bottom-up silvicultural rules for thinning intervals, thinning intensity and rotation lengths. We then mapped these changes in silvicultural rules to the GLOBIOM management classes, where intensive management was mapped to the BAU management, where fellings are close to the increment, decreased intensity was mapped to multifunctional forest management class (increase in rotation length and reduction in thinning intensity) and the lowest management intensity (further increase in rotation length and reduction in thinning intensity, conversion to continuous cover forestry) was mapped to close-to-nature management. The increment shares from the bottom-up simulations were then applied at the country level in GLOBIOM to replace fixed shares (Figure 32) and were tailored for each climate change scenario.

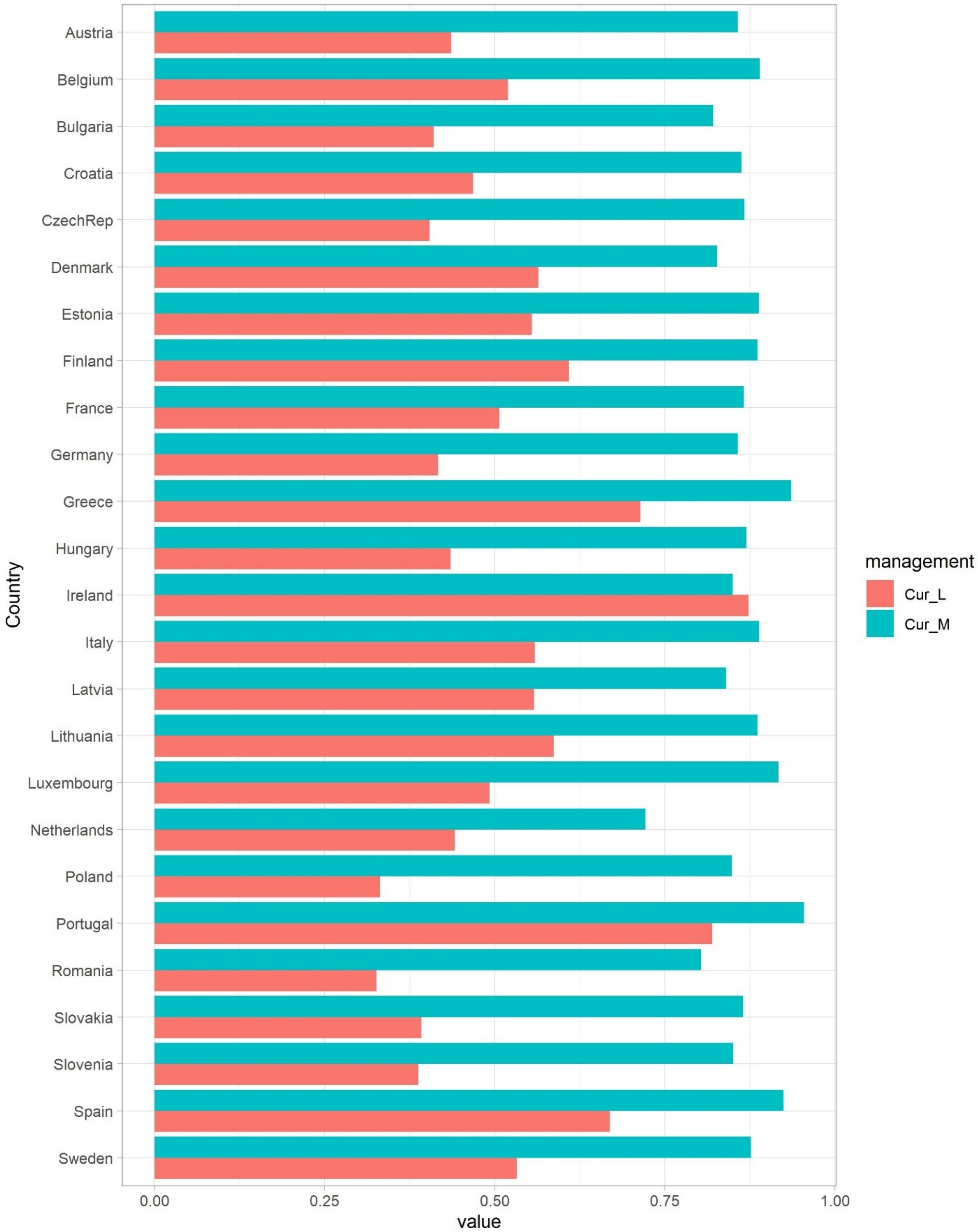

Figure 32. Calibration of forest management intensities.

4.1.4. Biodiversity impacts of forest management decisions

Considering biodiversity impacts in forest management decisions is essential for maintaining ecosystem health, resilience, and the long-term sustainability of forest landscapes. Biodiversity underpins key ecological processes such as nutrient cycling and pest control, all of which support forest productivity and stability. Disregarding the impacts of forest management decisions on biodiversity can lead to habitat degradation, species loss, and reduced ecosystem services. In contrast, promoting biodiversity helps safeguard ecological integrity and enhances forests' ability to adapt to stressors like climate change.

In this context, we have coupled the outcomes of the iBIS.iSDM model (https://www.forestnavigator.eu/wp-content/uploads/FN-D4.3-iBIS_final.pdf). iBIS.iSDM generates species-specific areas of habitat for multiple forest taxa based on climatic parameters and forest structural features, such as deadwood stocks, standing volume, among others. In an initial step, species richness considering all taxa was generated based on coupled simulations with i3PGmiX, for the same management regimes considered in the recalibration of management intensities. The changes in species richness were then mapped from these management to the GLOBIOM management classes (including forest development without management) and applied to the model, in the corresponding climate scenarios (different GCM and RCP combinations). The changes in species richness are then computed based on the forest management portfolio in the solution at each time step, disregarding the temporal dynamics of the transitions within the 10-year time steps considered in the model.

Figure 33 shows the trends in forest species richness for different climate scenarios for the EU and for member states. Trends emerge from both climate trajectories and the area under different management intensities, in addition to local species composition. At the EU27 level, species richness remained stable, with a slight increase towards the end of the century. However, more intense climate change under RCP7.0 and RCP8.5 led to lower species richness levels, compared to RCP2.6.

Although species richness remained stable at the EU27 level, at the country level, the trends diverged. For example, in Fennoscandia and Central-Western Europe, changes in species richness were minor, with slight decreases in Sweden and Germany. In General, countries in Eastern Europe and the Mediterranean showed higher sensitivity for species richness with gains up to 20-40% by the end of the century (Figure 33).

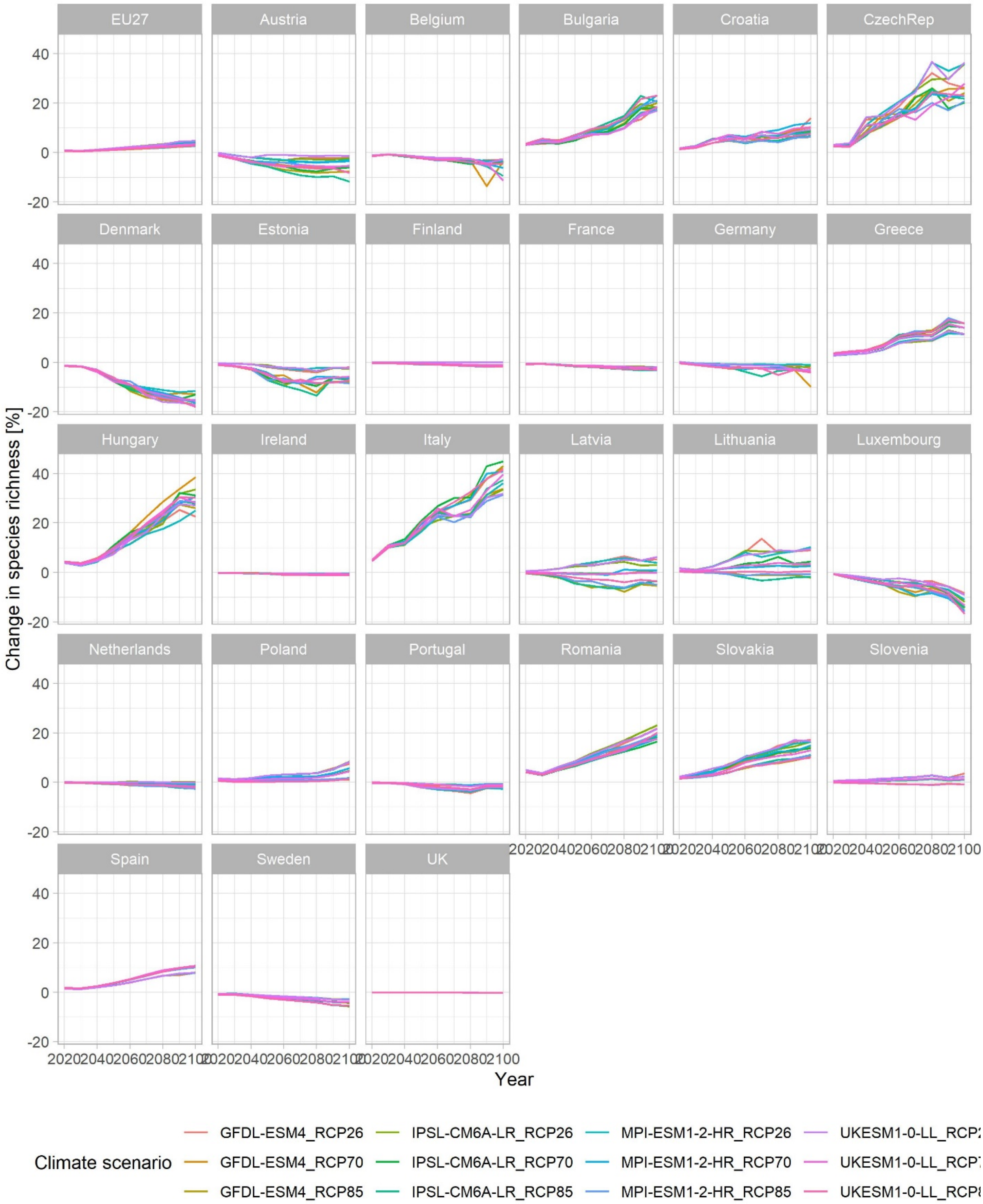

Figure 33. Biodiversity impacts expressed as changes in species richness along the simulation period, compared to the year 2015.

4.1.5. Climate feedback from afforestation and forest management

Considering local climate feedback is crucial when evaluating the impacts of afforestation, as these effects can influence broader climate outcomes. While afforestation promotes carbon sequestration potential, the local biophysical effects, such as changes in albedo, evapotranspiration, and surface roughness, can either amplify or offset the intended climate benefits in terms of local temperatures. For example, afforestation with coniferous species in snow-covered regions can reduce surface reflectivity and lead to local warming, despite increased carbon uptake. Similarly, afforestation in dry regions may alter water balances and reduce streamflow, potentially stressing ecosystems and human water needs. Therefore, afforestation strategies should not only account for carbon storage but also integrate local climate dynamics to ensure that land-use decisions provide net environmental benefits across spatial and temporal scales.

To address these aspects in the pathways computed by GLOBIOM/G4M, we have coupled the afforestation outputs to the MESMER-L-X climate emulator (ForestNavigator D4.5 - MESMER-L-X climate feedback emulator at the service of EU forest policy modelling). MESMER-L-X leverages simulations of COSMO-CLM² to emulate local temperature effects of afforestation and deforestation, including forest type characteristics, namely the conversion to broadleaved or coniferous forests. We coupled the model with the outputs from GLOBIOM/G4M, in terms of afforestation and deforestation areas in 0.5° resolution along the simulation period. For each grid cell, we then evaluate the land cover transitions, considering:

1. Forest to bare land
2. Forest to cropland/grassland
3. Cropland/grassland to coniferous forest
4. Cropland/grassland to broadleaved forest

The areas of these transitions are fed together with local climate data to derive temperature anomalies due to afforestation/deforestation decisions. Monthly outputs for the reference scenario are shown in Figure 34. The preliminary results show a pattern of decreasing local temperatures during summer, while temperature during winter is generally increased by afforestation decisions. The decrease in local summer temperatures is more pronounced in the Mediterranean regions, where the share of afforestation with broadleaf forests is larger, which have more beneficial climate effects, and the increase in evapotranspiration leads to cooling due to changes in latent heat. The magnitude of afforestation impacts is limited, however, due to the moderate afforestation share in the grid cells. More pronounced climate effects, with up to 1 °C changes in mean monthly temperatures, could be obtained in case larger afforestation areas are considered (the entire grid cells). On the other hand, maximum monthly temperatures may increase with increasing afforestation areas.

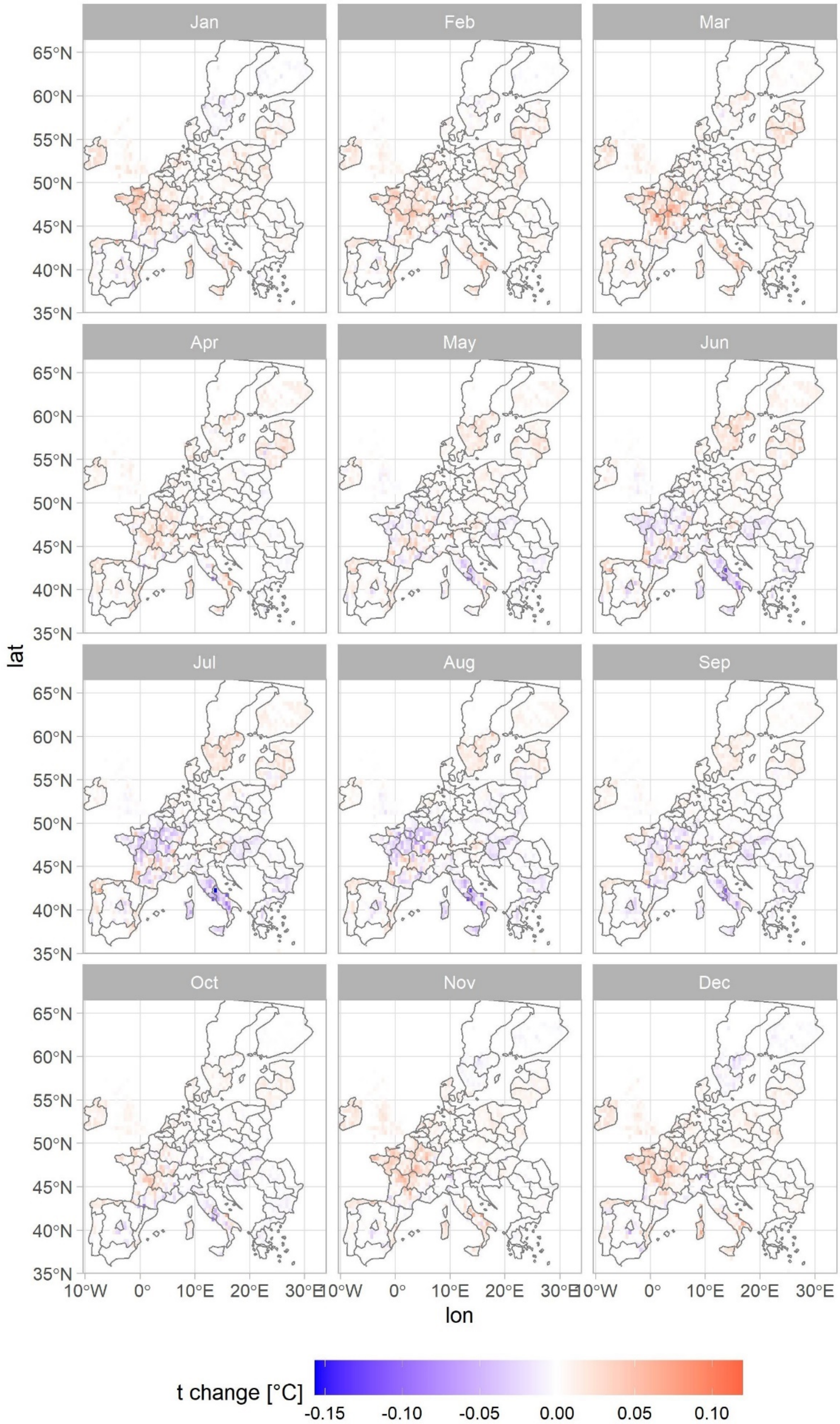

Figure 34. Local temperature effect of afforestation and deforestation.

4.1.6. HWP calculator

A HWP calculator has been developed for post-hoc assessment of HWP (Harvested Wood Products) emissions and removals based on the output from GLOBIOM wood production and trade volumes. The calculator is based on the IPCC (2019) "Production Approach" to be linked to the production volumes and trade volumes from GLOBIOM scenarios results and annualising the impacts on the HWP carbon pool emissions. The calculator applies to the IPCC (2019) Tier 1 first-order decay method, where the carbon remaining in each semifinished product class declines exponentially over time. Specifically, the exponential decay function Equation 12.2 of the IPCC (2019) is used to calculate biogenic CO_2 emissions and removals based on changes in the relevant carbon stocks for the selected approach.

Accordingly, the calculator quantifies annual carbon stock changes in wood products by combining long-term forest harvest projections from GLOBIOM with historical FAOSTAT calibration data. GLOBIOM provides 10-year step projections (e.g., 2000, 2010, 2020...2100) for semifinished products categories at national levels. These are linearly interpolated to annual values for smooth HWP stock and emissions tracking in the assessment of the HWP pool change.
The HWP calculator covers six semifinished wood product categories, each associated with distinct carbon storage characteristics, i.e., Sawnwood, Wood-based Panels, Paper and Paperboard, Dissolving Pulp, Other Wood Biomass, and Energy wood.

GLOBIOM-projected volumes for semifinished products are further translated into carbon using product-specific IPCC (2019) default conversion factors (e.g., 0.225 tC/m^3 for coniferous sawnwood).

Half-life times assumed for the decay of the harvested wood products are the default ones according to IPPC (2019) and set as:

- Sawnwood: 35 years
- Wood Panels: 25 years
- Paper & Pulp: 2 years
- Dissolving Pulp: 2 years
- Other Wood Biomass: 6 years
- Energy Wood: 0 years (assumed instant oxidation unless BECCS is applied)

The calculator initializes the HWP carbon stock pool according to historical FAOSTAT production data from 1961–2020 retrieved by country. From 2021 onward, the volumes are linearly interpolated from GLOBIOM 10-year time steps projections by country and semifinished product.
To align with IPCC reporting under the "Production Approach" only domestically produced HWP originating from domestic harvest (primary products are considered). In the case of GLOBIOM, the historical trade data (e.g., from FAOSTAT and COMTRADE) informs the ratio on semifinished products that are obtained from domestically harvested wood for each product and country. Accordingly, the relevant domestic feedstock factors for calculating the share of HWP from domestic harvest, i.e. in order to exclude carbon in imported HWP, are calculated by using Equation 12.8 from the IPCC (2019).

For energy-related wood products, the default assumption is an immediate oxidation; however, this condition can be changed in the calculator, where a dynamic share of energy wood is routed through Bioenergy with carbon capture and storage (BECCS) pathways, using scenario-specific assumptions derived from energy models (e.g., PRIMES, MESSAGE).

The GLOBIOM HWP calculator, based on the information above, produces annual values for:

- Carbon inflows (new products entering the pool)
- Outflows (carbon decayed/emitted)
- Net stock change (HWP emissions)

The calculator was deployed for projection at the Member State level for EU27 of the Baseline scenario “ForestNavigator D5.1 RCP1p9_12”.
This “Baseline scenario” extrapolates the latest development in the field of bioenergy demand and the use of wood in the construction sector while maintaining baseline development in recycling rates for mechanical wood fibres. Under this scenario, at the EU27 level, there is an increase in roundwood harvest (sawlogs, pulpwood and fuelwood) of 13 % between 2020 and the 2040s decade due to both an increasing demand for bioenergy and for wood for the construction sector, with the harvest level stabilising afterwards (by 2050). Looking only at the production of industrial roundwood (sawlogs and pulpwood), it increased by 18 % during the same period.

According to GLOBIOM projections, when considering the sum of the EU27 country projections, the HWP pool sink would increase from – 38 $MtCO_2$ in 2020 to a maximum value of -58 $MtCO_2$ in 2030 and to a value of -37 $MtCO_2$ in 2050 (Figure 35). The future “trend” in HWP sink appears to be well aligned with the one observed in the projection of the WoodCarbonMonitor (see ForestNavigator D5.1) based on the same production and trade input. Compared with the WoodCarbonMonitor, projections in GLOBIOM generally appear smoother. This is because the WoodCarbonMonitor was recalibrated every 10 years using GLOBIOM production and trade data, whereas GLOBIOM applied linearly interpolated values in the HWP calculator.

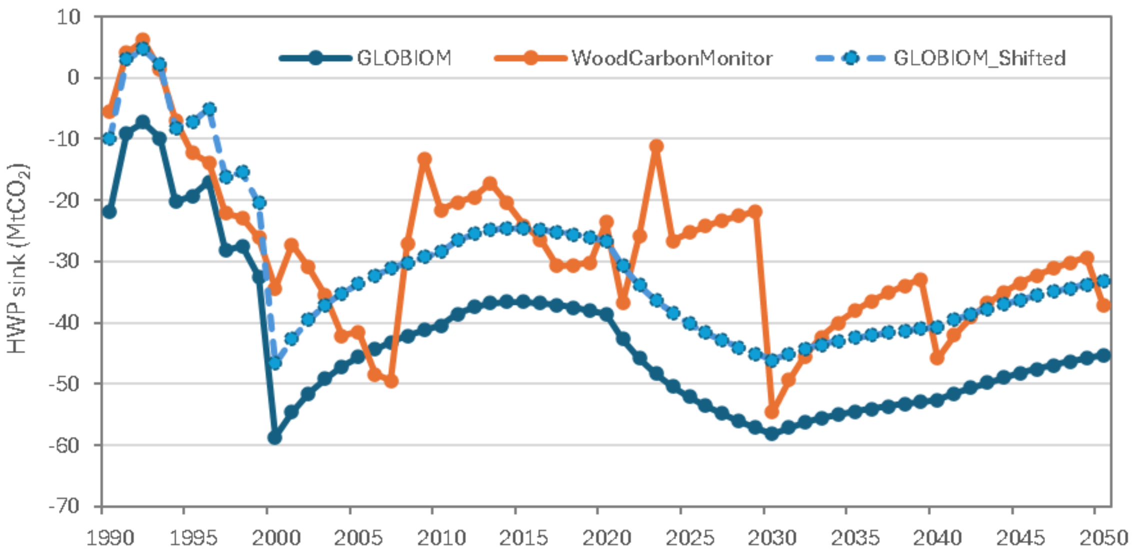

Figure 35. Comparison of EU27 HWP emissions and removals historical calibration (1990-2020) and projection (2020-2050) according to GLOBIOM HWP calculator and WoodCarbonMonitor under the Baseline scenario. GLOBIOM_shifted represents the shift of GLOBIOM projections for HWP according to the average difference to WoodCarbonMonitor in the GLOBIOM calibration period in the figure (1990-2020).

Historically, the GLOBIOM HWP calculator shows an average sink that is 11.9 MtCO2 higher than the WoodCarbonMonitor for the period 1990-2020. If we apply this historical difference (shifter) to the GLOBIOM HWP projection (GLOBIOM_Shifted) in Figure 35 the two projections become well aligned both in “trends” and “level” for future periods after the year 2023 (the latest year, where WoodCarbonMonitor uses statistical data for calibration). The difference observed in the “level” between the two calculators is due to their different levels of detail, where the

WoodCarbonMonitor considers a larger number of wood products in its calibration, more detailed decay factors and includes more national data for calibration of historical and trade volumes.

4.2. Climate change impacts in MS models

We applied a similar approach used for GLOBIOM/G4M-X to account for climate change impacts in the MS models, following Pilli et al. (2022). The same set of simulations conducted with i3PGmiX was employed to quantify growth shifters along the simulation period (2020-2070). These shifters were subsequently applied to the MS modelling frameworks to assess the implications of climate change impacts on MS forest productivity and forest sink.

4.2.1. CBM Czech Republic

In the current GHG emission inventory of the LULUCF sector in the Czech Republic (CHMI, 2025), the climate change impact is included indirectly within the observed effect on the growth of tree species. The input information comes from the compilation of the current annual increment (CAI) assessment based on the growth indices (i.e., species-specific growing stock–age relationships) and the national growth and yield tables (Černý et al., 1996). It is compiled centrally at the Czech Forestry Institute (NLI) that administers the database of forest management plans and guidelines (FMPG), which has served as the main input information on the national forest resources until 2025, when it was replaced by the information solely based on NFI. The annually updated data on CAI is used as a relative index able to quantify growth changes in the reporting period from 1990 to the latest inventory year (CHMI, 2025). Technically, it was implemented as a growth multiplier affecting the current yield tables in the model (Cienciala, 2022), in line with other CBM-CFS3 applications (Pilli et al., 2022). This effect integrates, apart from climate drivers, other factors of growth changes in recent decades, perhaps most prominently the increased nitrogen deposition in previous decades (Cienciala et al., 2016; Kahle, 2008).

With the current pilot recalibration of the Czech CBM-CFS3 model application solely based on NFI data as presented in this document (Chapter 3.1), climate effects will likely be included in the same way, using the observed changes in growth and biomass as reported by NFI for its 5-year assessment intervals (Máslo et al., 2023, 2024). For the calibration period (2011-2023), this component was not included yet due to time and capacity constraints and a need to prioritise implementing other necessary calibration steps. However, the effect of prescribed changes to growth in CBM will be included and demonstrated in a follow-up deliverable of this work package (D6.3), using the scenarios of climate shifters for the projections covering the projection period until 2070. An example of the pilot implementation of growth multipliers is shown in Figure 36.

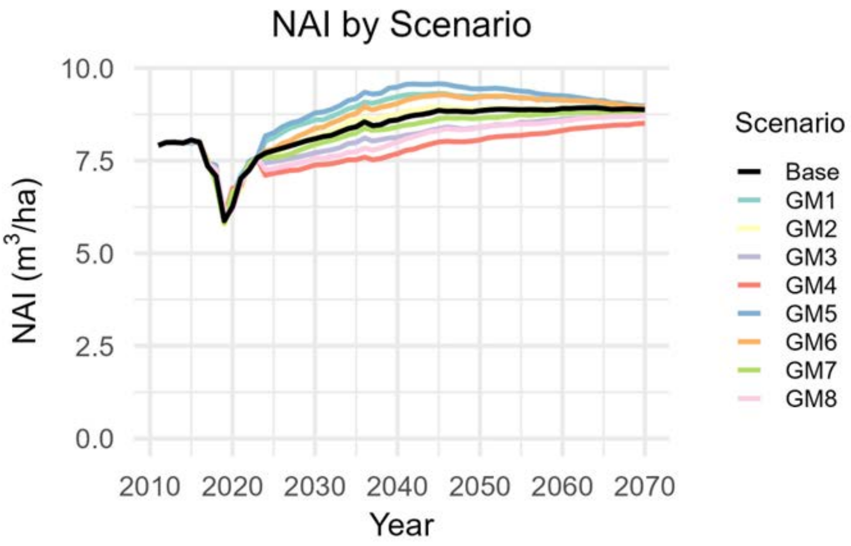

Figure 36. Effect of growth multipliers implementation on growth – average net annual increment (NAI) per hectare, shown for Base scenario in comparison to scenarios GM1 to GM8, combining successively the effects of two General Circulation Models (GFDL and UKESM), low and high medium emission scenarios (RCP 2.6 and 7.0), excluding or including the anticipated CO_2 effect on growth. Scenarios GM1 to GM8 are set to act from 2024 onwards.

4.2.2. CBM Ireland

Current GHG inventory and Irish climate change abatement policy projections (e.g. CAP24, see Black et al., 2025) for the GHG balance of the forest estate do not consider the impact of climate change. The impacts of climate change on the GHG profile in the CBM-CFS3 model can be simulated in two ways: a) by specifying changes in annual temperature and rainfall which influences the turnover and transfer rates of C between the dead organic matter pools (Kurz et al., 2009); and b) by applying an annual growth multipliers to growth curves to reflect annual changes in productivity due to climate related impacts (Pilli et al, 2022). If the frequency and magnitude of natural disturbance due to extreme events are available from global climate change prediction models, it is also possible to simulate the impact of extreme natural disturbance events (see details below).

Here, we developed a framework to include the impact of a range of future climate change scenarios on projected GHG profiles for Irish forests, which will next be used for detailed scenario analysis in the ForestNavigator project. The growth multipliers for each year were generated using the GFDL-ESM4 and UKESM1-0-LL climate change scenarios from the i3PGmiX model outputs (Augustynczik et al., 2025). Both scenarios assume CO_2 fertilisation impacts on forest growth. The GFDL-ESM4 scenario is a more optimistic outlook, where growth generally increases due to CO_2 fertilisation. In the more pessimistic UKESM-0_LL scenario, growth generally declines due to other physiological impacts, such as moisture deficits. For comparison, a baseline scenario (i.e. WEM, Black et al., 2025), which includes the Storm Éowyn impact in 2025 (see details below) with no climate change impact (i.e. a growth multiplier of 1), was run.

For the climate change scenarios, the same target harvest was set as WEM, regardless of whether there was an excess or a deficit of available timber supply due to the growth modification under climate change impacts.

No adaptation assumptions, such as a change of species, were considered to minimise the impact of climate change on productivity and the GHG profile.

A carbon-neutral disturbance matrix, i.e. a matrix where there is no reallocation of C between CBM-CFS3 pools, was created in the archive index database (AIDB) to implement the initiation of modification of growth using the annual growth multipliers (Pilli et al., 2022) from the year 2024 onwards. The growth multipliers were applied to two species groups, namely broadleaves and conifer-dominant stands (Table 14), so the modelled growth and GHG impacts are not species specific. Only one of the three RCP scenarios is presented in this study (spp126).

Table 14. Classification of species strata into the two broad species categories to which growth multipliers are applied.

Description of Species strata	Code	Spp Category
Conifer mixtures (> 75% of conifer mixtures)	CBmix	Conifer
Conifer broadleaf mixtures (< 75% mix with dominant broadleaf spp)	CBmix_BL	Broadleaf
Conifer broadleaf mixtures (< 75% mix with dominant conifer spp)	CBmix_Con	Conifer
Fast-growing broadleaves (>75% birch, ash, alder, sycamore etc.)	FGB	Broadleaf
Slow-growing broadleaves (> 75% oak, beech etc.)	SGB	Broadleaf
Semi-natural woodland or scrub on mineral soils	SNFGB_mineral	Broadleaf
Semi-natural woodland or scrub on organic soils	SNFGB_peat	Broadleaf
Other conifers (except Pine or Spruce)	OC	Conifer
Pine (Lodgepole, Scots pine and others) site index* 4-12 m	Pine4-12	Conifer
Pine (Lodgepole, Scots pine and others) site index 13-20 m	Pine13-20	Conifer
Spruce (Sitka spruce or Norway spruce) site index 4-12 m	Spruce4-12	Conifer
Spruce site index 13-16 m	Spruce13-16	Conifer
Spruce site index 17-20 m-thin	Spruce17-20_thin	Conifer
Spruce site index 17-20 m-no thin	Spruce17-20_nothin	Conifer
Spruce site index 20-24 m-thin	Spruce20-24_thin	Conifer
Spruce site index 20-24 m-no thin	Spruce20-24_nothin	Conifer
Spruce site index 24-30 m-thin	Spruce24-30_thin	Conifer
Spruce site index 24-30 m-no thin	Spruce24-30_nothin	Conifer

* Site index is a productivity index expressed as top height at 30 years of age

A common feature of the annual growth multipliers derived from the GCMs GFDL-ESM1 and UKESM-0-LL is that there are large interannual fluctuations (data not shown). This resulted in large GHG profile fluctuations for the two climate change scenarios, particularly evident in the initial years (2025-2050) of the simulation (Figure 37, left panel). For example, the UKESM1-0-LL conifer multiplier increased from 0.92 in 2025 to 1.2 in 2026, followed by a decline to 0.75 in 2027. This explains the large sink spike observed in 2026 for the UKESM1-0-LL scenario (Figure 37). Curiously, the growth multiplier interannual fluctuations were consistently variable across the period (2024-2070), but appear to stabilise over time, particularly from 2050 onwards.

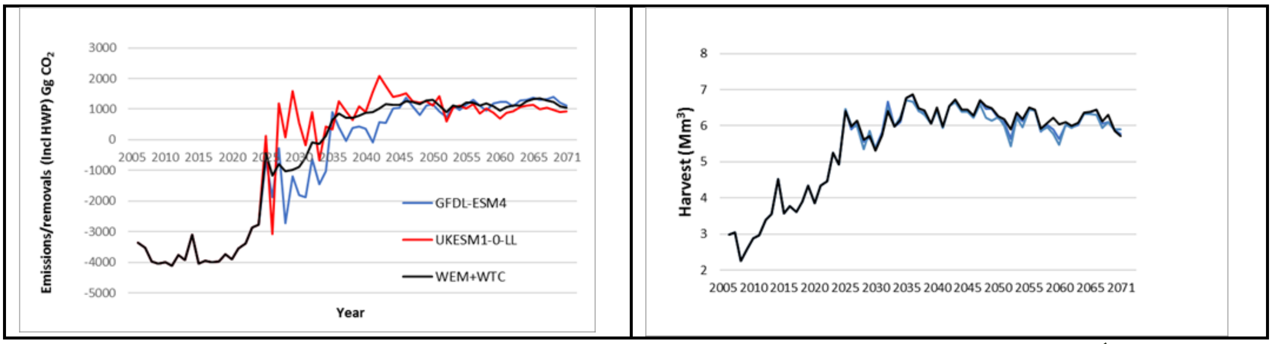

Figure 37. GHG net emission/removal profiles (left panel) and harvest (right panel) for the WEM, including storm Éowyn Scenario C in 2025 (WEM+WTC) and the optimistic (GFDL-ESM1) and pessimistic (UKESM1-0-LL) future climate change scenarios. For right harvest panel, blue and red lines are identical.

The target harvest demands were not altered for the different scenarios presented in Figure 37 (right panel). The WEM, including the 2025 storm Éowyn scenario (WEM+WTC) target harvest, was set for all scenarios. In some cases, the two climate change scenarios had a slightly lower harvest due to lower timber supply, resulting in losses in productivity (Figure 37, right panel, and Figure 38).

The impact of the climate change scenarios on the GHG profile is a result of changes in NAI and the harvest rate (Figure 38). Consistent with the growth multiplier trends, the interannual variation in NAI and harvest rates for the two climate change scenarios stabilised after 2050.

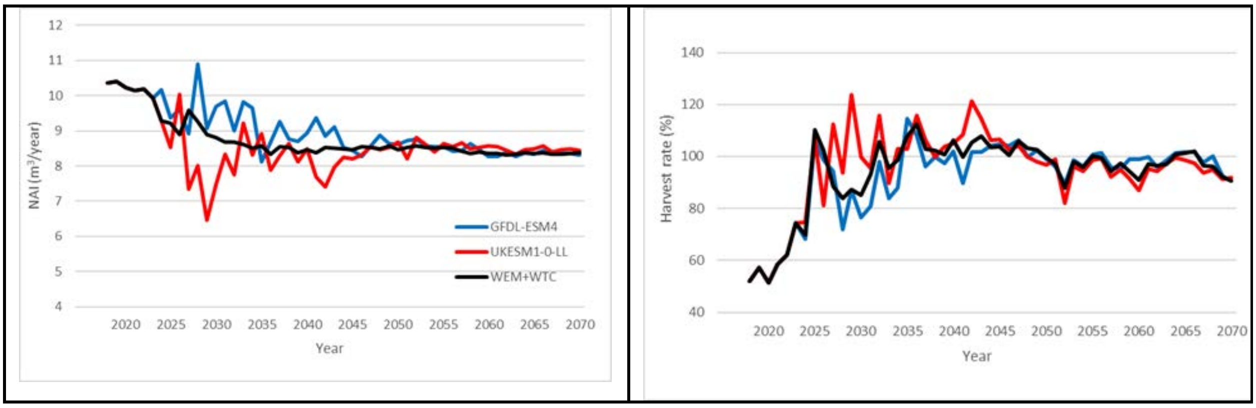

Figure 38. Net annual increment (NAI, left panel) and the harvest ratio (% harvest over increment right panel) for the WEM including storm Éowyn Scenario C 2025 (WEM+WTC) and the optimistic (GFDL-ESM1) and pessimistic (UKESM1-0-LL) future climate change scenarios.

The climate change scenarios presented here are for illustrative purposes, but more detailed analyses will be considered in the other deliverables in WP6. The two scenarios only present potential physiological impacts on growth without considering the following:

- The impact of large extreme natural disturbance events;

- The impact of increased temperatures or rainfall has not yet been included in the temperature and rainfall-dependent DOM decay model in CBM;
- The potential impact of climate change on emissions from organic soils is unclear.

The presented growth multiplier approach will be used for other tasks in WP6 to generate GHG profiles for different GCMs and Representative Concentration Pathways, including and excluding the impact of CO_2 fertilisation. The methodology developed to simulate windthrow events (see section 3.4.2 above) and frequency and intensity of extreme events from GCM outputs will also be used to simulate the impact of extreme windthrow events, which is the largest abiotic climate change risk for Ireland.

4.2.3. CBM Italy

General Methodological assumption

The impact of climate change was simulated by integrating, within the current model runs based on different future harvest scenarios, a dataset including specific growth multipliers (GMs) derived from different climate change scenarios and models (i.e., GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, UKESM1-0-LL). Each climatic model was run under four different Representative Concentration Pathways (RCP 2.6, RCP 4.5, RCP 7.0 and RCP 8.5) and two CO_2 fertilisation scenarios (with and without CO_2 fertilisation effects). For all runs, management activities and disturbance events were excluded during the future simulation period, as both factors are explicitly accounted for in subsequent CBM model runs.

The biomass stock estimated by each climatic model was used as a proxy to derive interannual fluctuations driven by climate change, differentiating between broadleaves and coniferous species groups, and rescaled by Climatic Units and administrative regions according to the CBM modelling framework. These values were then converted to five-year rolling averages, reducing inter-annual fluctuations due to stochastic climatic drivers, and applied as climate shifters by CBM.

The original climate shifters provided by each climatic model, scaled at the NUTS2 level, were first aggregated, for each CLU, at the national level, estimating the average GM attributed to each Climatic Unit, using as a weighting factor the forest area assigned to each NUTS region, for broadleaves and coniferous species groups. Each GM directly affects the annual growth rate attributed to coniferous and broadleaves species groups, within a specific climatic unit, as defined within the CBM modelling framework applied to Italy (Pilli et al., 2022).

The GMs dataset was linked to a specific disturbance event, applied to time step 20 (i.e. the year 2024), generating a multi-year effect on each of the following time steps, until 2070. The event associated with the GM is linked to a carbon-neutral disturbance matrix, i.e. a matrix where there is no reallocation of C between the various CBM pools, and it is applied to the entire forest area. Because this disturbance event can determine a temporary deviation of the amount of harvest expected in 2024, this year was assumed as a transition year between the historical period 2000 - 2023 and future model projections to 2070.

Preliminary results

This approach was tested by comparing a benchmark harvest scenario, without climatic shifters, with four climate change scenarios, defined by GFDL-ESM4, under RCP 8.5, 7.0, 4.5 and 2.6, excluding additional CO_2 fertilisation effects. The benchmark scenario was defined by maintaining a constant fellings rate (Fr) for the entire period 2024 – 2070, excluding land use change (i.e. afforestation and deforestation activities occurring from 2024 onward). The Fr, defined as the ratio between total fellings and NAI, was set to 0.30 of the NAI estimated on the total FAWS, corresponding to an average amount of removals equal to about 9.5 million m^3 yr^{-1} (this is the same harvest reported for 2018, before the Vaia windstorm, and consequent salvage logging activities carried out within the following years).

The amount of harvest expected within the period 2024 – 2070 was fully satisfied for all model scenarios (Figure 39). However, climatic shifters reduced the evolution of the forest C sink within the period 2024 - 2070, on average by 3%, 12%, 10% and 26%, under RCP 2.6, 4.5, 7.0 and 8.5, respectively (Figure 40). The same effect can be highlighted on the expected evolution of NAI from 2025 onward (Figure 41).

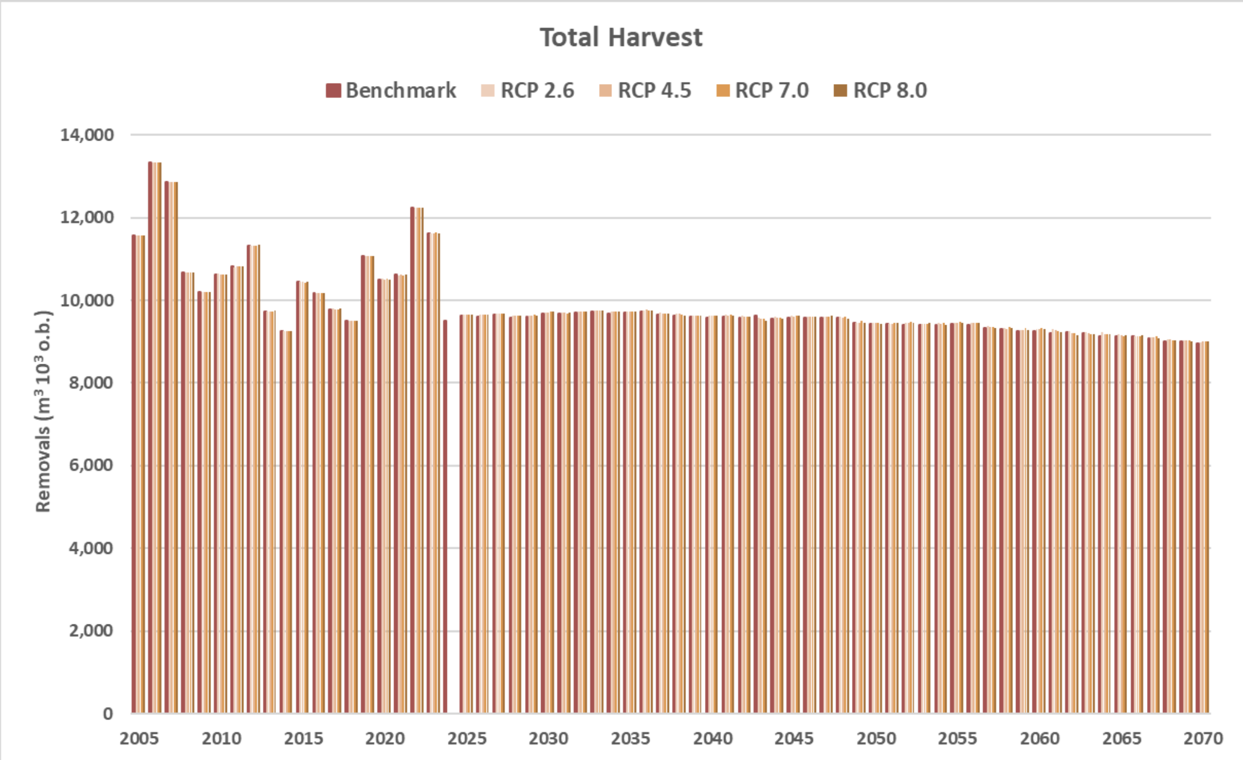

Figure 39. Comparison between the amount of harvest provided by CBM under the Benchmark scenario, excluding climatic effects for the entire simulation period and the Representative Concentration Pathways (RCP) scenarios, including the effects of climate change, as expected by GFDL-ESM4 from 2025 onward.

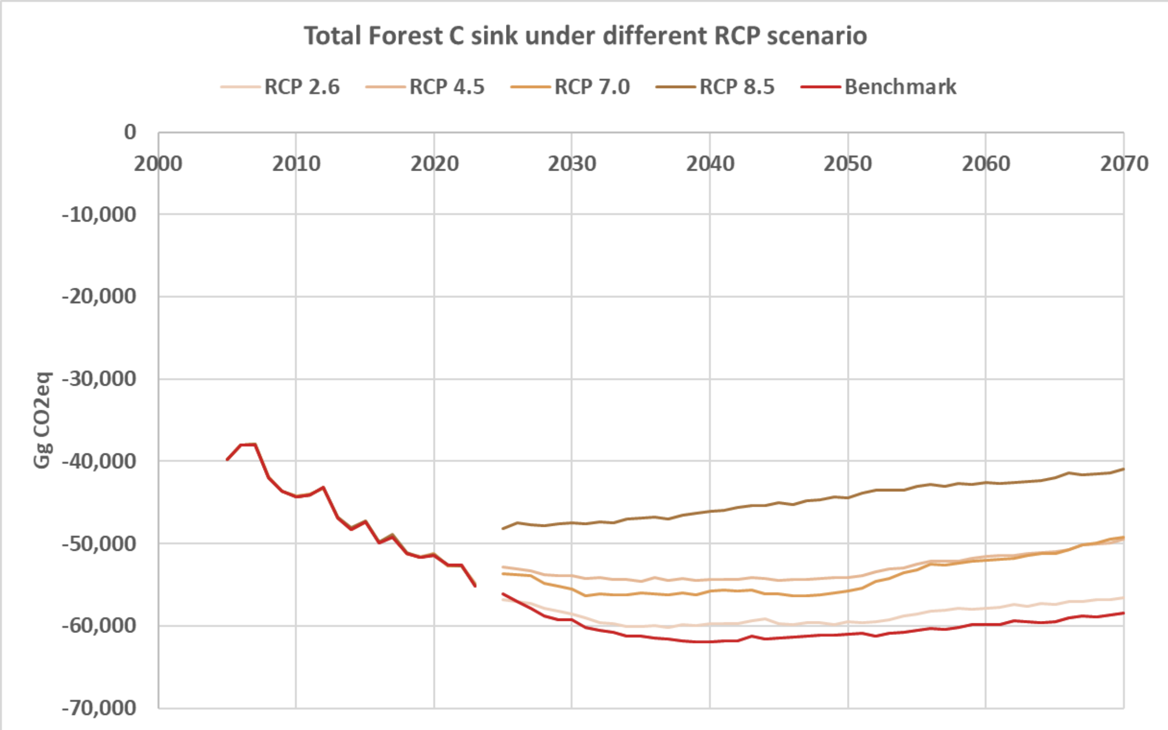

Figure 40. Expected evolution of the total forest C sink, from 2025 onward, under different climatic scenarios: the Benchmark scenario, excluding climatic effects for the entire simulation period and the Representative Concentration Pathways (RCP) 8.5, 7.0, 4.5 and 2.6 scenarios, including the effect of climate change, as expected by GFDL-ESM4.

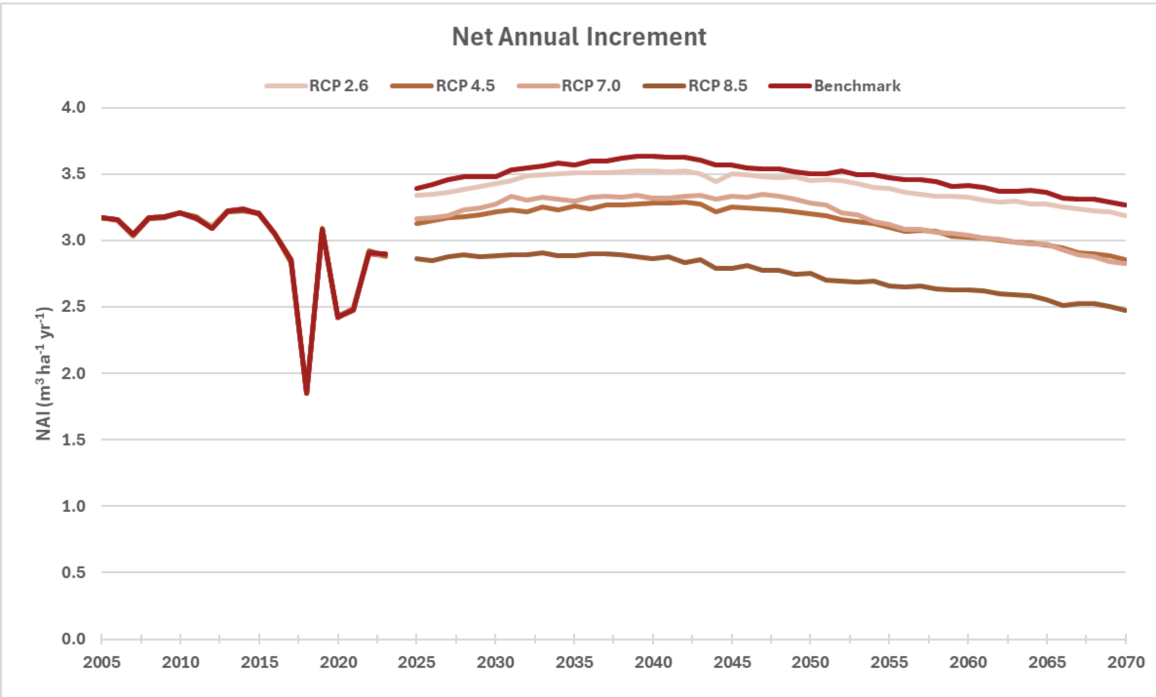

Figure 41. Expected evolution of the Net Annual Increment, from 2025 onward, under different climatic scenarios: the Benchmark scenario, excluding climatic effects for the entire simulation period and the Representative Concentration Pathways (RCP) 8.5, 7.0, 4.5 and 2.6 scenarios, including the effect of climate change, as expected by GFDL-ESM4.

These results are consistent with the expected impact of different RCP scenarios, as determined by the growth multiplier derived from climate models. Indeed, the average GM estimated by GFDL progressively increases from 0.99 to 0.79, moving from the RCP 2.6 to RCP 8.5 scenario (Figure 42). By preliminarily applying a five-year moving average to the model outputs, we probably reduced interannual variations due to extreme climatic events, likely included in the original model output.

Moreover, stochastic natural disturbances, not included within the current model run, can further amplify interannual variations.

Model/RCP	Conifers	Broadleaves	Average GM
GFDL-ESM4	**0.91**	**0.90**	**0.91**
RCP 2.6	0.99	0.99	0.99
RCP 4.5	0.95	0.94	0.95
RCP 7.0	0.91	0.91	0.91
RCP 8.5	0.81	0.78	0.79
IPSL-CM6A-LR	**0.90**	**0.89**	**0.89**
RCP 2.6	0.95	0.94	0.94
RCP 4.5	0.89	0.85	0.87
RCP 7.0	0.97	0.96	0.96
RCP 8.5	0.81	0.80	0.80
MPI-ESM1-2-HR	**0.91**	**0.90**	**0.90**
RCP 2.6	0.96	0.95	0.95
RCP 4.5	0.87	0.85	0.86
RCP 7.0	0.92	0.91	0.92
RCP 8.5	0.89	0.89	0.89
UKESM1-0-LL	**0.87**	**0.86**	**0.87**
RCP 2.6	0.94	0.93	0.94
RCP 4.5	0.85	0.84	0.85
RCP 7.0	0.87	0.87	0.87
RCP 8.5	0.83	0.80	0.82

Figure 42. Average Growth Multiplier (GM) estimated by each climatic model, under different RCP scenarios, further distinguished between coniferous and broadleaves species groups. Grey cells highlight the GM applied within the present study.

Apart from simulating other scenarios as expected by other climatic models, also including CO_2 fertilisation effects, further model runs can also include other refinements, such as (i) interannual variations of the Mean Annual Temperature considered by CBM from 2024 onward, according to the corresponding values provided by climate models (this variable affects the decay rates of DOM pools), and interannual fluctuations of the main natural disturbance events (wildfires) affecting Italian forests within the simulation period 2024 - 2070. This last parameter, currently assumed as constant and equal to the average area affected by wildfires within the calibration period, can be further calibrated according to other ancillary information provided by climate models.

4.2.4. Heureka

Effects on growth due to climate change can be included by adjusting the empirical growth functions based on results from an analysis (50 × 50 km2 grid over all Sweden) with the BIOMASS process-based vegetation model (McMurtrie et al., 1990). Three climate scenarios are available: ECHAM5_A1B, MPI 4.5, and MPI 8.5 (Freeman, 2009). The process-based vegetation model does not, however, account for increased risks that are expected to follow climate change, such as more frequent storm-attributed fellings, summer droughts and insect infestations. However, there are models/indices quantifying risks for root rot, spruce bark beetle and storm damage. Disturbances by wind can further be explicitly simulated at predefined time points and strengths when using RegWise.

Carbon accounting

Sweden annually reports emissions of greenhouse gases to the Climate Convention and to the EU. SLU is responsible for the land use sector, Land use, Land use change and Forestry (LULUCF). RegWise, together with data from the NFI, is used as a projection tool within the national carbon accounting framework (European Union, 2018). The development of the carbon pools living biomass, soil carbon (including stumps), deadwood and harvested wood products within the LULUCF sector is simulated and transformed into emissions of CO2. One example of these projections is the Forest Reference Level (Ministry for the Environment, 2019). According to the Paris Agreement, EU member states were obliged to set a reference level for the LULUCF sector for the period 2020–2030 to which the actual emissions are compared. This was done by mimicking forestry as it was carried out during the period 2000–2009 during the simulations.

5. Conclusion and next steps

There are numerous emerging challenges in the management of forest resources in the EU, driven by the combined pressures of climate change, biodiversity loss, increasing disturbance events, and evolving socio-economic demands. These pressures create complex trade-offs between climate mitigation, biodiversity conservation, and bioeconomy objectives, making decision-making increasingly difficult. Model-based policy impact assessments offer a powerful means to address these challenges, as they can integrate diverse data sources, simulate multiple management strategies, and project outcomes under different climate and policy scenarios. By providing evidence-based insights, such modelling frameworks can support policymakers in designing adaptive, forward-looking forest management approaches that maintain ecosystem resilience, enhance the carbon sink, and balance competing land-use priorities.

To address these challenges, however, modelling frameworks used in policy impact assessment need to be equipped to integrate climate change impacts, biodiversity and bioeconomy aspects when computing climate mitigation pathways. To address this issue, we have recalibrated and updated EU and MS models used for policy impact assessment to better represent the development of the forest sink in the EU and account for climate change impacts on forest productivity. In this context, we present an approach to assess the impact of disturbances on the national forest GHG profile using remote sensing data, NFI plot data, and forest modelling. This approach can serve as an early indicator of storm damage impacts, two years before GHG inventory data are submitted to the UNFCCC. The model can also support salvage logging scheduling and planning, while simultaneously assessing impacts on the national forest GHG balance. Further model development would enable the integration of windthrow events into scenario analysis for policy and climate change scenarios in WP 6.

We have additionally coupled GLOBIOM/G4M-X with biodiversity and local climate impact models, enabling us to derive the implications of management decisions to biodiversity and the influence of afforestation and deforestation on local temperature. Preliminary results show that climate change may have a substantial impact on climate and biodiversity outcomes of forest management, with a decline in the EU forest sink in more extreme climate change scenarios and a decrease in species richness under more intense management and climate change. Local climate impacts of afforestation remained limited due to the restricted land availability and the afforestation area considered in the baseline.

In the next steps, we also strive to integrate trends in the occurrence of disturbances into the MS models to shift historical patterns, depending on the climate change scenario, since an increase in the severity of wildfires and bark beetle outbreaks can be expected in the EU in the future. The disturbances will be modelled consistently across the EU, based on the same mechanistic models (see D3.2 and D3.4). Additionally, the updated and recalibrated EU and MS models will be deployed in Task 6.3 to compute the baseline scenario for the EU forest sector and will serve as a basis for the reconciliation between MS and EU climate mitigation pathways in WP6.

6. Appendix

Table A1. Forest types in CBM Italy.

CBM Forest Type	INFC category	CBM species group	INFC area (kha)	Share of forest area
AA	Silver fir	**Con**	68.4	1%
BP	Broadleaves plantations	**Broad**	40.1	0%
CP	Coniferous plantations	**Con**	15	0%
CS	Chestnut	**Broad**	788.4	9%
FS	Beech	**Broad**	1,035.1	12%
LD	Larch & mountain pines	**Con**	382.4	4%
OB	Other broadleaves	**Broad**	994.8	11%
OC	Other conifers	**Con**	63.4	1%
Oca	Hornbeam	**Con**	852.2	10%
OE	Other evergreen	**Broad**	84.7	1%
PA	Norway spruce	**Con**	586.1	7%
PM	Mediterranean pines	**Con**	226.1	3%
PN	Black pine	**Con**	236.5	3%
PP	Poplar plantations	**Broad**	66.3	1%
PS	Scots pine	**Con**	151.7	2%
QC	Turkey oak	**Broad**	1,010.1	12%
QI	Evergreen oak	**Broad**	620.3	7%
QR	Common oak	**Broad**	1,084.2	12%
QS	Cork oak	**Broad**	168.6	2%
RF	Riparian forests	**Broad**	229	3%
Total Italy (excluding temporary unstocked area)			8,703.4	

Table A2. Regions in CBM Italy.

CBM region	Italian administrative region /Autonomous province	NUTS Code
AA	Provincia Autonoma di Bolzano/Bozen	ITH1
Ab	Abruzzo	ITF1
Ba	Basilicata	ITF5
Cal	Calabria	ITF6
Cam	Campania	ITF3
ER	Emilia-Romagna	ITH5
FVG	Friuli-Venezia Giulia	ITH4
La	Lazio	ITI4
Li	Liguria	ITC3
Lo	Lombardia	ITC4
Ma	Marche	ITI3
Mo	Molise	ITF2
Pi	Piemonte	ITC1
Pu	Puglia	ITF4
Sa	Sardegna	ITG2
Si	Sicilia	ITG1

CBM region	Italian administrative region /Autonomous province	NUTS Code
Tn	Provincia Autonoma di Trento	ITH2
To	Toscana	ITI1
Um	Umbria	ITI2
Va	Valle d'Aosta	ITC2
Ve	Veneto	ITH3

Table A3. Climate units in CBM Italy.

CBM Climatic Unit	Mean Annual Temperature (°C)	Annual Precipitation (mm)
25	7.5	450
26	12.5	450
27	17.5	450
34	2.5	750
35	7.5	750
36	12.5	750
37	17.5	750
43	-2.5	1,050
44	2.5	1,050
45	7.5	1,050
46	12.5	1,050
53	-2.5	1,350
54	2.5	1,350
55	7.5	1,350
56	12.5	1,350
63	-2.5	1,650
64	2.5	1,650

Table A4. Age classes in CBM Italy.

CBM Age Class	Age interval	Italian National Forest Inventory (INFC) age class distribution	Correction factor (CF_{Age})
AGEID0	0	Temporary unstocked area	n.a.
AGEID1	1-10	0-10	n.a.
AGEID2	11-20	11-20	n.a.
AGEID3	21-30	21-30	n.a.
AGEID4	31-40	31-40	n.a.
AGEID5	41-50	41-80	0.3
AGEID6	51-60	41-80	0.3
AGEID7	61-70	41-80	0.2
AGEID8	71-80	41-80	0.2
AGEID9	81-90	81-120	0.3
AGEID10	91-100	81-120	0.3
AGEID11	101-110	81-120	0.2
AGEID12	111-120	81-120	0.2
AGEID13	121-130	>120	0.3
AGEID14	131-140	>120	0.3
AGEID15	141-150	>120	0.2
AGEID16	151-160	>120	0.2
AGEID17	161-170	available during the model run	
AGEID18	171-180	available during the model run	
AGEID19	181-190	available during the model run	
AGEID20	191-200	available during the model run	
AGEID21	>200	available during the model run	

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