Report on new Forest Management Practices (FMP) in forest models and implications for land cover change parametrisation in climate models

D2.2

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About Opt4EU

OptFor-EU wants to co-develop a Decision Support System (DSS) with forest managers and other forest stakeholders, that provides them with suitable climate adaptation and mitigation options for science-based optimising forest ecosystem services (FES) (including decarbonisation) and enhancing forest resilience and its capacities to mitigate climate change across Europe.

The project 'OPTimising FORest management decisions for a low-carbon, climate resilient future in Europe (OptFor-EU)' will build a DSS to provide forest managers and other relevant stakeholders with tailored options for optimising decarbonisation and other Forest Ecosystem Services (FES) across Europe.

Based on exploitation of existing data sources, use of novel Essential Forest Mitigation Indicators and relationships between climate drivers, forest responses and ecosystem services, OptFor-EU has five specific objectives:

- Provide an improved characterisation of the Forest-Climate Nexus and FES;
- Utilise end-user focused process modelling;
- Empower forest end-users to make informed decisions to enhance forest resilience and decarbonisation;
- Provide a novel DSS service; and
- Bridging different EU strategic priorities, robust science, and stakeholders in the forest and forest-based sectors.

Based on a supply-demand approach, the methodology combines an iterative process of data consolidation, modelling, and co-development of solutions alongside forest managers and other practice stakeholders in all European Forest Types. The DSS will be designed and tested at 8 Case Study Areas (CSA), to provide a ready-to-use service, near to operational (TRL7) at European level, while a user adoption and up-take plan will maximise the societal and business impact.

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List of abbreviations

Acronym / Abbreviation	Meaning / Full text
AC	Age Class
AFM	Adaptive Forest Management
BAU	Business As Usual forest management
CSA	Case Study Area
EFT	European Forest Type
FMP	Forest Management Practice
LAI	Leaf Area Index
NOM	No Forest Management
PFT	Plant Functional Type
RCM	Regional Climate Model
RCP	Representative Concentration Pathways

EXECUTIVE SUMMARY

The present deliverable reports on new forest management practices in the Case Study Areas (CSAs) of OptFor-EU, their relevance under different climate scenarios, and the implications for land cover parameterization in climate models.

The first section includes the context of this deliverable.

The second section includes 1) brief descriptions of the forest models used (i.e., PICUS and 3D-CMCC-FEM); 2) the data needed to initialize the models; 3) the simulation protocol adopted for simulations; and, 3) the European Forest Types (EFT) with the respective descriptions of Forest Management Practices (FMP) for the three preliminary analyzed CSAs (i.e., Austria, Romania and Italy).

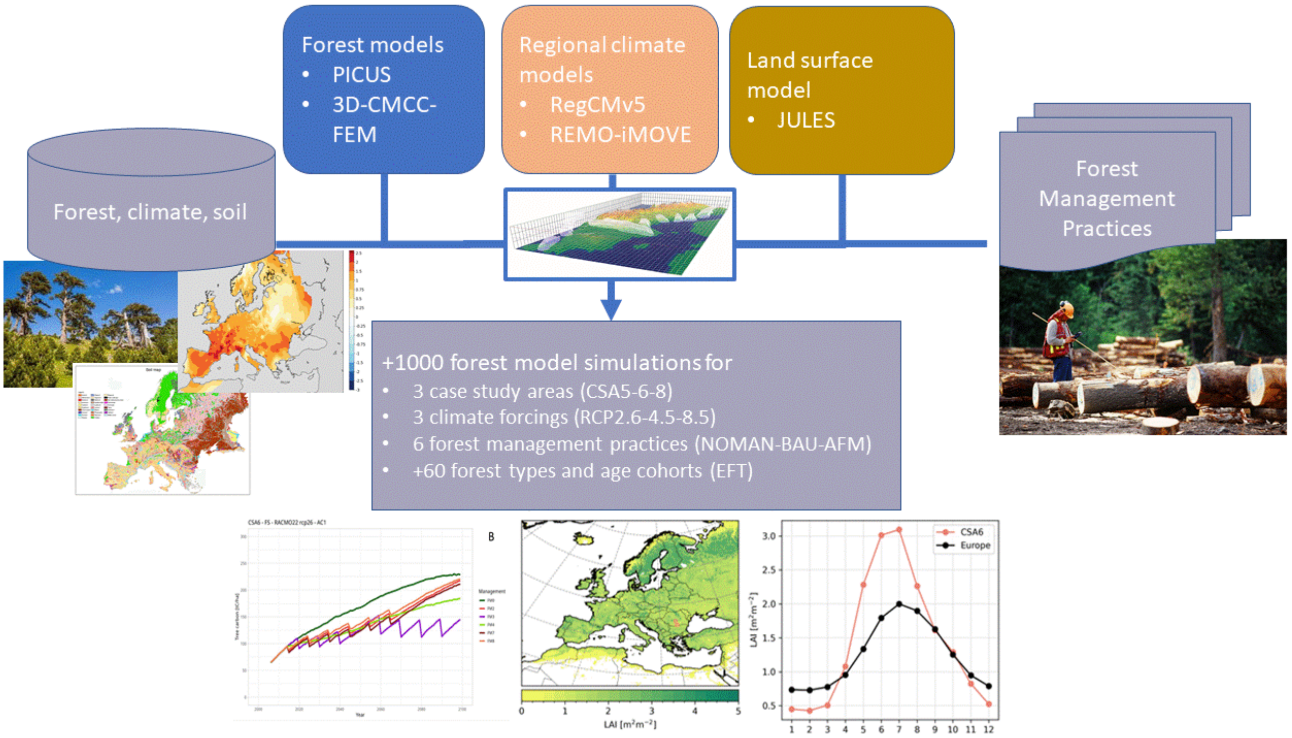
The third section of the deliverable reports preliminary results from forest model runs, comparing diverse FMP at the stand level and for different age classes and the effects of climate change scenarios, and including various forest management options at the regional level.

The fourth section describes the integration of land cover parameterization and FMP into climate models (i.e., REMO-iMOVE and RegCM) by adapting land cover parameterization and creating new plant functional types (PFT).

The fifth section briefly describes the link between forest and climate models. It outlines various approaches to integrate forest dynamics into climate simulations, accenting the importance of accurately representing forest characteristics and management practices.

The final sixth part is a synthesis and summary of the next steps.

Graphical abstract



Forest models
- PICUS
- 3D-CMCC-FEM

Regional climate models
- RegCMv5
- REMO-iMOVE

Land surface model
- JULES

Forest, climate, soil

Forest Management Practices

+1000 forest model simulations for
- 3 case study areas (CSA5-6-8)
- 3 climate forcings (RCP2.6-4.5-8.5)
- 6 forest management practices (NOMAN-BAU-AFM)
- +60 forest types and age cohorts (EFT)

1 Context

Modelling is a valuable analytical tool for understanding ecosystem dynamics, assessing future scenarios, and making informed decisions, particularly crucial for forest ecosystems due to the long-life cycle of trees.

In WP2 of the OptFor-EU project, various model types, including forest, climate, and land surface vegetation models, are used to simulate forest dynamics. Modelling is applied to specific forest areas, including individual stands or spatial pixels.

One of the central aspects of the OptFor-EU project, including this deliverable, is the development of new Forest Management Practices (FMPs). The existing FMPs, such as Business as Usual (BAU) and No Management (NOM), outlined in the deliverable D2.1 - Forest Management Practices and their relevance in case study areas (Neumann et al., 2023), will serve as a basis for incorporating new management schemes within model runs. More specifically, D2.1 provided rules for observed thinning and final harvesting for each CSA and EFT. D2.1 represents current FMPs and a review of the contributions of EFT, to identify the most frequent forests in the CSA, based on covered area. Since most European forests are managed (FOREST EUROPE 2020), defining FMPs is crucial. Therefore, any model aiming to produce accurate and unbiased results should incorporate management activities.

The objectives of D2.2 are (1) to implement both current and new Forest Management Practices (FMPs) within two forest models to evaluate the role of forest management under various climate change scenarios, and (2) to examine the implications of FMPs for land cover change parameterization, identifying optimal integration approaches between forest and climate models.

2 Model simulation framework

Using (i) climate data compiled in WP1, (ii) forest data collected in CSA amended with forest inventory data, and (iii) management rules detailed in the deliverable D2.1, we conduct preliminary simulations of selected forest stands (see following sections) using two forest models, i.e., PICUS and 3D-CMCC-FEM, covering the period from 2006 to 2100.

Forest Models Description

PICUS is a hybrid 3D patch model using process-based stand-level production algorithms (Irauschek et al., 2021). PICUS considers forests as an array of 10x10 m patches, which interact with each other in light regimes and seed dispersal. Trees exceeding 1.3 m in height are placed as individuals within these patches and simulated individually. PICUS structure and model parameters have been validated extensively (see papers cited in Irauschek et al., 2021). Needed soil input data (water holding capacity and available nitrogen) are extracted for the locations of forest data using Soil Grids dataset (Poggio et al., 2021).

The 3D-CMCC-FEM is a dynamic, process-based model that simulates eco-physiological, biogeochemical, and biophysical processes driving forest growth dynamics in both homogeneous and heterogeneous stands (Collalti et al., 2014, 2018, 2024; Dalmonech et al., 2022). It accounts for various tree species, or EFT or PFT, considering differences in age, tree diameter, and height classes. The model is designed to simulate carbon, nitrogen, and water cycles in forest ecosystems at commonly 1-hectare spatial resolution and the main eco-physiological processes (e.g., photosynthesis) at daily temporal resolution.

Both models have been developed and applied for European forests in many studies and thus, can be considered to provide robust results (PICUS - Huber et al., 2013; Seidl et al., 2010; Irauschek et al., 2021; 3D-CMCC-FEM – Collalti et al., 2016; Marconi et al., 2017; Morichetti et al., 2024; Vangi et al., 2024a). Simulations are always subject to model uncertainty. Uncertainty in forest model simulations involves assessing variations from real values due to factors like assumed parameters, model structure, and input data. Key sources of uncertainty include insufficient data for model initialization and boundary conditions, accurate parameterization and representation of non-equilibrium situations. Ecosystem disturbances, such as climate change, further complicate parameter stability, impacting the importance of certain processes and model sensitivity over time. Uncertainty of simulation results can be quantified using validation against independent data.

Input Data and FMP setting

In OptFor-EU, we group forest stands based on similarity in (1) species composition to allocate forest data to the relevant EFT, and (2) stand age using 20-year-steps age classes to capture differences in development stages (Table 1). We choose 50 as the minimum number of plots to consider an EFT for simulations, based on preliminary analysis. This ensures that we have enough samples to capture the heterogeneity of represented actual forest stands and conditions.

Table 1 – Age classes and stand age range covered

Age class	Min-max age (years)
1	0-20
2	21-40
3	41-60
4	61-80
5	81-100
6	101-120
7	121-140
8	>140 years, potentially including old-growth forests

BAU and NOM are described for each case study area in D2.1. We describe new alternative forest management (AFM) rules based on consultations with stakeholders as part of D2.1 (Neumann et al., 2023) and literature (Dalmonech et al., 2022). AFM represents deviations from BAU to meet other objectives not commonly accounted for at the sites. The considered forest management practices (FMP) are:

- No management, NOM (FM0)
- Business-as-usual, BAU - Clearcut (FM1)
- Business-as-usual, BAU - Shelterwood (FM2)
- Business-as-usual, BAU – Continuous Forest cover using single tree harvesting (FM3)
- Continuous harvesting at low intensity, limited by increment (FM4)
- Increasing thinning intensity of FM1 (BAU - Clearcut) by plus 20%, to emulate higher demand for forest products with larger dimensions (FM5)
- Decreasing thinning intensity of FM1 (BAU - Clearcut) by minus 20%, to represent less intensive management leading to denser forests with higher carbon stocks (FM6)

- Increasing thinning intensity of FM2 (BAU - Shelterwood) by plus 20%, to emulate higher demand for forest products with larger dimensions (FM7)
- Decreasing thinning intensity of FM2 (BAU - Shelterwood) by minus 20%, to represent less intensive management leading to denser forests with higher carbon stocks (FM8)
- Business-as-usual, BAU - Coppice management (FM9)

For general descriptions of clearcut, shelterwood, continuous cover forests and coppice, we refer to literature (Lundquist et al., 2017; Nicolescu et al., 2017; Pommerening et al., 2024) and for visualization to Fig. 1. Briefly, clearcut represents tree harvesting without leaving remaining trees and the new stand is formed by natural regeneration or tree planting. Shelterwood represents the gradual removal of trees to initiate natural regeneration underneath the shelter of the canopy of remaining trees (usually at least two interventions, see D2.1 for details). Both clearcut and shelterwood result in an even-aged forest stand, after regeneration is completed. Continuous cover forest using single tree harvesting represents a management alternative, where only single trees are removed and over time the stand is converted into an uneven-aged forest stand (in contrast to clearcut, shelterwood). Thinning intensity denotes the share of removed trees, which is 100% in the case of clearcut and can be as low as 10% for shelterwood.

Figure 1 - Illustrative images of selected FMPs (photo credit: Mathias Neumann)

We use single-tree data (i.e., age, species, stand density, diameter at breast height, tree height) to initialize the carbon pools and stand structure in PICUS and 3D-CMCC-FEM.

PICUS needs information on soil, litter and deadwood, to initialize these carbon pools. The 3D-CMCC-FEM forest model requires, in addition to data on stand conditions at the beginning of simulations, annual atmospheric CO_2 concentrations.

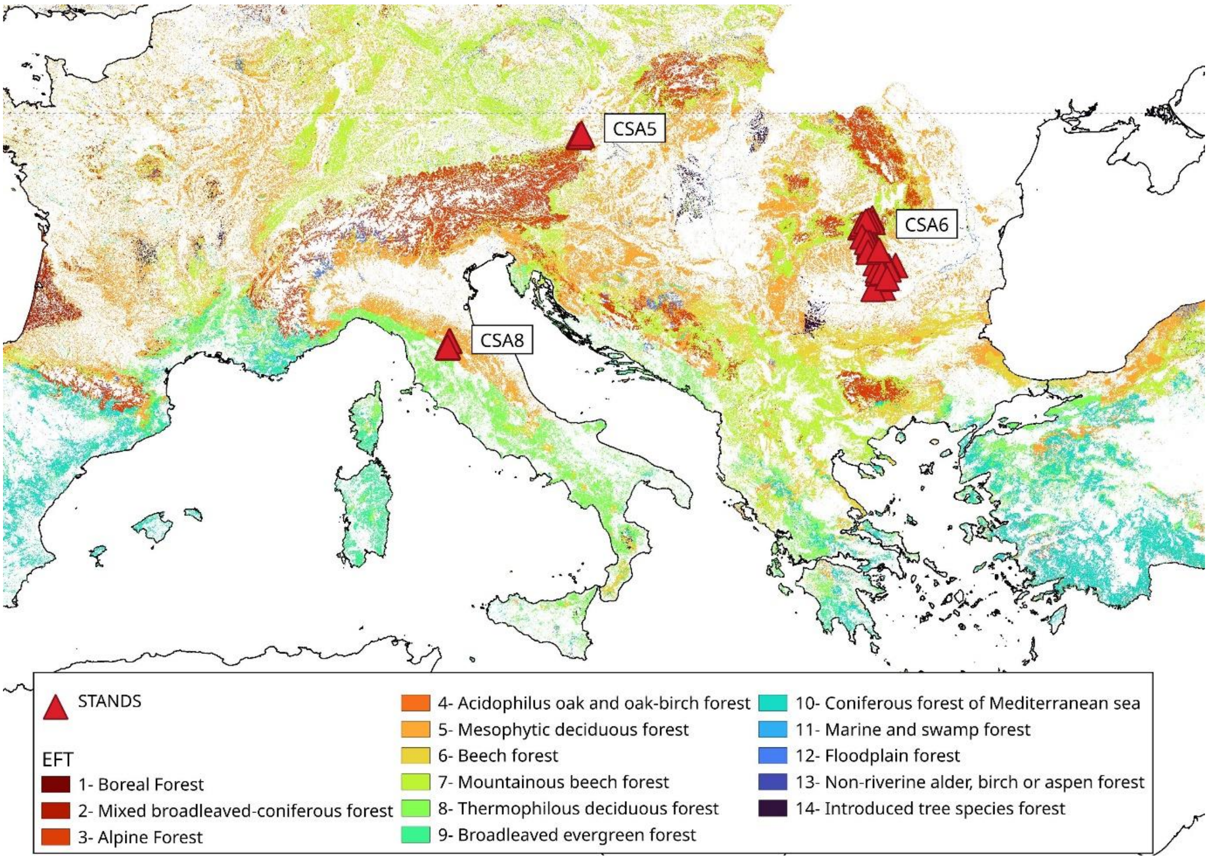


Figure 2 - Location of CSA (CSA5 - Biosphere Reserve "Wiener Wald" - Austria, CSA6 - Arges Vedea Watershed - Romania and CSA8 - Florentine Mountains - Italy). Gridded dataset of European Forest Types (D1.1 - Giannetti and Zorzi, 2023)

We start with the following case study areas: Austria (CSA5), Romania (CSA6) and Italy (CSA8) (plots in the Rincine regional forestry complex). From the EURO-CORDEX generation CMIP5/6 downscaling experiments, high-resolution climate input data is available from the regional climate models (RCMs) HIRHAM5 HADGEM2ES and RACMO22E HADGEM2ES, for the Representative Concentration Pathways (RCPs and SSPs) 2.6, 4.5 and 8.5 (Jacob et al., 2020).

The following sections describe the EFTs considered and the management rules applied for each of them. We use the same rules for PICUS and for 3D-CMCC-FEM for the sake of comparability. We select the case study areas in Austria, Romania and Italy as test sites, as they represent a wide range of forest conditions from alpine, temperate to Mediterranean ecosystems as well as contrasting FMPs (see D2.1 and Fig. 2).

2.1 Austria

The considered EFTs are EFT5 (*Quercus petraea* (Matt.) Liebl.) and EFT6 (*Fagus sylvatica* L.) (Table 2). The full list of all EFTs can be found in Fig. 2 and D1.1 (Giannetti and Zorzi 2023).

Table 2 – Rules of FMP for Austria (CSA5)

EFT	FM0	FM2	FM7	FM8
5	None	Final harvesting at age 130 years, five thinnings at a stand age of 30, 45, 60, 75 and 90 years, thinning intensity of 30% in the first thinning and 20% in the remaining. A pre-harvest with an intensity of 40% is carried out 10 years before the final harvest. After 5 years of natural regeneration trees are planted up to the target stem density of 5000 ha^{-1}.	Final harvesting at age 130 years, five thinnings at a stand age of 30, 45, 60, 75 and 90 years, thinning intensity of 36% in the first thinning and 24% in the remaining. A pre-harvest with an intensity of 40% is carried out 10 years before the final harvest. After 5 years of natural regeneration trees are planted up to the target stem density of 5000 ha^{-1}.	Final harvesting at age 130 years, five thinnings at a stand age of 30, 45, 60, 75 and 90 years, thinning intensity of 24% in the first thinning and 16% in the remaining. A pre-harvest with an intensity of 40% is carried out 10 years before the final harvest. After 5 years of natural regeneration trees are planted up to the target stem density of 5000 ha^{-1}.
6	None	Final harvesting at age 130 years, two thinnings at a stand age of 30 and 50 years, thinning intensity ranges from 20% up to 55% (mean 35%) depending on the stand structure. A pre-harvest with an intensity of 30% is carried out 10 years before the final harvest. After 5 years of natural regeneration trees are planted up to the target stem density of 2000 ha^{-1}.	Final harvesting at age 130 years, two thinnings at a stand age of 30 and 50 years, thinning intensity ranges from 24% up to 66% (mean 42%) depending on the stand structure. A pre-harvest with an intensity of 30% is carried out 10 years before the final harvest. After 5 years of natural regeneration trees are planted up to the target stem density of 2000 ha^{-1}.	Final harvesting at age 130 years, two thinnings at a stand age of 30 and 50 years, thinning intensity ranges from 16% up to 44% (mean 28%) depending on the stand structure. A pre-harvest with an intensity of 30% is carried out 10 years before the final harvest. After 5 years of natural regeneration trees are planted up to the target stem density of 2000 ha$_{-1}$.

2.2 Italy

The considered EFTs are EFT3 (*Abies alba* Mill.), EFT5 (*Quercus cerris* L.), EFT6 (*Fagus sylvatica* L.), EFT10 (*Pinus nigra* J.F. Arnold) and EFT14 (*Pseudotsuga menziesii* (Mirb.) Franco) (Table 3).

Table 3 - Rules of FMPs for Italy (CSA8)

EFT	FM0	FM2	FM7	FM8
3	None	Final harvesting at age 80 years, three thinnings at a stand age of 20, 40 and 60 years, thinning intensity 10%. A pre-harvest with an intensity of 30% is carried out 10 years before the final harvest. After 5 years of natural regeneration trees are planted up to the target stem density of 2500 ha^{-1}.	Final harvesting at age 80 years, three thinnings at a stand age of 20, 40 and 60 years, thinning intensity 12%. A pre-harvest with an intensity of 30% is carried out 10 years before the final harvest. After 5 years of natural regeneration trees are planted up to the target stem density of 2500 ha^{-1}.	Final harvesting at age 80 years, three thinnings at a stand age of 20, 40 and 60 years, thinning intensity 8%. A pre-harvest with an intensity of 30% is carried out 10 years before the final harvest. After 5 years of natural regeneration trees are planted up to the target stem density of 2500 ha^{-1}.
6	None	Final harvesting at age 90 years, three thinnings at a stand age of 20, 40 and 60 years, thinning intensity 10%. A pre-harvest with an intensity of 40% is carried out 10 years before the final harvest. After 5 years of natural regeneration trees are planted up to the target stem density of 2000 ha^{-1}.	Final harvesting at age 90 years, three thinnings at a stand age of 20, 40 and 60 years, thinning intensity 12%. A pre-harvest with an intensity of 40% is carried out 10 years before the final harvest. After 5 years of natural regeneration trees are planted up to the target stem density of 2000 ha^{-1}.	Final harvesting at age 90 years, three thinnings at a stand age of 20, 40 and 60 years, thinning intensity 8%. A pre-harvest with an intensity of 40% is carried out 10 years before the final harvest. After 5 years of natural regeneration trees are planted up to the target stem density of 2000 ha^{-1}.

EFT	FM0	FM1	FM5	FM6
10	None	Final harvesting at age 80 years, initial target stem density 2500 ha-1, three thinnings at stand age of 20, 40 and 60 years, thinning intensity 10%.	Final harvesting at age 80 years, initial target stem density 2500 ha-1, three thinnings at stand age of 20, 40 and 60 years, thinning intensity 12%.	Final harvesting at age 80 years, initial target stem density 2500 ha-1, three thinnings at stand age of 20, 40 and 60 years, thinning intensity 8%.
14	None	Final harvesting at age 80 years, initial target stem density 2500 ha-1, three thinnings at stand age of 20, 40 and 60 years, thinning intensity 10%.	Final harvesting at age 80 years, initial target stem density 2500 ha-1, three thinnings at stand age of 20, 40 and 60 years, thinning intensity 12%.	Final harvesting at age 80 years, initial target stem density 2500 ha-1, three thinnings at stand age of 20, 40 and 60 years, thinning intensity 8%.

EFT	FM0	FM9
5	None	Final harvest every 35-40 years, leaving 60 trees per ha^{-1}. Regeneration via sprouting and new shoots from roots. (PICUS and 3D-CMCC-FEM cannot model coppice sprouting at the moment)
6	None	Final harvest every 35-40 years, leaving 60 trees per ha^{-1}. Regeneration via sprouting and new shoots from roots. (PICUS and 3D-CMCC-FEM cannot model coppice sprouting at the moment)

The content of deliverable D3.3 ensures a comprehensive understanding of the concerns, needs, expectations, and perceptions of forest managers and other stakeholders in relation to FMP and FES in the CC context. Addressing the real needs and problems that stakeholders are facing, D3.3 facilitates the transition toward sustainable and resilient forest management. This deliverable enables the identification of effective strategies and good practices for CC adaptation and mitigation of forest ecosystems, considering the stakeholders' requirements identified in each CSA as an input in the development of a tailored DSS. Additionally, stakeholders' engagement workshops and Expert survey outputs emphasize threats and challenges that must be overcome for sustainable forest management under climate change.

2.3 Romania

The considered EFTs are EFT3 (*Picea abies* (L.) H. Karst), EFT5 (*Quercus petraea* (Matt.) Liebl.), EFT6 (*Fagus sylvatica* L.) and EFT14 (*Robinia pseudoacacia* L.) (Table 4).

Table 4 – Forest management rules for Romania (CSA6)

EFT	FM0	FM1	FM4	FM5	FM6
3	None	Final harvesting at age 110 years, initial target stem density 2500 ha^{-1}, six thinnings at stand age of 25, 35, 45, 55, 65 and 75 years, thinning intensity in the same order as the years 16%, 12%, 10%, 9%, 8% and 7%.	Continuous harvesting at low intensity (5 m^3 $ha^{-1}year^{-1}$), limited by increment.	Final harvesting at age 110 years, initial target stem density 2500 ha^{-1}, six thinnings at stand age of 25, 35, 45, 55, 65 and 75 years, thinning intensity in the same order as the years 19%, 14%, 12%, 11%, 10% and 8%.	Final harvesting at age 110 years, initial target stem density 2500 ha^{-1}, six thinnings at stand age of 25, 35, 45, 55, 65 and 75 years, thinning intensity in the same order as the years 13%, 10%, 8%, 7%, 6% and 6%.

EFT	FM0	FM2	FM4	FM7	FM8
5	None	Final harvesting at age 125 years, six thinnings at a stand age of 25, 35, 45, 55, 65 and 75 years, thinning intensity in the same order as the years 15%, 13%, 10%, 9%, 8% and 7%. A pre-harvest with an intensity of 40% is carried out 10 years before the final harvest. After 5 years of natural regeneration trees are	Continuous harvesting at low intensity (5 m^3 $ha^{-1}year^{-1}$), limited by increment.	Final harvesting at age 125 years, six thinnings at a stand age of 25, 35, 45, 55, 65 and 75 years, thinning intensity in the same order as the years 18%, 16%, 12%, 11%, 10% and 8%. A pre-harvest with an intensity of 40% is carried out 10 years before the final harvest. After 5 years of natural regeneration trees are planted	Final harvesting at age 125 years, six thinnings at a stand age of 25, 35, 45, 55, 65 and 75 years, thinning intensity in the same order as the years 12%, 10%, 8%, 7%, 6% and 6%. A pre-harvest with an intensity of 40% is carried out 10 years before the final harvest. After 5 years of natural regeneration trees are planted up to the target stem density of 5000 ha_{-1}.

		planted up to the target stem density of 5000 ha^{-1}.		up to the target stem density of 5000 ha^{-1}.	

EFT	FM0	FM2	FM3	FM4	FM7	FM8
6	None	Final harvesting at age 125 years, six thinnings at a stand age of 25, 35, 45, 55, 65 and 75 years, thinning intensity in the same order as the years 13%, 14%, 13%, 12%, 10% and 9%. A pre-harvest with an intensity of 40% is carried out 10 years before the final harvest. After 5 years of natural regeneration trees are planted up to the target stem density of 2000 ha^{-1}.	Continuous harvesting every tenth year with an intensity of 25%, starting at a stand age of 70 years. Younger stands are thinned at a stand age of 30, 40 and 50 years with an intensity of 20%.	Continuous harvesting at low intensity (5 m^3 ha^{-1} $year^{-1}$), limited by increment.	Final harvesting at age 125 years, six thinnings at a stand age of 25, 35, 45, 55, 65 and 75 years, thinning intensity in the same order as the years 16%, 17%, 16%, 14%, 12% and 11%. A pre-harvest with an intensity of 40% is carried out 10 years before the final harvest. After 5 years of natural regeneration trees are planted up to the target stem density of 2000 ha^{-1}.	Final harvesting at age 125 years, six thinnings at a stand age of 25, 35, 45, 55, 65 and 75 years, thinning intensity in the same order as the years 10%, 11%, 10%, 10%, 8% and 7%. A pre-harvest with an intensity of 40% is carried out 10 years before the final harvest. After 5 years of natural regeneration trees are planted up to the target stem density of 2000 ha^{-1}.

EFT	FM0	FM9
14	None	Final harvest every 11-20 years, removing 15-25% of the basal area. Regeneration via sprouting and new shoots from roots. (PICUS and 3D-CMCC-FEM cannot model coppice sprouting at the moment)

3 Forest model runs

3.1 Comparing diverse forest management options at the stand level

A key aspect of the OptFor-EU decision support system is comparing different management options for the same initial forest condition and under the same climate forcing. This reflects the perspective of a forest manager, who has to select an alternative management scheme for a particular stand. For example, we show here tree carbon stocks (in tons of carbon per hectare, including live trees only) indicating changes in carbon storage under different forest management options for the CSA6 (Romania), EFT 6 (*Fagus sylvatica* L.), starting initialization at AC1 (age class 0-20) derived by RACMO22E and RCP 2.6 scenario (Fig. 3). FM0 has the highest tree carbon stocks for both forest models, since no carbon is removed through harvesting and carbon stocks are allowed to accumulate until the potential carbon storage.

FM2 in all simulated CSA represents shelterwood management, with final harvesting at 125 years, six thinnings every 10 years between the stand ages of 25 to 75, and an average intensity of about 12%. This FMP balances the demand for forest products with maintaining forest density, achieving high tree carbon stock values that are close to those of FM0. Increasing thinning intensity by 20% (FM7) addresses the need for larger-sized forest products, while reducing it by 20% (FM8) encourages less intensive management, leading to denser forests and higher carbon storage. Tree carbon stocks are increasing from FM7 to FM2 to FM8 (Fig. 3).

FM3 is a continuous forest cover management system that employs single-tree harvesting, removing individual trees every ten years starting at age 70, with an intensity of 25%. Over time, this method converts the stand into an uneven-aged forest. Primarily designed for production forests, FM3 can also be used in forests with specific protection roles, supporting sustainable management and maintaining forest structure. As a result of the selective thinning, the carbon stored in trees ranges between 100 and 200 tC ha^{-1} (Fig. 3), with this range remaining stable throughout the 21st century.

FM4 involves continuous low-intensity harvesting, removing 5 m^3 ha^{-1} per year, constrained by current forest increment. The low-intensity, continuous thinning creates a linear growth pattern, similar to FM0, but with lower maximum of tree carbon values. This gradual approach prevents the forest from reaching its highest potential stocks, maintaining more moderate levels over time. FM4 is well suited for forest stands on steep slopes, those managed for protection purposes, or areas prone to natural disturbances like windthrow, snow damage, or insect infestations, if wood harvesting at low levels is desired.

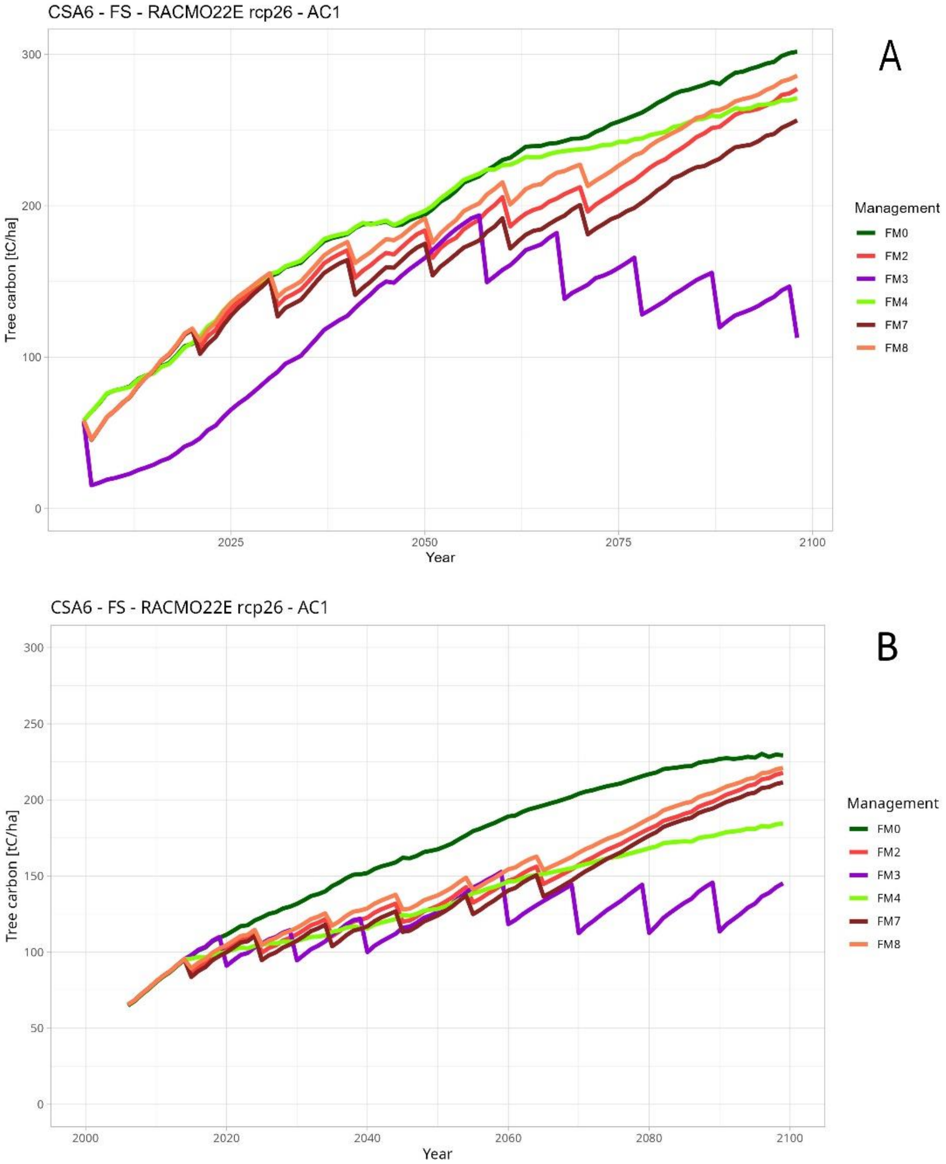


Figure 3 - Comparing forest carbon stocks (tC ha^{-1}) for one simulation unit (CSA6, EFT 6, initialization at age class 1, RACMO22E and RCP 2.6) simulated forest management options (see table 2) and using forest model PICUS (A) and 3D-CMCC-FEM (B).

3.2 Comparing effects of climate change scenarios at the stand-level

Comparing the impact of different future climate conditions (represented by varying climate forcing datasets) is important to judge feedback of climate and stand development. To make the results comparable between the two forest models and between the climate scenarios, the same FMP must be considered. This way we can isolate the effect of the climate conditions from that of management practices. Figure 4 shows the annual average temperature based on data from the regional climate model RACMO22E HADGEM2ES. These datasets correspond to the climate scenarios RCP 2.6, 4.5, and 8.5, extracted for the coordinates of the European beech stand EFT6 (*Fagus sylvatica L.*), located within the CSA6 in Romania. The scenarios begin to noticeably diverge after 2050, showing increasing variation in projected temperatures.

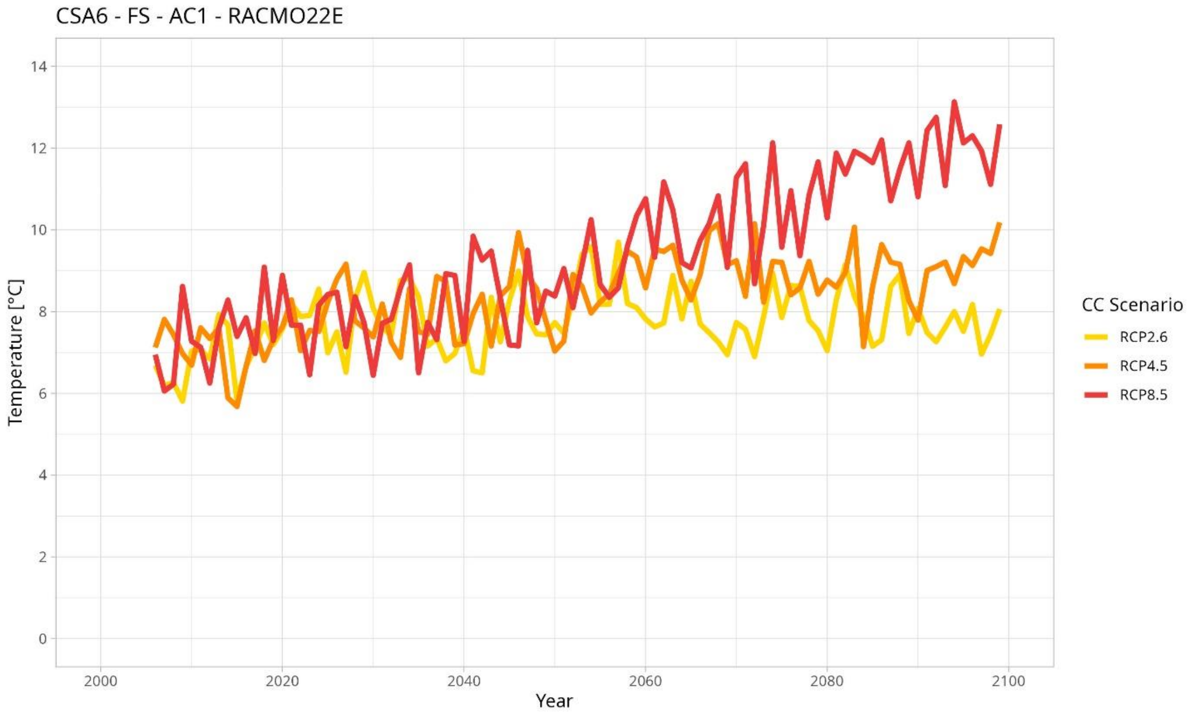


Figure 4 - Comparison of three climate input datasets (RACMO22E HADGEM2ES) using annual average temperature (°C) for CSA6 and EFT6.

Both forest models, PICUS and 3D-CMCC-FEM, exhibit sensitivity to climate variables, which results in varying simulated forest conditions depending on multiple factors. Specifically, the response of each model to changing climatic conditions is shaped by the different sensitivities of tree species and age classes to climate deviations. As shown in Fig. 5, the AC1 of EFT6 for CSA6 highlights how these sensitivities lead to diverse growth patterns for stand carbon storage and overall forest dynamics under different RCP scenarios. The tree carbon for the selected simulation unit is significantly influenced by temperature and atmospheric CO_2 concentration, both of which vary across climate scenarios. Certain trends become apparent when analyzing those values in the context of climate change.

Under RCP2.6, which represents a low-emission scenario designed to limit global warming, temperature rise is minimal (Fig. 4), and CO_2 concentrations remain relatively low due to strict mitigation efforts. Trees generally thrive in cooler environments with moderate CO_2 levels, which support efficient photosynthesis without inducing excessive heat stress. As a result, tree stands in RCP2.6 maintain the highest carbon stocks.

In contrast, RCP8.5, the scenario with highest emissions, projects rapid warming and much higher CO_2 concentrations. While elevated CO_2 can initially enhance tree growth through the CO_2 fertilization effect, the long-term adverse impacts of higher temperatures, such as reduced growth and diminished carbon storage capacity, outweigh the initial gains.

RCP4.5, which represents an intermediate pathway, displays similar but less severe effects. Although CO_2 levels are not as high as in RCP8.5, the temperature rise still exceeds the optimal range for many tree species. Therefore, carbon sequestration rates remain lower than in RCP2.6. Interestingly, during certain year intervals (Fig. 5), tree carbon levels in RCP4.5 are unexpectedly lower than in RCP8.5 probably due to local variations in climate impacts and tree species responses (*Fagus sylvatica L.*).

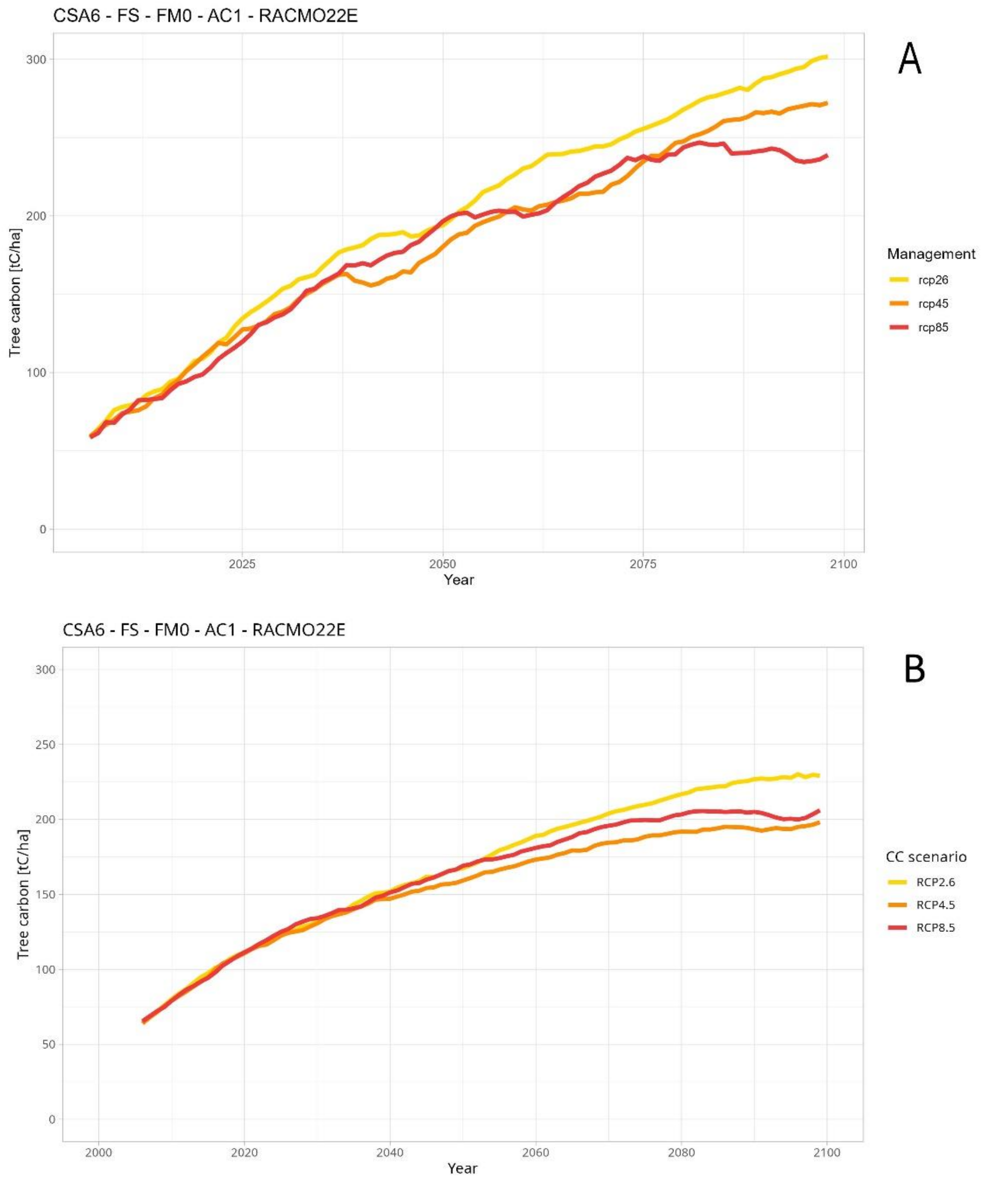


Figure 5 - Comparing tree carbon stocks (tC ha^{-1}) for one simulation unit (CSA6, EFT 6, age class 1, RACMO22E HADGEM2ES) using RCP scenarios (2.6, 4.5 and 8.5) and forest model PICUS (A) and 3D-CMCC-FEM (B).

3.3 Comparing diverse forest management options at the regional level

Forests consist of various development stages, typically categorized into stands of varying ages (cohorts) with a size of often less than 1 hectare. For regional assessments such as assessments of a forest enterprise or a management unit, the stands need to be aggregated to evaluate the effects of changing management on the considered area. We accomplish this by aggregating the simulation results of single stands for each year from 2006 until 2100. We can consider uneven distributions of age classes or EFTs at the initial state, by applying more weight to more frequently occurring age classes of EFTs. This aggregated view on multiple forest stands is important for modelling forests by RCM, for instance by simulating forests as a mosaic in pixels with a 3 to 10 km size. In these pixels the location of the forest stands is unknown, but stand properties such as leaf area index, albedo or roughness length affect the calculations and have to represent realistic conditions or need to be calibrated (Fig. 6).

For demonstration purposes, we here consider as the simplest case that every age class is present at the same share (8 age classes, each covering 12.5 % of the area).

This overview of forest management reveals two distinct groups of tree carbon storage levels. The first group, FM0 and FM4, shows similar and closely aligned trends; the second group, which includes FM2, FM3, FM7, and FM8, exhibits lower carbon storage values, falling into a distinctly lower range compared to FM0 and FM4.

FM0 consistently has the highest carbon stocks across stands, as no carbon is removed through thinning. FM4, on the other hand, employs a low-intensity continuous harvesting strategy, and while this approach also fosters a steady growth pattern, similar to FM0, the gradual thinning limits the forest carbon storage capacity. As a result, the total carbon stocks under FM4 remain lower than FM0.

The harmony tree carbon range values among FM2, FM3, FM7, and FM8 lies in their effort on sustainable forest management through regulated harvesting. Each of these FMP aims to balance the extraction of forest products with maintaining forest health and carbon storage, although they vary in thinning intensity and harvesting techniques.

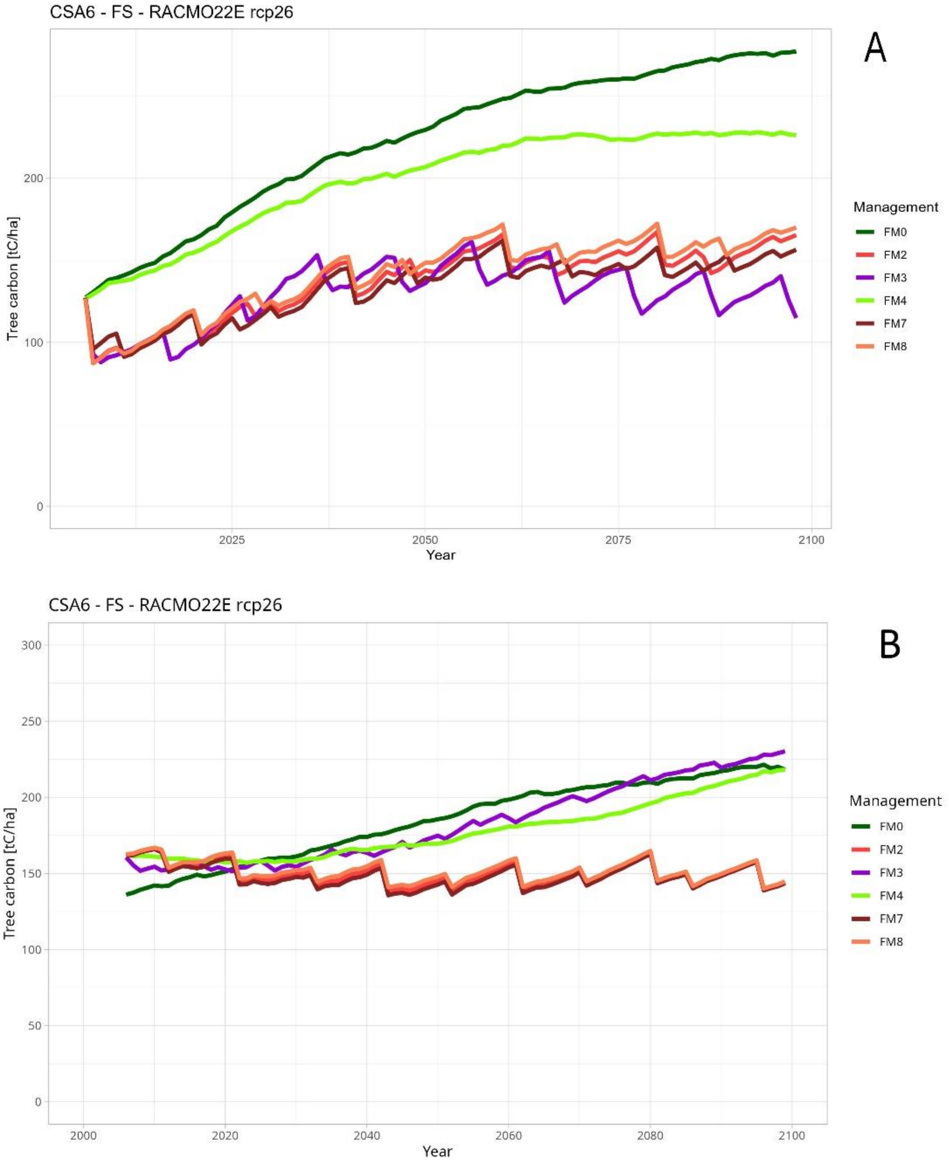


Figure 6 - Comparing averaged tree carbon stocks (tC ha^{-1}) for all age classes in one forest type (CSA6, EFT 6, RACMO22E HADGEM2ES and RCP 2.6) using simulated forest management options (see table 2) and forest model PICUS (A) and 3D-CMCC-FEM (B).

4 Implications of land cover parameterization in climate models

Changes in forest management can be considered by adapting land cover parameterization for RCMs and creating new PFT representing forest management alternatives. By considering varying thinning intensity, we will include shifting (1) from BAU to NOM, (2) from NOM to AFM, and (3) from BAU to AFM. To this end, a review of the characteristics of climate models and how they represent forest conditions and management practices has been conducted.

Two RCMs, REMO-iMOVE and RegCM, were used to study the response of climate forcing and management alternatives on climate indicators. Based on a multi-model ensemble approach, both models follow the same experiment protocols, enhancing the produced data's comparability.

Within OptFor-EU, we employ the new version of the 3d regional climate model REMO. REMO was developed as a hydrostatic atmospheric circulation model (Jacob & Podzun, 1997), which was constantly developed and received a non-hydrostatic dynamical core (Goettel, 2009). In our setup, REMO is interactively coupled to its mosaic-based vegetation module iMOVE (Wilhelm et al., 2014) enabling the interactive representation of processes between land-atmosphere and vegetation. This coupled version is named REMO-iMOVE. In REMO-iMOVE, the lower boundary of one model grid cell can be represented with separated tiles of land, water and sea ice with separated surface fluxes (Semmler et al., 2004). These fluxes are aggregated with regard to their fraction and transmitted to the atmosphere. In addition to fluxes, parameters of the separate tiles such as the surface roughness length are transmitted to the atmosphere by following the blending height concept after Claussen et al., (1991).

RegCM climate model has a non-hydrostatic dynamical core and uses map projections of Navier-Stokes equations using Lambert functions. Numerical discretisation uses an Eulerian frame, in a sign a vertical coordinate, split-explicit time integration (Arakawa-B with special treatment of topography). Physical parameterisations, adapted for climate simulations have multiple options for convection (mass-flux Tiedtke, Kuo, Grell, Emmanuel), explicit moisture (Pall, 2014), delta-edington radiation including H_2O, O_3, O_2, CO2, NO_2, CH_4, CFCs, option for non-local treatment of boundary layer process (Stull, aerosol direct/indirect, lake model, and few options for the land surface scheme. RegCMv5 uses optionally two land surface schemes BATS (Dickinson et al., 1993) and CLM (Oleson et al, 2013; Bonan, 1998). The Europe area simulations: control, historical and scenarios are performed with CLM4.5 land model. Forest ecosystem is parameterised to simulate water, carbon and simplified nitrogen fluxes (Running and Gower, 1991). CLM45 (scheme 1) includes updates regarding canopy process (radiation, multi-canopy layer, leaf process (Bonan et al., 2012); stomatal conductance model (Sun et al, 2012), hydrology (Swenson et al., 2012), updated litter and soil carbon and nitrogen pool (Koven at al., 2013), updated fire model (natural and anthropogenic triggers/ suppression, Li et al., 2013).

RegCM can consider 100-500 m spatial resolution data as input in “mosaic type” simulations. This allows using a higher resolution sub-gridding for representing surface conditions, performing flux computations at each sub-grid cell, while meteorological variables are disaggregated from the coarse atmospheric grid to the fine one based on the elevation difference. Mosaic approach will be used for management scenarios at high resolution. The comparison in this work, against full fine-resolution over an entire CSA, will allow estimates of the impacts of feedbacks versus bulk approach. Feedbacks are among the main sources of uncertainty in climate models. In fact, these are strongly linked to model parameterisations and interactions. In an earlier work (Caian et al., 2018), we found that using RegCM model and machine learning genetic algorithms can lead to significant skill improvement allowing to design an optimal set-up over a region, using multiple cross-parameterisations in the model. A more recent work (Kalmar et al., 2024) showed for the same area (CSA6) that the convection scheme in RegCM shows higher sensitivity, being a main uncertainty source, as well as through its interactions with other parameterizations (land-surface, microphysics).

Both regional climate models within OptFor-EU, REMO-iMOVE and RegCMv5 using CLM land surface scheme represent the land tile by using the concept of plant functional types (PFTs) (Wilhelm et al., 2014; Zeng et al., 2002). PFTs aggregate plant species with similar phenological and physiological characteristics while considering climate zones (Bonan et al., 2002; Wullschleger et al. 2014). Employing PFTs became a key feature representing vegetational processes in Earth System Modeling (Poulter et al., 2015). The number and the type of forest PFTs depend on the land surface parameterization of the regional climate model (RCM). For our experiments within WP2, REMO-iMOVE and RegCM+CLM employ the LUCAS LUC dataset (Hoffmann et al., 2022a, Hoffmann et al., 2022b) as well as the LANDMATE PFT dataset (Reinhart et al., 2022), which both have originally six different tree PFT classes:

- Tropical broadleaf evergreen trees
- Tropical deciduous trees
- Temperate broadleaf evergreen
- Temperate deciduous trees
- Evergreen coniferous trees
- Deciduous coniferous trees

REMO-iMOVE and RegCM can represent the land surface heterogeneity at the subgrid-scale by representing the land tile with multiple PFTs within one model grid cell. PFTs follow defined phenological behaviors and vegetational processes, which affect surface parameters directly and indirectly. The surface parameters of different PFTs are averaged based on their fraction affecting the land-atmosphere exchange processes. In the following section, we define the most important surface parameters and their role in land-atmosphere interactions.

Albedo plays an important role in the surface energy balance. It defines how much radiation is reflected by the surface, which directly affects the surface and near-surface temperature. Forest management practices can alter species composition and canopy cover thereby affecting albedo and its impact on temperature dynamics (Alkama and Cescatti, 2016).

Surface roughness influences the vertical wind profile and therefore it drives all turbulent exchange processes between the surface and the atmosphere. Forest management practices most commonly decrease canopy height by removing higher trees, in the case of an intensive thinning, or, as in the case of final harvesting of all trees. Low-intensity thinnings or thinnings targeting understory trees, will keep canopy height and thus surface roughness largely unchanged.

Leaf Area Index (LAI) varies with the annual cycle (much between deciduous species). It is an important driver of photosynthesis and evapotranspiration, in the last by influencing the transpiration of the plant as well as the interception of the leaves and reducing soil evaporation. Evapotranspiration affects the near-surface temperature as well as the moisture exchange between the land surface and the atmosphere. Forest management by removing trees and their leaf area, reduces LAI at least on short time frames. Trees remaining after thinning extend their branches and crowns and LAI will eventually recover to pre-thinning levels.

Due to the different model approaches and different spatial scales of regional climate models, land surface models and forest models, we will further analyze the FMP "thinning". Thinning is an important FMP in all CSAs and it is one (as its intensity and frequency) of the driving FMP in the simulation of the forest models.

From a biogeophysical point of view, thinning reduces biomass as well as LAI. In forest models, thinning is represented across different EFTs, with varying intensities and timescales. This information can be translated to the land surface parameterizations of the RCMs. Table 5 shows the current parameters describing vegetation properties and determining their response to climate conditions in REMO-iMOVE. Modified parameters sets could be an option to account for changes in forest conditions and/or management practices. Fig. 7 shows as an example of the LAI development in CSA6, under the current vegetation parameters set (Table 5). Fig. 8 shows mean changes contribution from Europe due to land-cover changes (dynamical LUCAS LUC data) in albedo and soil moisture, as simulated by RegCMv5, for the actual climate. Land-cover change succeeds to slightly increasing the albedo in summer (decreasing it otherwise with up to 9%) while for soil moisture, although decreasing in surface and mid-layers, it enhances the deep soil reservoir. PFT optical parameters used in the simulations are shown in Table 6.

Table 5 - Parameters used in REMO-iMOVE for describing forest types.

Name	Phenology type	Maximum carboxylation rate [1.E-6 Mol(CO2)/m^2/s]	Maximum electron transport rate [1.E-6 Mol/m^2/s]	Maximum LAI used in the LogoP scheme [m^2/m^2]	Carbon content per leaf area in [m2(leaf)/ mol(C)]	vegetation albedo	roughness length	Litter albedo value	Litter albedo factor
Tropical broadleaf evergreen trees	raingreen	62	118	7	0.264	0.12	2.0	0.36	4
Tropical deciduous trees	raingreen	76	152	7	0.376	0.135	1.0	0.36	4
Temperate broadleaf evergreen	raingreen	41	82	6	0.152	0.15	1.4	0.36	4
Temperate deciduous trees	summer green	35	70	5	0.307	0.175	1.0	0.24	3
Evergreen coniferous trees	evergreen	29	52	5	0.110	0.155	1.4	0.24	3
Deciduous coniferous trees	summer green	53	95	5	0.301	0.155	1.4	0.24	3

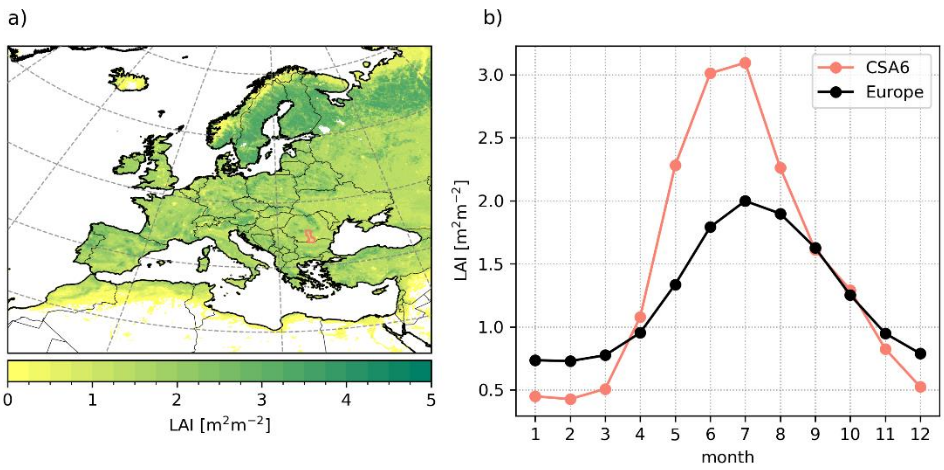


Figure 7 - Example output from REMO-iMOVE simulations using LUCAS LUC 2015 and forced with ERA5 at 0.11° horizontal resolution from 1981 - 2010 showing a) the LAI as temporal mean as spatial distribution over the European continent, and b) the development of the LAI over as mean annual cycle as area average over CSA6, Romania (red) and Europe (black).

Table 6 - Plant functional type optical properties in RegCM+CLM4.5

PFT	λL	αvl	αnl	αvs	αns	τvl	τnl	τvs	τns
NET Temperate	0.01	0.07	0.35	0.16	0.39	0.05	0.10	0.001	0.001
NET Boreal	0.01	0.07	0.35	0.16	0.39	0.05	0.10	0.001	0.001
NDT Boreal	0.01	0.07	0.35	0.16	0.39	0.05	0.10	0.001	0.001
BET Tropical	0.10	0.1	0.45	0.16	0.39	0.05	0.25	0.001	0.001
BET temperate	0.10	0.1	0.45	0.16	0.39	0.05	0.25	0.001	0.001

BDT tropical	0.01	0.1	0.45	0.16	0.39	0.05	0.25	0.001	0.001
BDT temperate	0.25	0.1	0.45	0.16	0.39	0.05	0.25	0.001	0.001
BDT boreal	0.25	0.1	0.45	0.16	0.39	0.05	0.25	0.001	0.001
BES temperate	0.01	0.07	0.35	0.16	0.39	0.05	0.10	0.001	0.001
BDS temperate	0.25	0.1	0.45	0.16	0.39	0.05	0.25	0.001	0.001
BDS boreal	0.25	0.1	0.45	0.16	0.39	0.05	0.25	0.001	0.001
C3 arctic grass	-0.30	0.11	0.35	0.31	0.53	0.05	0.34	0.120	0.25
C3 grass	-0.30	0.11	0.35	0.31	0.53	0.05	0.34	0.120	0.25
C4 grass	-0.30	0.11	0.35	0.31	0.53	0.05	0.34	0.120	0.25

Notes: NET=Needleleaf evergreen tree; NDT=Needleleaf deciduous tree; BET=Broadleaf evergreen tree; BDT=Needleleaf deciduous tree; BDS=Broadleaf deciduous shrub; α = reflectances (v=VIS, n=NIR); τ = transmittances ; λL = the departure of leaf angles from a random distribution (=1 for horizontal leaves, 0 for random and -1 for vertical leaves)

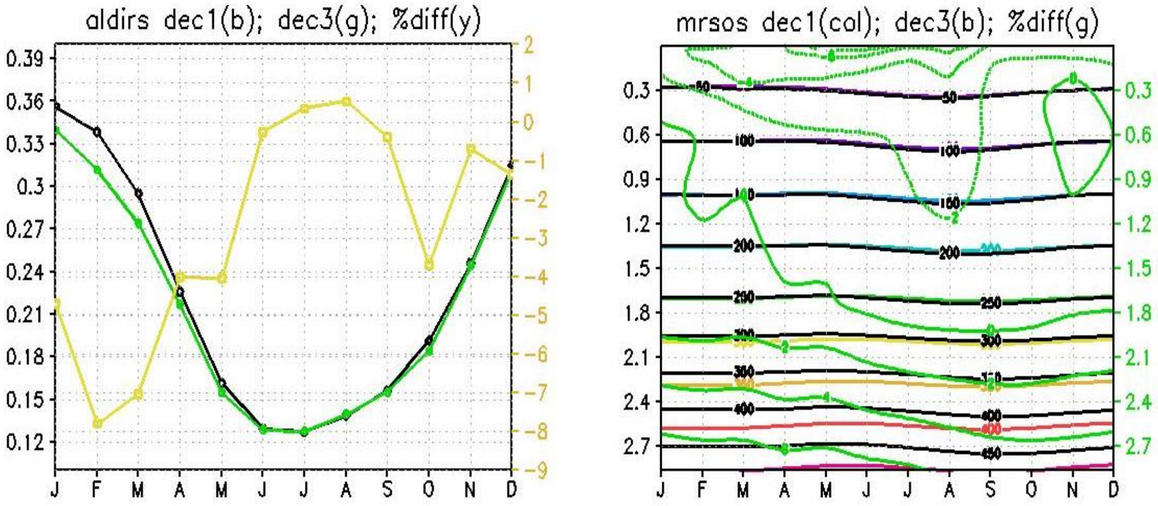


Figure 8 - Change in mean continental Europe albedo (left panel) due to land-cover change in LUCAS data: difference for decade 1996-2005 (green) relative to decade 1976-1985 (black; yellow line and labels show percent of change relative to 1976-1985); same results for the change in soil moisture (right panel, levels on Oy axis, [m]); simulations with RegCMv5 model with CLM4.5 land scheme.

5 Linking options of forest and climate models

In general, forest models and climate models are closely linked through the fact that forest models include climate data as forcing to prescribe climate information to plant processes. In OptFor-EU, this forcing data was selected from 2 members of the EURO-CORDEX initiative - HIRHAM5 and RACMO22E (Section 2). However, in OptFor-EU the link between forest and climate models should also be established in reverse.

The link between the regional climate models and the forest models can be established by using information on the FMP from the forest models and implementing it into the regional climate model process. Here, the link between forest and climate models can be accomplished by (1) modifying the model input, for instance by increasing forest cover and/or changing from broadleaf to coniferous forests. The parameters and fluxes of the modified PFT fractions in one grid cell will be aggregated and transmitted to the atmosphere. Another option is (2) modifying forest-specific parameters and/or forest properties, based on information from forest models' simulations. Climate models often see forests as similar to a single "big-leaf" and do not consider single stands (size ranging commonly from <1 to 10 hectares), but as a mosaic representing the forests in the simulation unit. Thus, climate models consider forests as aggregated units, rather than discrete forest stands with defined properties, located somewhere in a landscape or pixel. Another option is (3) to add vegetation parameters into climate models, such as canopy heterogeneity or the response of forests to thinning or harvesting. Roughness can vary between or within model grid pixels. As an example, a forest composed of trees with the same tree height of 20 m and a forest composed of small and large trees with a mean tree height of 20 m will have the same mean canopy height, but presumably different roughness by the spatial heterogenous canopy. Removing trees for natural or anthropogenic reasons creates gaps in the canopy and such interventions do not typically occur annually. After a silvicultural intervention, leaf area is commonly reduced and the recovery to pre-harvest condition can take several years to attain. Option (2) and (3) would require modifying the code model structure, whereas option (1) modifies the land cover input dataset.

We selected the FMP "Thinning" due to its important role in BAU and to its various options of implementation into the regional climate models. Following option (1), we are able to modify the forest - grass relation using information on thinning intensity and timing, whereas in option (2) we could include a new PFT. The most suitable approach is currently being explored.

Both regional climate models first, conduct simulations for the entire European continent on 12.5 km horizontal resolution for the historical and the future period under SSP126, which includes intense afforestation using the dynamic land cover changes from LUCAS LUC. This step allows the testing of effects of land cover changes on a coarser scale, while including all CSAs. In the second step, high-resolution simulations at convection-permitting scale (~ 3 km horizontal resolution) using the non-hydrostatic model versions are conducted for selected CSAs (i.e. CSA6 and CSA4) introducing the new FMP. CSA6 is covered by forest models and is thus chosen. Using CSA4 as a case study area will shed light on challenges forests are facing under climate stressors. Since 2018, the region has experienced extensive damage from storms, drought stress, and insect infestations, with high mortality in Picea abies stands leading to approximately 40,000 hectares of newly open areas, predominantly former Picea abies forests. In Lower Saxony, average crown transparency remains at record-high levels since data collection began in 1984, signaling significant tree cover loss (NW-FVA 2021). Nationally, forest losses totaled about 501,000 hectares from January 2018 to April 2021, a pattern also observed across Europe (Thonfeld et al., 2022; Knutzen et al., 2023). Findings from CSA4, particularly from Eastern Lower Saxony with its sandy soils and narrow selection of tree species, provide crucial insights for local adaptive strategies. These insights can also be scaled up to guide broader forest management practices in similarly affected regions, supporting carbon sequestration, rainfall absorption, and moderating local temperatures in response to climate change.

In order to further establish the link between forest and climate models, in OptFor-EU we will also use the project results to make recommendations for Earth System modeling. To demonstrate, we use the JULES land-surface model, a component of the UK Earth System model. The forest models' parameterisation of the EFTs and their results for different FMPs are being used to develop additional plant model tiles (similar in concept to the REMO-iMOVE plant functional types described above). Some parameters (e.g. leaf photosynthesis parameters, water stress, soil) can be translated directly from the forest model 3D-CMCC-FEM to JULES, as both can use similar schemes internally. So far, we have established a mapping from 3D-CMCC-FEM parameters to JULES parameters for 25 JULES plant tile input parameters, 3 JULES water stress input parameters and 9 JULES soil input parameters. Other JULES input parameters do not have a direct correspondence in 3D-CMCC-FEM. Critically, this includes the 4 plant tile input parameters that determine the relationship between the tree height, peak summer LAI and stem carbon on each plant tile. Varying the relationship between these parameters will enable us to capture the same FMPs. For example, this has the potential to allow JULES to model the difference between NOM (FM0) and continuous harvesting (FM4). So far, we have successfully calibrated these parameters to 3D-CMCC-FEM model output from NOM Pinus sylvestris runs, to show proof-of-concept. The forest model runs for distributions of age classes (described above) will be particularly useful to calibrate against, as creating a JULES plant tile that corresponds to the bulk properties of these runs reduces the number of plant tiles within JULES (as a separate tile is not needed for each age class). As noted for REMO-iMOVE above, JULES simulates forested area as “aggregated units”, and thus properties like “tree height” are aggregated properties, and only have one values per plant model tile, limiting the flexibility JULES has to represent additional structure within the tile. We will investigate whether other FMPs, e.g. clearcut, may be modelled better by utilizing the bioenergy module within JULES, which has an implementation of harvesting. In this case, separate tiles can be used for the thinned and non-thinned areas. Given that these tiles would only interact via root water availability, this module cannot be used for modelling FMPs where, for example, canopy shading is important. We will compare these alternatives against the forest model runs to ensure that these new plant tiles are correctly capturing the carbon and water fluxes for these EFT and FMP (D2.4). In this way, the forest model configurations and outputs from OptFor-EU (Section 2 and 3) will be used to calibrate new plant tiles that can improve the representation of European forests and their management strategies within Earth System Models.

6 Conclusions and next steps

Response of both forest models (i.e., PICUS and 3D-CMCC-FEM) on forest properties is stronger for alternative management options, than for different climate forcings, such as temperature, precipitation or CO2 concentrations (see Figs. 3 and 4 in this report and Dalmonech et al., 2022; Vangi et al., 2024b). This is a crucial finding highlighting the importance of forest management in mitigating climate change impacts, reinforcing the role of adaptive strategies in forest conservation.

No tree harvesting (FM0) and extensive tree harvesting (FM4, that is, continuous harvesting at low intensity) results in accumulating tree carbon, leaf area index and other forest characteristics related to stand density and tree size. While the removal of trees through different FMP (i.e., FM2, FM3, FM7 and FM8) leads to an evident reduction in tree carbon at the stand level stocks, compared to FM0 (Fig. 3), aggregating multiple forest stands into a mosaic the overall impact is buffered, but still detectable (Fig. 4). This is because the loss in one stand, especially associated to final harvest at the end of rotation period, is compensated by growth in others. Still the effects of forest management remains detectable for aggregated stands and thus forests across larger scales. This finding emphasizes the importance of considering forest management impacts on small-scale (forest stands), that combined determine the properties of forests on larger scales (i.e., regions, forest enterprises, countries), when implementing forest management in climate or land-surface models.

The differences between PICUS and 3D-CMCC-FEM in estimating potential carbon stocks without interventions stem from variations in biomass allometries and varying self-thinning, and mortality processes. These differences create uncertainty in model outputs, which can be addressed by validating the models with reference satellite data (e.g. net primary production, gross primary production, LAI, evapotranspiration) and ground observations. Examining uncertainty is a crucial next step to enhance the consistency of forest models and ensure they closely align with real present conditions.

Forest and climate models will be linked using simulation results derived from selected FMP (see section 2). Forest simulation outputs will provide critical data, such as LAI, canopy height, and other forest structure metrics, which can be applied in climate (RegCM and REMO-iMOVE) and land-surface (JULES) models. First, this data can be integrated to update and refine the land cover input datasets, allowing for more accurate representations of current forest conditions. Otherwise, the data can be used to adjust the model's parameterization by incorporating a new PFT. Both approaches ensure that the FMP influences the model representation of surface fluxes, as well as other key surface parameters within climate model grid cells. As a result, these changes influence land-atmosphere interactions, affecting local and regional climatic processes. Including FMP in climate models enhances the accuracy of future climate predictions by capturing the mutual relationship between forest dynamics and climate under varying management practices.

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