Deliverable C2.1, Part 3: LULUCF model

Documentation of Methods and Models for Climate Mitigation Mid-century Strategy Scenario Analysis

Final report

LIFE ClimatePath2050 (LIFE16 GIC/SI/000043)

Projekt LIFE ClimatePath2050 (LIFE16 GIC/SI/000043) je sofinanciran iz sredstev LIFE, finančnega inštrumenta Evropske unije za Okolje in podnebne spremembe na prednostnem področju Podnebno upravljanje in informacije in iz sredstev Ministrstva za okolje in prostor RS, Sklada za podnebne spremembe.
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Deliverable C2.1: Documentation of Methods and Models for Climate Mitigation Mid-century Strategy Scenario Analysis, Part 3: LULUCF model, final report

Poročilo projekta št. C2.1, Metode in modeli za analizo strateških scenarijev blaženja podnebnih sprememb do sredine stoletja, Tretji del: Model rabe zemljišč, spremembe rabe zemljišč in gozdarstva (LULUCF), končno poročilo

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Table of Contents

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Introduction

In the scope of LIFE ClimatePath2050[1] the **Deliverable C2.1: Documentation of Methods and Models for Climate Mitigation Mid-century Strategy Scenario Analysis**, **Part 3: LULUCF model** was prepared. The document presents the information on the models developed or updated in the scope of the project along with some basic results.

The composite deliverable C2.1: Documentation of Methods and Models for Climate Mitigation Mid-century Strategy Scenario Analysis consists of several parts, namely:

- **Part 1: Summary report on methods and models for scenario analysis**, condense summary report on methods and models for scenario analysis;
- **Part 2: Energy sector models**, includes the detailed information on sectoral models used for climate mitigation scenario analysis, the report enlightens general approach and presents final energy demand and supply models including households, services and agriculture energy use, energy use in transport and industry, models for district heating expansion analysis and CHP cross sectorial impact, distributed electricity production assessment and optimisation of power sector operation;
- **Part 3: LULUCF model**, includes the detailed information on Carbon Budget Model (CBM-CFS3) that is used for simulating the dynamics of forest carbon pools, considering various assumptions such as the type of forest management, land use changes, the occurrence of natural disturbances and timber harvesting;
- **Part 4: Other IPCC sectors agriculture, sector process emissions, IPCC sector waste**, includes information on the models used for assessing agriculture sector, process emissions and waste in accordance with IPCC;
- **Part 5: Macroeconomic model**, includes the detailed information on the newly developed multi-sectoral Computable General Equilibrium model (CGE) of the Slovenian economy (GreenMod Slovenia) that was developed and used specifically for the analysis of energy and environmental issues, considering the quantitative results of the energy sector models.

The deliverable **Part 3: LULUCF model**, includes the detailed information on Carbon Budget Model (CBM-CFS3) that is used for simulating the dynamics of forest carbon pools, considering various assumptions such as the type of forest management, land use changes, the occurrence of natural disturbances and timber harvesting. The model has been developed and revised in the scope of LIFE ClimatePath2050 project.

1 LIFE ClimatePath2050 (Slovenian Path Towards the Mid-Century Climate Target)

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1 Purpose of the model

The Carbon Budget Model of the Canadian Forest Service (CBM-CFS3) (Kurz et al., 2009) is a freely available model that allows simulation of changes in forest carbon stocks using five forest carbon pools: 1) aboveground biomass, 2) belowground biomass, 3) deadwood, 4) mineral soils, and 5) litter. The model is primarily intended for modelling even-aged forests but can also be applied to uneven-aged forests, as demonstrated in the case of Italy (Pilli et al., 2013).

The model works on the basis of a forest inventory database and yield curves describing the development of growing stock in relation to the age of forest stand age. The CBM-CFS3 simulates the dynamics of forest carbon pools, considering various assumptions such as the type of forest management, land use changes, the occurrence of natural disturbances and timber harvesting. The model is consistent with the concept of the Intergovernmental Panel on Climate Change (IPCC) reporting standards. The spatial scale can range from individual forest stands to forest types and landscape spatial units. Simulation results are provided on an annual basis, separately for all five carbon pools (Kurz et al., 2009). Advanced options for viewing displaying the results allow analyses of carbon transitions between forest carbon pools, the atmosphere, and harvested wood products.

The LIFE ClimatePath 2050 project developed growth curves for different forest types, updated Archive Index Database (AIDB) parameters, and adapted the disturbance matrix to Slovenian conditions. The model was used to generate GHG projections for forest land until 2050 (NECP, 2020), simulate the impact of forest management on carbon sink dynamics (Jevšenak et al., 2020) and provide guidance in setting future forest policy in Slovenia.

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2 Model Inputs

2.1 Internal Input Parameters

Data sources and data preparation

Two basic data sources were used to run the model, both provided by the Slovenia Forest Service (SFS): 1) the 2014 Forest Compartment Database and 2) the Permanent Sample Plot (PSP) Database. The Forest Compartment Database consists of approximately 53,000 forest compartments with an average size of 22 ha, which are permanent forest planning categories and include information on all forests in the country. For each compartment, various forest attributes are available, such as forest area, forest type, growing stock, and tree species composition. Based on the forest type data, similar forest compartments were grouped together and represent the baseline forest condition in 2014. PSPs are part of the control sampling method in Slovenia (Kovač and Hočevar, 2010). Each plot (500 m^2 each) is resurveyed every ten years, and common tree attributes are collected for each tree in the plot, such as location, tree species, DBH, height of selected trees, and status between successive inventories (e.g. unchanged, harvested, dead, ingrown).

The input data of the model (Figure 1) are represented by seven independent matrices created in Microsoft Access format:

1. the Classifiers and Values matrix defines the number of model units and the classifiers that define them. In our case, the classifiers were defined by the individual forest types and further subdivided by the proportion of conifers / deciduous trees.
2. the Age Classes matrix defines the range of existing age classes and the degree of transition from one age class to another. The age class matrix defines the number of years included in each age class and hence the maximum age of the forest types.
3. the Inventory matrix describes the initial state of the forests, which includes the areas of each forest type, further divided into mixture and age classes.
4. the Growth and Yield matrix determines the development of woody biomass in the forests as a function of age for each forest type.
5. the Transition Rules matrix can be used to describe the transition from one forest type to another. For example, a large-scale disturbance affecting a mature spruce stand may result in a different forest type with a higher proportion of deciduous trees and thus greater resilience to natural hazards. In our project, we did not use the transition rules matrix because the 30-year time frame is realistically too short to implement such transitions in real life.
6. the Disturbance Types matrix precisely defines disturbances and their influence and later links them to the disturbance parameters defined in the Archive Index Database. The Disturbance Types Matrix includes natural and man-made disturbances, including harvesting. More than 100 disturbance types are available, ranging from wildfires to bark beetle outbreaks to various types of timber harvesting. In addition, the user has the

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option of determining the type of disturbance and the intensity of its impact on the forest carbon pool itself.

7. the Disturbance events matrix defines the amount of biomass removed from each forest type on an annual basis. Disturbances can be expressed in absolute spatial units or as a proportion of area over which the disturbance can occur. For each year of the simulation, the disturbance must be associated with a specific forest type and its age class and linked to one of the available disturbance types from the archive index database.

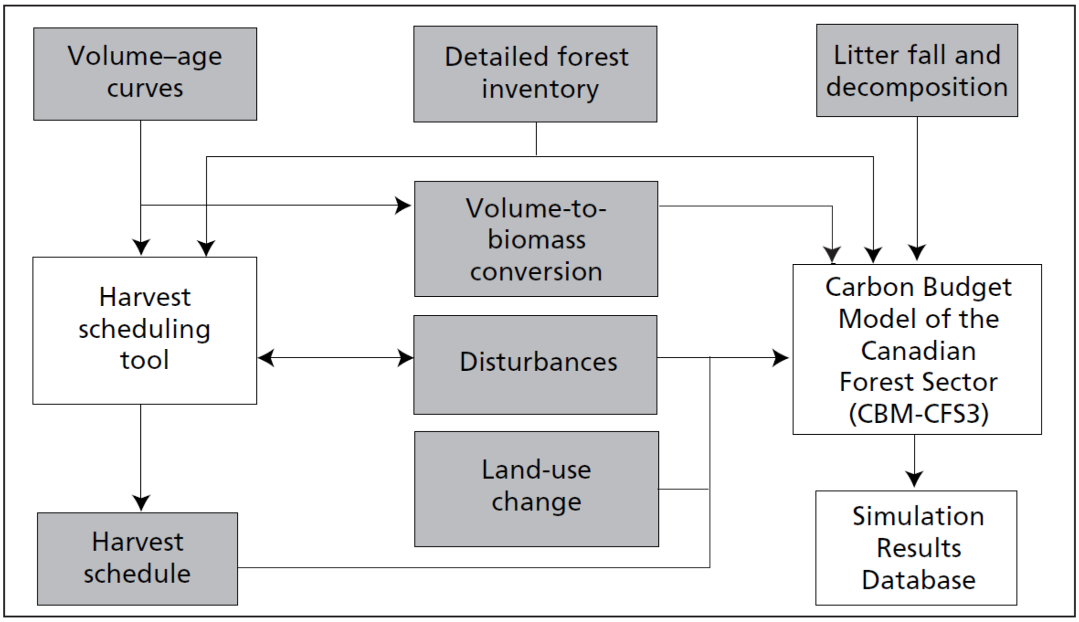

Figure 1: Data input (grey boxes) required by the CBM-CFS3 (Kull et al., 2016)

The definition of model classifiers

Model classifiers were defined as a combination of forest type and tree species mixture. Forest type was determined according to the typology of Slovenian forest sites (Kutnar et al., 2012) (Table 1). Tree species mixture was represented by three categories based on the predominant tree species: 1) if the total growing stock of broadleaves within a compartment was greater than or equal to 75%, the forest compartment was classified as broadleaf forest; 2) if the total growing stock of conifers was greater than or equal to 75%, the forest compartment was classified as coniferous forest; and 3) in all other cases, the forest compartment was classified as mixed forest, which was the predominant category in all forest types (Table 1). Finally, 43 actual model classifiers were defined.

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Tab. 1: Forest types defined by Kutnar et al. (2012), assigned climate unit from the Archive Index Database, total share of areas among different forest types and the share of broadleaved (BRD), coniferous (CON) and mixed (MIX) stands within each forest type

Short	Forest type	Climate unit	Total share	BRD	CON	MIX
FT1	Forests of *Salix* spp. with *Populus* spp., forests of *Alnus glutinosa* and of *A. incana*	Slovenia CLU35	0.02	0.04	0.01	0.95
FT2	Forests of *Carpinus betulus* and of *Quercus petraea* on carbonate and mixed bedrock	Slovenia CLU45	0.07	< 0.01	< 0.01	0.99
FT3	Forests of *Carpinus betulus* with *Quercus petraea* on silicate bedrock	Slovenia CLU45	< 0.01	< 0.01	< 0.01	0.99
FT4	Submontane *Fagus sylvatica* forests on carbonate and mixed bedrock	Slovenia CLU55	0.16	< 0.01	< 0.01	0.99
FT5	Submontane *Fagus sylvatica* forests on silicate bedrock	Slovenia CLU45	0.16	< 0.01	< 0.01	0.99
FT6	Montane, altimontane and subalpine *Fagus sylvatica* forests on carbonate and mixed bedrock	Slovenia CLU55	0.13	< 0.01	0.01	0.99
FT7	Montane and altimontane *Fagus sylvatica* forests on silicate bedrock	Slovenia CLU54	0.08	0.01	0.02	0.97
FT8	Forests of *Fagus sylvatica* with *Abies alba*	Slovenia CLU55	0.14	0.01	0.01	0.98
FT9	Forests of *Acer* spp., of *Fraxinus excelsior* and of *Tilia* spp.	Slovenia CLU55	< 0.01	0.01	0.01	0.98
FT10	Thermophilous *Fagus sylvatica* forests	Slovenia CLU55	0.06	0.01	0.01	0.98
FT11	Forests and woodlands of thermophilous broadleaves	Slovenia CLU56	0.08	< 0.01	0.02	0.98
FT12	Forest of *Pinus sylvestirs* and of *Pinus nigra*	Slovenia CLU55	0.02	< 0.01	0.02	0.98
FT13	Forests of *Abies alba* and of *Picea abies* on carbonate and mixed bedrock	Slovenia CLU54	0.01	< 0.01	0.10	0.90
FT14	Forests of *Abies alba* and of *Picea abies* on silicate bedrock	Slovenia CLU54	0.04	< 0.01	0.06	0.94
FT15	Forests of *Larix decidua* and *Woodlands of Pinus mugo*	Slovenia CLU54	0.01	0	0	1.00

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The archive index database

All parameters needed to initialise the model are contained in the Archive Index Database (AIDB), which has been adapted for the Member States of the European Union. The AIDB is a Microsoft Access database that keeps track of the relationship between model inputs and outputs, tracks the status of simulations, and stores all the default information and parameters that the model applies when a new project is created. The EU-AIDB contains 1034 spatial units resulting from the intersection of 204 European administrative regions and ecological boundaries representing 35 climatic units (Figure 2, Table 1). It also contains updated parameters for 192 of the main tree species listed in the national forest inventories of each EU country. More specifically, it provides an appropriate set of ecological parameters that are necessary and have an impact on the carbon cycle, such as the decay rate of dead organic matter, the transfer of carbon between carbon pools and litterfall characteristics, and the set of volume-to-biomass conversion coefficients for European tree species which are important for the correct conversion of merchantable volume to biomass and foliage components. The majority of forest types were classified into the following climatic units: Slovenia-CLU55 (central and southern Slovenia), Slovenia-CLU45 (Savinja and Styria regions) and Slovenia-CLU54 (montane and altimontane forests at higher altitudes in the Alps and Pohorje Mountains).

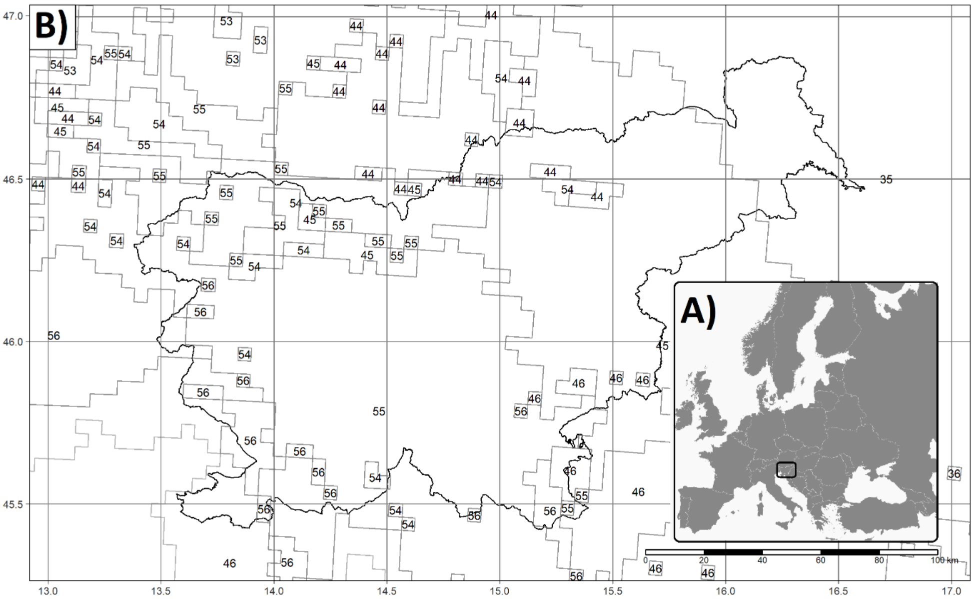

Figure 2: Map of Slovenia and Europe and climate units from the Archive Index Database

Development of growth curves and determination of age

To initialise and run the CBM-CFS3, at least the following input data are required for each classifier: areas by age classes and yield curves. Areas were calculated from the Forest Compartment Database and yield curves from the Permanent Sampling Plots (PSP) database. In Slovenia we do not classify forest stands into age classes when planning forest management, moreover we manage a significant area of uneven-aged stands, we had to define the (approximate) age of each stand on PSPs, first. We did that following the ensuing methodology.

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The dominant diameter DBHdom per plot (i.e. mean DBH of the 100 thickest trees per hectare) was calculated for the two most recent measurements (DBHdom.0 and DBHdom.1); both were then classified into DBH classes of 5 cm. For each PSP, the average diameter increments of dominant trees (IDBH.dom) was calculated as the difference between DBHdom.1 and DBHdom.0. Based on the IDBH.dom, the transition periods that dominant trees needed to overgrow the observed DBH class were calculated for each forest type. By summing these transition periods from that of the lowest DBH class to that of the observed DBH class on a plot, we estimated the age of a stand on each PSP. When the age of a stand was calculated, we assumed that dominant trees need 20 years to achieve the DBH measurement threshold of 10 cm, regardless of the forest type they grow in. With all that data, we could finally classify stands on PSPs into age classes spanning 20 years each. We classified 10 age classes, each ranging 20 years, but the oldest age class (AGEID09) included all stands with an age greater than 181 years (Table 2).

The forest area was calculated for each forest type by summing the areas of the compartments of that forest type. The total area of each forest type was then proportionally divided into mixture types and age classes according to the share of PSPs of each combination of mixture type and age class. Since PSPs are generally not tallied in young forests, the youngest age class (0-20 years) included the areas of young forests obtained from the stand map of the SFS.

For each classifier, the yield curve was calculated using Equation 1, where GS represents growing stock, AGE is the middle age of an age class, and a, b, c represents model parameters. For all forest types, yield curves for 43 classifiers were developed (Figure 3) according to the method described.

GS = a + b · AGE + c ·AGE2 (Equation 1)

Tab. 2: Share of harvesting for each age class

Age Class	Age	Share
AGEID00	0 – 20	0.000
AGEID01	21 – 40	0.001
AGEID02	41 – 60	0.001
AGEID03	61 – 80	0.019
AGEID04	81 – 100	0.233
AGEID05	101 – 120	0.431
AGEID06	121 – 140	0.230
AGEID07	141 – 160	0.070
AGEID08	161 – 180	0.010
AGEID09	181 +	0.006

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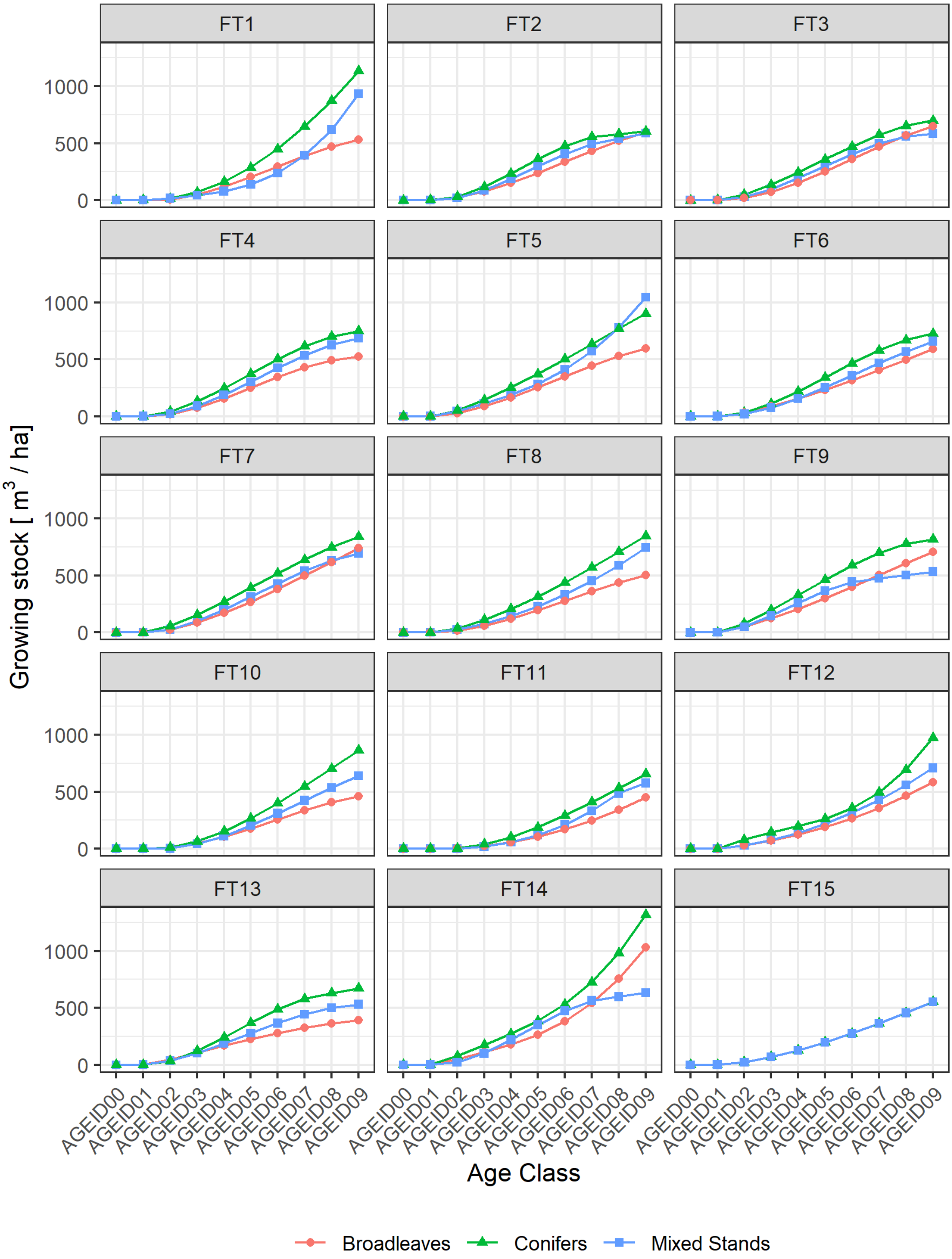

Figure 3: Growth curves by forest type (FT) and tree species mixture categories

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Distribution of felling by forest types and age classes

In a disturbance matrix, we defined the type and amount of felling by classifiers and age classes for each year of the simulation. The annual felling rate was first allocated to classifiers in line with the existing volume shares in 2014. The highest harvesting amounts were therefore directed towards classifiers with the largest volume share in the inventory database, such as FT4 and FT5 mixed forests (Table 1). For each classifier, the harvest amount was then distributed by age classes according to the proportions representing the actual timber harvest in the last ten years (Table 2). These shares were estimated on the basis of information from the SFS harvesting databases. Two disturbance types, namely commercial thinning and final felling were defined, whereby for each year a portion of final felling was allocated to the oldest forests. The stand maps were used to determine the percentages of final felling, which were 16% (BAU, PLAN and LH), 18% (HAZ) and 20% (HH). Final felling affects the regeneration of stands, since the model starts a new succession stage with age equal to 0.

2.2 Key assumptions, scenarios and border conditions

To simulate the dynamics of the carbon sink in Slovenia until 2050, we defined 5 different forest management scenarios. All scenarios are based solely on the assumption of future harvest intensity and the amount of harvested biomass, as the latter most strongly determines the dynamics of the carbon stock (Figure 4):

1. business-as-usual (**BAU**),
2. harvesting in line with current forest management plans (**PLAN**),
3. more frequent natural hazards (**HAZ**),
4. high harvest (**HH**),
5. low harvest (**LH**).

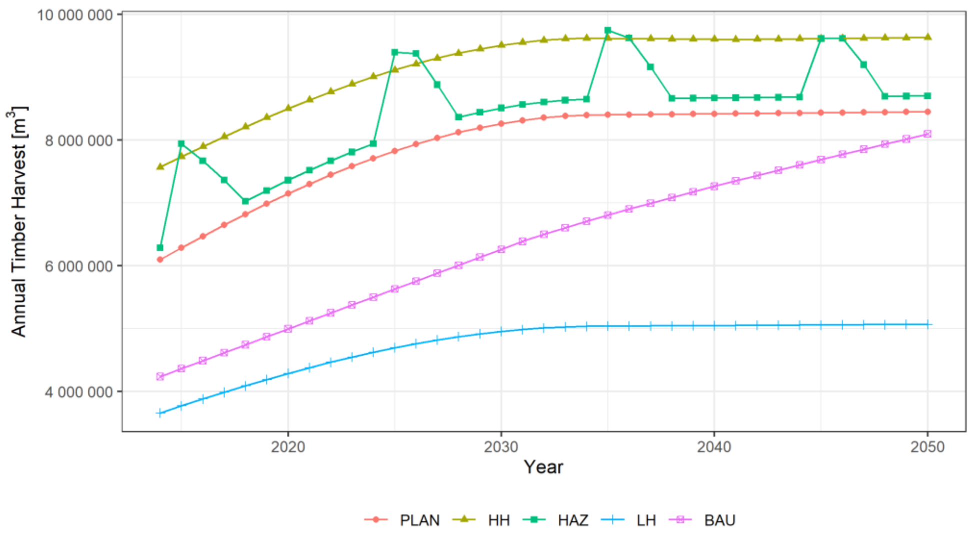

Figure 4: Annual timber harvest in the period 2014–2050 for five scenarios: business-as-usual (BAU), forest management planning (PLAN), natural hazards (HAZ), high harvest (HH) and low harvest (LH)

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Note that the assumptions according to the scenario with existing measures (WEM) included in the NECP are similar to those of the BAU scenario, but the trend in harvest volume is slightly different. The scenario foresees the implementation of measures in line with the adopted strategies for the LULUCF sector. The demand for wood, i.e. the volume and composition of wood products extracted, is in line with the trends of recent years. It is assumed that market participants do not change their habits. The rate of increase due to the abandonment of agricultural activity is roughly equal to the rate of deforestation, which means that the forest area remains unchanged. Trends in land use change remain the same as in previous years.

The BAU scenario is based on the realised timber harvest in the past 10 years. Importantly, the BAU scenario does not account for additional harvesting due to natural disturbances. Based on the amount of timber harvested in the period 2004–2019 (SFS, 2019) and omitting data from years in which natural disturbance events occurred (2014–2016, 2018), the harvest intensity was regressed as a function of time ($R^2 = 0.789$). Prior to 2030, we used the calculated function to estimate annual timber harvest, while it was assumed that the harvest amount would increase by 1% per year in the period 2030–2050. Thus, we assumed a progressive increase in harvesting, which is expected to exceed 8 million m^3 in 2050. When determining the PLAN scenario, we followed the recommendations from forest management plans where the annual allowable cut is defined at rate of 75–90% of the annual stand volume increment (SFS, 2019). The annual harvested amount in the PLAN scenario was determined by fitting the negative exponential function, with the dependent variable being the increase in the rate of planned harvest compared to the planned harvest in the previous year ($R^2 = 0.358$). To calculate the adjusted values, we used the planned harvest in 2004 of 4,162,662 m^3 (SFS, 2005) as a starting point. Until 2035, the degree of increase of the harvested biomass took place pursuant to the calculated function; after 2035, a constant level of increase of 0.04% per year was used. The HAZ scenario was also based on the PLAN scenario and assumed a 3% increase in harvesting levels on an annual basis, as well as four extraordinary natural disturbances, appearing in an interval of approximately 10 years and assuming an increase in harvest intensity over the following three years, which is usually a consequence of bark beetle outbreaks (de Groot and Ogris, 2019). The HH and LH scenarios are primarily based on the assumption of the annual allowable cut of the PLAN scenario, but the intensity of harvesting in the HH scenario was increased by approximately 30% and in LH reduced by 40%. With the selected increase and reduction, we wanted to obtain higher range of annual harvesting levels, which could be potentially beneficial for the evaluation of harvesting levels on carbon stocks.

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3 Model structure

3.1 Methodology

The CBM-CFS3 is a landscape-level model of forest ecosystem carbon dynamics that forest managers and analysts can use to assess carbon stocks and changes in carbon stocks in their operational forest areas. It was initially developed for use in even-aged forests where the age of the trees is known. However, if the yield curves realistically describe the development of individual stands of different species, the model can also be used in mixed forests with uneven age, typical of Slovenia (Bončina, 2000). Although the model was primarily developed to assess carbon dynamics at the operational scale, it can also be used to study carbon dynamics for smaller areas down to the stand level. The model can be used to assess past changes in carbon stocks using information on past management actions and natural disturbances, or to assess future changes that would result from scenarios of management actions and natural disturbances. The CBM-CFS3 accounts for carbon stocks and stock changes in the tree biomass and dead organic matter pools (DOM) (Kull et al., 2016).

The structure of the CBM-CFS3 model includes three or four main steps, depending on the purpose for which the model is used (Figure 5): 1) a pre-processor program that prepares the inventory database and generates the dead biomass pool, 2) compiling assumptions and simulations, 3) a pre-processor program that calculates carbon stocks for individual pools and sites on an annual basis during simulation, and 4) an archive index database that contains model parameters and links them to input data and simulation results. Changes in belowground biomass are calculated using the method presented by Li et al. (2003). One of the key definitions included in the CBM-CFS3 model is growing stock, which is defined as the gross volume of merchantable biomass comprising the volume within the bark of the main stem, excluding tops and stumps but including defective and decayed wood of trees or stands (Kull et al., 2016).

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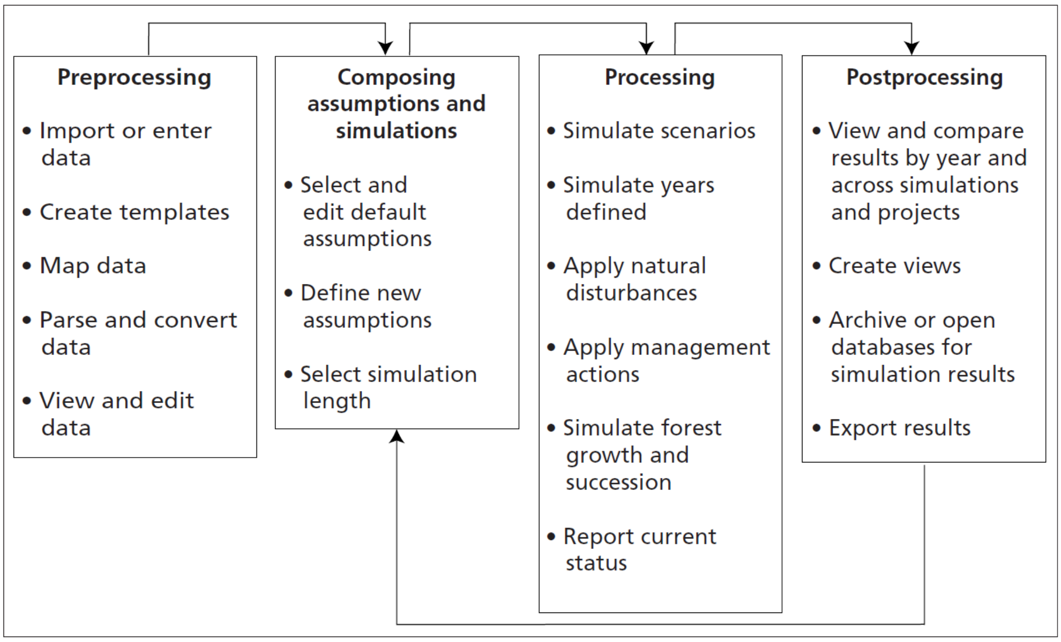

Figure 5: The main stages of the analysis using the CBM-CFS3 model (Kull et al., 2016)

3.2 Technologies, sectors, processes

The forest sector was the only sector considered in the simulations using the CBM-CFS3 model. The projections of GHG emissions and removals in other LULUCF sectors, such as grasslands, croplands, etc., were produced using standard methods used for annual reporting according to the IPCC Guidelines. Note that carbon stock changes in harvested wood products were not estimated by the CBM-CFS3 model, but also by applying the IPCC methods.

3.3 Connections with other models

The CBM-CFS3 is a stand-alone model and does not depend on any other model.

3.4 Future development of the model and research challenges

Other challenges of the model include identifying sources of uncertainty and improving the disturbance matrix, but this depends on improving assumptions about natural disturbances and climate change.

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4 Model results

The accumulation of carbon stock in living above- and below-ground biomass coincides with the predicted harvest intensity for each scenario, whereby the accumulation is the highest for the LH and BAU scenarios. Both of these scenarios envisage the lowest harvesting up to 2050 compared to the other scenarios (Figure 4). An increase in carbon stocks in above-ground biomass is generally expected, as the anticipated harvesting levels are mainly lower than the annual volume increment in Slovenian forests of approximately 9 million m^3 (SFS, 2019). After 2025, the HH scenario assumes that harvesting will exceed the total volume increment (Figure 5). By 2050, the carbon stock in above-ground biomass increases by 28.4% (LH), 19% (BAU), 10% (PLAN), 6.5% (HAZ) and 1.2% (HH) compared to the base year of 2014. In the case of below-ground biomass, these shares were the highest in the LH (16.9%), BAU (8.4%) and PLAN (1.1%) scenarios, while stocks in below-ground biomass in the HAZ and HH scenarios decreased by 1.2% and 6.3%, respectively. The analysis of the temporal dynamics, considering the change in carbon stocks in living biomass (i.e. above- and below-ground), show that Slovenian forests will remain a carbon sink under all scenarios, with the exception of the HH and HAZ scenarios in some years (Figure 5). The average annual CO_2 sinks in the period 2014–2050 according to the scenarios are as follows: −4187 (LH), −2455 (BAU), −1093 (PLAN), −648 (HAZ) and −5 (HH) Gg CO_2 (Figure 6).

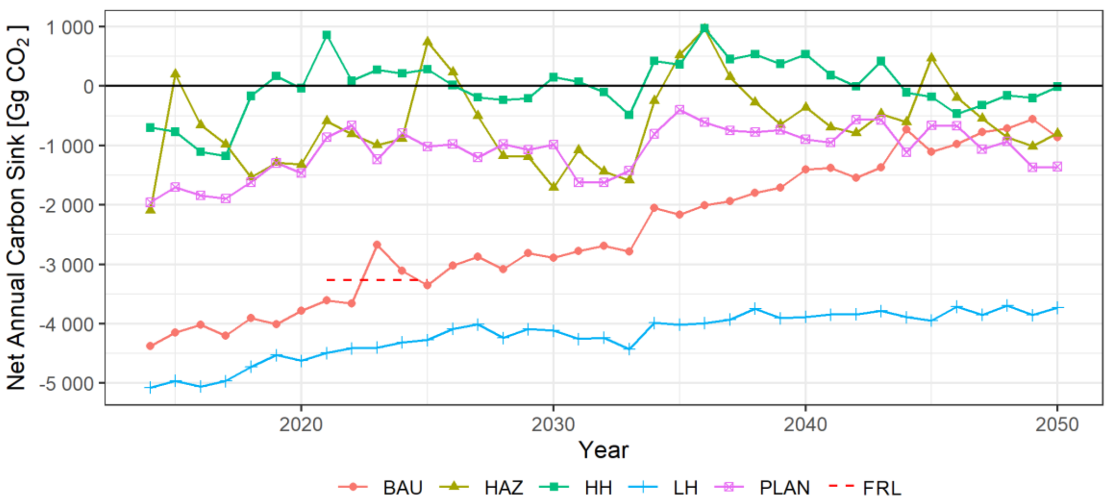

Figure 6: Carbon sink scenarios for Slovenian forests up to 2050 in gigagrams (Gg) of CO2. Note that only living biomass pools (above- and below-ground) are compared here. The short dashed line depicts the Forest Reference Level (FRL), which refers to the proposed forest reference level determined by Slovenia for the 2021–2025 period (European Commission, 2020)

Higher harvesting levels have a negative effect on carbon stock in litter and soil, but also a positive effect on accumulation of carbon stock in deadwood (Figure 7). The effect on the carbon stock in the soil and litter becomes more pronounced after 2030 and 2035, respectively,

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when the differences between the scenarios begin to increase. Carbon stock in deadwood has doubled (scenario LH) or tripled (scenarios HH, PLAN and HAZ) in 2050 compared to the base year 2014. However, deadwood accumulation largely depends on conservation measures and the attitude of forest owners towards deadwood, thus the results might not reflect the true dynamics in Slovenian forests.

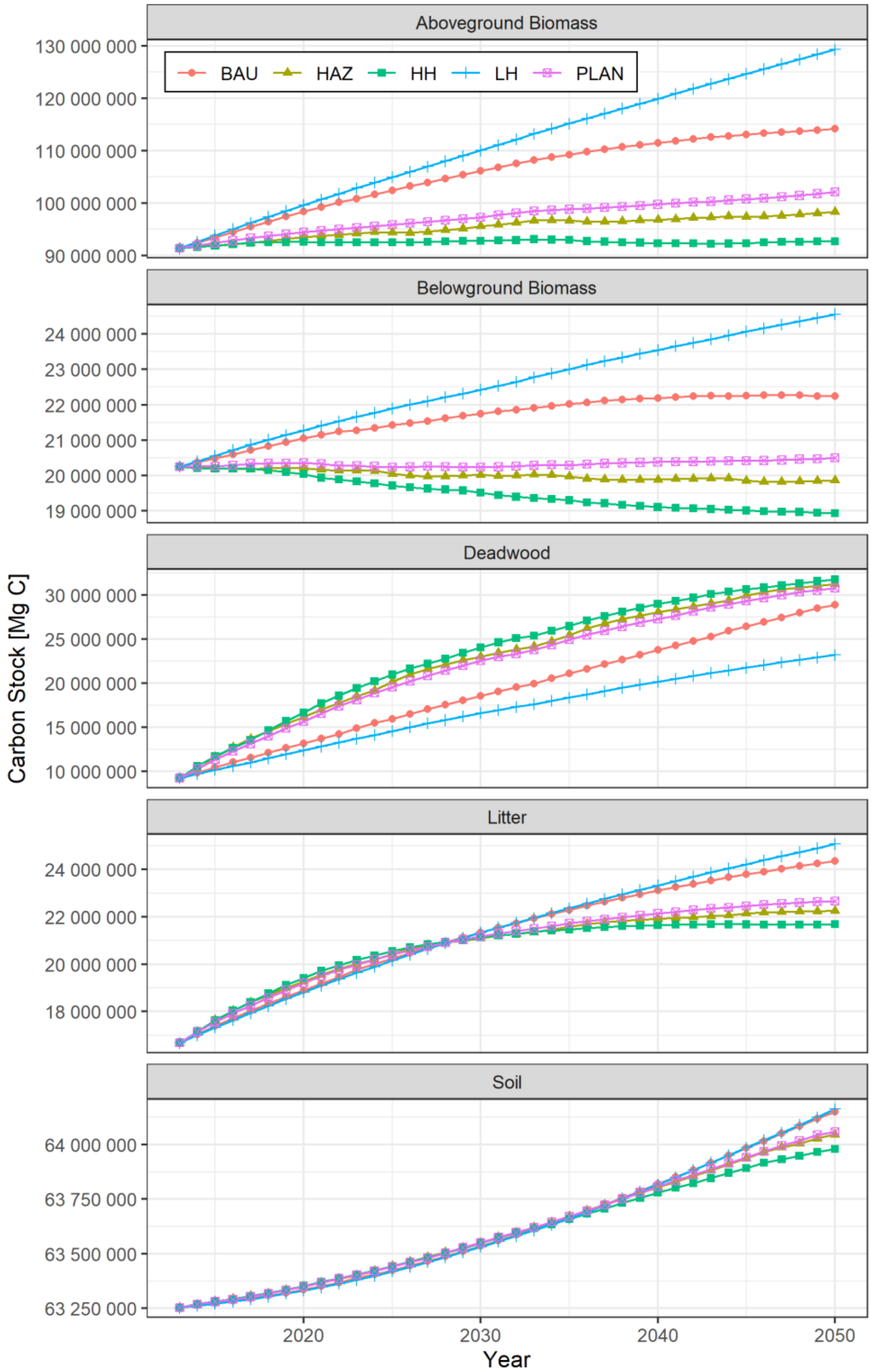

Figure 7: Carbon stocks in megagrams (Mg) for five forest carbon pools according to harvesting scenarios

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5 Literature

Bončina, A., 2000. Comparison of structure and biodiversity in the Rajhenav virgin forest remnant and managed forest in the Dinaric region of Slovenia. Global Ecol. Biogeogr. 9, 201-211.

de Groot, M., Ogris, N., 2019. Short-term forecasting of bark beetle outbreaks on two economically important conifer tree species. For. Ecol. Manage. 450, 117495.

European Commission, 2020. Forest Reference Levels proposed by EU Member States. Commission Expert Group on Land Use Land Use Change and Forestry.

Integrated National Energy and Climate Plan of the Republic of Slovenia. 2020. Ljubljana, Vlada Republike Slovenije.

Jevšenak, J., Klopčič, M., Mali, B., 2020. The effect of harvesting on national forest carbon sinks up to 2050 simulated by the CBM-CFS3 model: a case study from Slovenia. Forests 11, 1090.

Kovač, M., Hočevar, M., 2010. Short Description of Forest Inventories and Control Sampling Method Around the World and in Slovenia. Control Sampling Method in Slovenia-History, Characteristic and Use. Ljubljana: Slovenian Forestry Institute. Studia forestalia Slovenica 136, 7-10.

Kull, S.J., Rampley, G., Morken, S., Metsaranta, J., Neilson, E.T., Kurz, W., 2016. Operational-scale Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) version 1.2: user's guide. Natural Resources Canada Canadian Forest Service Edmonton, Alberta.

Kurz, W.A., Dymond, C.C., White, T.M., Stinson, G., Shaw, C.H., Rampley, G.J., Smyth, C., Simpson, B.N., Neilson, E.T., Trofymow, J.A., Metsaranta, J., Apps, M.J., 2009. CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards. Ecol. Model. 220, 480-504.

Kutnar, L., Veselič, Ž., Dakskobler, I., Robič, D., 2012. Typology of Slovenian forest sites according to ecological and vegetation conditions for the purposes of forest management. Gozdarski vestnik 70, 195-214.

Li, Z., Kurz, W.A., Apps, M.J., Beukema, S.J., 2003. Belowground biomass dynamics in the Carbon Budget Model of the Canadian Forest Sector: recent improvements and implications for the estimation of NPP and NEP. Can. J. For. Res. 33, 126-136.

Pilli, R., Grassi, G., Kurz, W.A., Smyth, C.E., Blujdea, V., 2013. Application of the CBM-CFS3 model to estimate Italy's forest carbon budget, 1995–2020. Ecol. Model. 266, 144-171.

SFS, 2005. Annual Forest Report. Slovenian Forest Service, Ljubljana, p. 114.

SFS, 2019. Annual Forest Report. Slovenian Foret Service, Ljubljana, p. 135.

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6 Abbreviations, figures and tables

6.1 List of abbreviations

AIDB	Archive Index Database
BAU	Business-as-usual
CBM	Carbon Budget Model
DBH	Diameter at breast height
DBHdom	Dominant Diameter at breast height
EU	European Union
EU-AIDB	Europe Archive Index Database
FRL	Forest Reference Level
GHG	Greenhouse Gas
GS	Growing stock
HAZ	Name of the scenario: More frequent natural hazards
HH	High Harvest
IDBH.dom	Average diameter increments of dominant trees
IPCC	Intergovernmental Panel on Climate Change
LH	Low Harvest
LIFE	EU's funding instrument for the environment and climate action
LTS	Long Term Strategy
LULUCF	Land Use, Land-Use Change and Forestry
NEC	National Emission reduction Commitments
NECP	National Energy and Climate Plan
PLAN	Name of the scenario: Harvesting in line with current forest management plans
PSP	Permanent Sample Plot
SFS	Slovenia Forest Service
UNFCCC	United Nations Framework Convention on Climate Change
WAM	With Additional Measures
WAMa	With Additional Measures - ambitious
WEM	With Existing Measures

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6.2 List of figures

6.3 List of tables

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