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Forest Resources Projection Tools: Comparison of Available Tools and Their Adaptation to Polish Conditions

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Abstract: Over the years, various methods for estimating and projecting forest resources have been developed and are used by countries where the forest sector is important. Therefore, the obligation to report and account for forest resources, including changes in carbon stocks in a forest area, has gained attention. The latest regulations (Land Use, Land Use Change and Forestry—LULUCF) requires European Union (EU) members to annually report and publish national accounting plans estimating emissions and removals from managed forest areas (Regulation EU 2018/841). The major challenge is to choose and adapt a unique tool for this accounting. At the same time, they need to provide reliable estimates that are recognized by regulators and control authorities. This study focuses on comparing the adaptation of two accounting frameworks: the Operational-Scale Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) and the European Forest Dynamics Model (EFDM). Both tools are based on National Forest Inventory (NFI) data. It is assumed that the EFDM can provide similar results to the CBM-CFS3, which is already used in Poland. Implementing the EFDM and adapting it to Polish conditions could facilitate forest management decision-making and the preparation of forest policies. The main objective of this study was to compare and validate the accuracy of the results obtained with the EFDM framework. Metrics compared using both tools included growing stock volume, biomass of growing stock expressed in carbon units and age–class distribution over area. The comparison was based on the agreement of EFDM with CBM-CFS3 results. The volume of logging was taken from the EFDM and compared with the values obtained by Statistics Poland. This study also provides a guide for framework parameterization directly from the Polish National Forest Inventory data from the 2010–2015 cycle. Our main findings are that the results of the two models are reasonably comparable (the extent of deviation is acceptable). Moreover, the first implementation of the EFDM showed that it is an easy-to-use open-source program that allows forest managers to implement their own settings according to their needs. This document elucidates the concept of using both frameworks under Polish conditions and provides an impression of their performance for future modelers, students and researchers.

Keywords: European forest dynamic model; Carbon Budget Model of the Canadian Forest Sector; forest resources; modeling; National Forest Inventory

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1. Introduction

Modeling forest resources dynamics and accounting for forest carbon pools are the subject of global discussions on climate change and meeting the 2 °C target for the Earth's average temperature increase [1]. Various models exist to forecast forest resources in Europe and around the world. They can facilitate forest management practices and development. New frameworks are being created regularly, and those that are already working still need improvement [2]. Forest carbon sequestration has been defined as one of the most effective ways to reduce greenhouse gas emissions. Therefore, new regulations are being introduced to control the reliability of reported carbon stocks in forestry. Regulations EU 2018/841 and 842 (also known as LULUCF) required all EU member states to record and report their forestry reference levels (FRLs) and prepare their national forest management plans

(NFAPs). This action has made a large quantity of data available to the EU community on forests and forest management practices in all member states. The publication of these data by the member states also enabled the identification of some important problems, such as the lack of a common methodological approach or model for calculating carbon stocks and greenhouse gas emissions, as well as forest area trends, which they include in FRL reporting [3]. One solution to this problem would be to introduce a common tool that can be easily adapted to local and European forest conditions and forest management practices. For a detailed description of the models used so far in EU countries, see the European Commission's Joint Research Centre (JRC) report Forest reference levels under Regulation EU 2018/841 for the period 2021–2025 [3]. It was worth mentioning here the tools that can be successfully used to project living biomass in FRL. Member countries that are required to report on changes in living biomass use a variety of approaches. The most popular approaches for living biomass modeling are the CBM-CFS3, ad hoc FRL model, IPCC C stock change combined with ancillary approaches, and others, including the European Forest Dynamics Model. For GHG intensity modeling, approaches are similar, and most countries use either the IPCC C stock change model or the IPCC Gain–Loss model [3]. On the other hand, many National Forest Inventory (NFI)-based tools can be used to model forest resources. An example of such a tool was the European Forest Information Scenario Model (EFISCEN), which was proposed by the European Forest Institute and is widely used in modeling. This model generates scenarios using information about forests in Europe and was used to analyze the consequences of climate change impacts and forest management practices at the European level. The tools used for comparison in this study are the Operational-Scale Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) and the European Forest Dynamics Model (EFDM). Although there are so many carbon models, it was still a challenge to find a common tool to assess forest resources and develop international guidelines for carbon accounting.

Both models (EFDM and CBM-CFS3) have been widely used in forest management and allow for projections of forest resource levels, facilitating the development of forest policies [4]. The tools used for comparison were selected based on the breadth of their applications and the potential adaptation of data from the National Forest Inventory [5–7]. Both tools can be applied at the stand level as well as at the national or regional level. Differentiation by species, forest ownership types and forest management activities were possible. The European Forest Dynamics Model was a freely available model developed through a collaboration between the JRC, the Finnish Forest Research Institute (LUKE) and the Swedish College of Agricultural Sciences (SLU) [8]. It was developed with the aim of harmonizing forest resource reporting at the national and European levels. The program was built to allow the implementation of data from structured European National Forest Inventories [2]. For this study, we focused on the EFDM because it provides promising results and offers forest managers and policymakers another way to assess forest resource information. The main advantage of the EFDM framework was that it was freely available and can be used under the European Union Public License (EPLO) code. The open-source code was written in the R programming language, is easy to understand and can be adapted to country-specific needs. It also allows modifications to the internal functionalities so that any type of forest area can be modeled. The downside was that the tool does not have a graphical user interface (GUI), so the results were not easy to read, and one has to refer to the provided documentation to understand the derived metrics.

In this study, the other software (CBM-CFS3) serves as a first model for cross-validation of the newly tested EFDM. The tool was developed by a team from Natural Resources Canada's Canadian Forest Service in collaboration with the Canadian Model Forest Network [9]. The CBM-CFS3 is currently freely available after user data registration. It was developed in 2002 and released to the public in 2005. Since then, it has been tested in almost all EU countries [6], as it is consistent with carbon estimation methodologies developed by the Intergovernmental Panel on Climate Change (IPCC). The simulations also meet the criteria for reporting forest carbon resource dynamics set out in the United Nations Kyoto

Protocol [5]. The CBM-CFS3 has been used to model forest carbon stocks in Poland since 2017, and its results have been reported annually (since 2018) to the European Commission in the National Forest Accounting Plan [10]. The CBM-CFS3 is a yield-data-driven model that uses country-specific volume–biomass conversion algorithms. It can also simulate anthropogenic or natural disturbance events that can be specified by the modeler [5]. The tool was developed using Visual Basic, C++ and C# programming languages and is not open to user modification. However, the GUI was translated into Polish, which facilitates dataset preparation and simulation. Some other parameters, such as natural regions, soil types and species, were also adapted to the model, making it easy to implement. The first implementation of the EFDM showed that it was an easy-to-use open-source program that allows forest managers to implement their own settings according to their needs. This document elucidates the concept of using both frameworks under Polish conditions and provides an impression of their performance for future modelers, students and researchers.

The authors attempted to answer the question of whether using different forest growth modeling tools based on comparable input data produces similar results. The objective of this study was to evaluate the feasibility of implementing the EFDM. The performance of the EFDM framework was compared with the results of the CBM-CFS3. We expected that if the input data were comparable, the same would be true of the projection results if the same models were used. We believe that this study can lead to promising projections of forest development that can be further developed as needed.

2. Materials and Methods

2.1. Software and Tools Used

This study used the European Forest Dynamics Model (version 2.0, European Commission's Joint Research Centre, EU), found in the European Commission repository on the cloud-based hosting service "GitHub" (https://github.com/ec-jrc/efdm, accessed on 5 October 2016) and the Carbon Budget Model (version 1.2.7271.303, Canadian Forest Service, CA), available at https://carbon.nfis.org/cbm, accessed on 4 December 2019. Input data for the CBM-CFS3 framework were prepared in Microsoft Access (archive database) and Microsoft Excel. All input parameters for the EFDM framework were prepared in Microsoft Excel and transferred to a text file for later modification to meet program requirements. R Studio v. 3.6.1 statistical environment [11] was mainly used to run the EFDM code. All calculations were performed using pre-installed packages prepared for the R environment; the multidimensional array package "abind" (version 1.4-5 released 21 July 2016) was used, while the probability matrices were created using the "hackfunctions" package available in the EC GitHub repository. Visualization of the results was carried out in R Studio using the package "ggplot2" (version 3.3.6 released 3 May 2022). Tables and some charts were created using Microsoft Excel.

2.2. Investigation Area and Data

According to the Central Statistical Office of Poland, the forest area amounts to 9230 thousand ha [12], excluding the lands associated with forest management, which is 29.5% of the forest area. However, during the 1st and 2nd cycles of NFI in Poland, measurements were carried out only in forests registered in the Land and Property Register (area of 9395 thousand ha, as of 1 January 2016, including lands associated with forest management). Forest ownership in Poland was dominated by public forests (80.8%), including state forests (77.0%). Conifers dominate 68.5% of the Polish forest area. According to the NFI data, pine occupies 58.2% of the total forest area of all ownership types [13].

Data from the Polish National Forest Inventory [13] were used for modeling. The NFI covers all forests in Poland, regardless of their ownership type or stand age. All plots were surveyed in 5-year cycles, so 20% of plots were surveyed each year. NFI sample plots were grouped into "L"-shaped clusters systematically arranged throughout the country in a 4 × 4 km grid. Each cluster consisted of 5 permanent circular sample plots separated by a distance of 200 m. The inventories were conducted according to the Instructions for

the National Forest Inventory approved by the Minister of Environment of the Republic of Poland [14]. The NFI data from the second cycle were chosen as the reference period (2010–2014). This period provides an opportunity to derive the past condition of the forest from the previous data of the first cycle (2005–2009). The current 5-year increment volume could also be calculated, as well as the volume of harvested or dead trees. Forest resource dynamics were modeled using only NFI plots undivided on subplots [13]. Therefore, subplots were discarded to ensure sample homogeneity and avoid interpretation and classification problems; otherwise, plot volume could have been affected by the presence of individual trees or shrubs. Only 19,404 plots were selected from the 21,500 circular plots that were fully surveyed [13]. The area of a parcel was estimated to be 315.39 ha. This results in a modeled forest area of approximately 6,119,827.56 ha. The same area was used for both programs.

2.3. Stratification

We can describe the Polish NFI data as a systematic sample without stratification. Forest stand information was considered as a single unit in both frameworks (EFDM and CBM-CFS3). For modeling purposes, general groupings by species and 10-year age classes were considered. In addition, ownership was also considered as a grouping factor. Ten leading tree species were selected for stratification and were grouped into eight classes (Table 1). Two ownership types were used: Group I, forests managed by the State Forest National Forest Holding, accounting for about 77% of the total forest area, and Group II, "Other", describing privately owned forests, forests managed by national parks, agricultural holdings of the State Treasury, and other forests of the State Treasury and community forests.

Table 1. Summary of the initial state of the forest (in reference period 2010–2014) used for the input to the EFDM and CBM-CFS3 framework.

Dominant Tree Species (Code Used in Model)	Ownership	Number of NFI Plots	Area (Thous. ha)	Volume (m^3*ha^{-1})
Beech (FS)	state forest	878	276.91	341
	other	217	68.44	430
Birch (BT)	state forest	1095	345.35	197
	other	390	123.00	179
Oak (QR)	state forest	899	283.54	286
	other	174	54.88	230
Other broadleaves (OB)	state forest	140	44.15	269
	other	98	30.91	237
Other coniferous (OC)	state forest	681	214.78	332
	other	234	73.80	338
Black alder (AG)	state forest	716	225.82	284
	other	278	87.68	273
Scots pine (PS)	state forest	10,133	3195.85	306
	other	2258	712.15	262
Norway spruce (PA)	state forest	944	297.73	305
	other	269	84.84	270
Total		19,404	6119.83	293

2.4. CBM-CFS3 Implementation

The Operational-Scale Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) was a yield-data-driven framework that allows simulation of carbon dynamics throughout the forest ecosystem, above- and belowground biomass, dead organic matter (DOM) and soil [5]. Similar to the EFDM, the CBM-CFS3 can be applied to NFI data. Each forest unit was described by stand area, age, soil class and other classifiers (up to 10) that may relate to administrative or ecological boundaries or forest management characteristics.

Input data for the framework must be organized in the MS Access (.mdb) format, which the program refers to as the Archive Index Data Base (AIDB). The AIDB was crucial

for implementing and performing all calculations in the program. This database later stores all projects created during one or more simulations. A detailed description of the database requirements can be found in the source material [9,15]. The flowchart below gives an overview of input data required to run the simulation (Figure 1). A detailed description of each element is provided in this section.

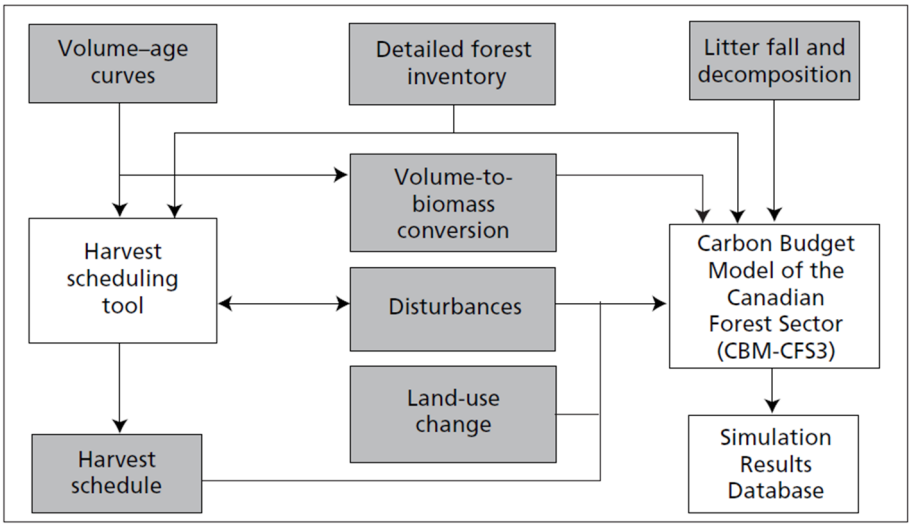


Figure 1. Chart representing input data (gray boxes) necessary to run simulation in Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) Reprinted/adapted with permission from Ref. [16].

In order to adapt the AIDB, the standard database was first adapted to European conditions [6] and then to Polish specifics. These changes were mostly made based on parameters applied by the JRC [6,9,17] and partly using country-specific data. To reflect Polish forests in the model, several changes were required: (1) most of the default administrative units specified in the "AdminBoundaryName" table were removed, and only those applicable to Poland (16 different regional units) were retained; (2) the default "EcoBoundaryName" was changed, and natural forest regions (so-called climatic units, 9 different regions) were assigned; (3) the "ClimateDefault" table was used as prepared for the AIDB for European countries [9]; (4) in the "SPUDefault" table, the records that did not fit the simulation for Polish conditions only (i.e., data including other countries) were removed; (5) from the "SpeciesTypeDeafult" table, only species occurring in Poland were selected; (6) the "BioTotalStemwoodSpeciesType" table was used as prepared for Polish conditions by Margaret Penner of Forest Ltd.

The simulations in this accounting framework (CBM-CFS3) were based on yield tables describing gross trade volume (roundwood) production for each age group and species. Consequently, species-specific allometric equations [18] converted the marketable volume per ha indicated by the growth curves (i.e., YT, yield tables) into tons of dry biomass, including above- and belowground biomass, stemwood or foliage. Because yield tables were the critical characteristics describing stands for implementation in the CBM-CFS3 system, NFI-derived data on current annual increment (CAI) and volume (average) were included for each forest type and region. To meet the requirements of the model, two independent sets of yield tables were created [19]. The first was used as a "historical" dataset, based on the National Forest Inventory. For the historical forest condition, the NFI data were scaled back to 2000 to obtain the original age–class distribution. This dataset was necessary to preserve historical management activities and disturbance events. To model carbon stock changes in forest area, the following metrics were considered:

- Biomass expansion factors (BEFs);
- Wood densities;
- Natural and forest regions in Poland;

- Growth curves derived from NFI data.

Each simulation also required an additional input file reflecting the forest stand being modeled. In our case, two Excel input files were used for initialization. For the input file, the database created by the Bureau for Forest Management and Geodesy was used, based on the National Forest Inventory data from the second inventory cycle (2010–2014). Forest stands were grouped into stratification groups according to their area and dominant species, age classes and forestry types (Table 1) in the order species, region, age class, area.

For the simulation, historical data of the forest were prepared in the other Excel file (as for the period 2000–2009). Based on species diversification, the felling ages were adapted as follows: beech—110 years, oak—140 years, pine—100 years, spruce—80 years, birch—80 years, alder—80 years, other broadleaved species—60 years and other coniferous species—100 years. In a modeling process, the forest ecosystem was divided into individual components, and as a result, tons of carbon were included in the calculation of the total biomass value (also given in tons of carbon).

2.5. EFDM Implementation

The simulation of the growing stock volume/wood resources development and the estimation of the volume of harvested wood were carried out with the European Forest Dynamics Model based on the Polish NFI data described in an earlier subsection. The tested program (EFDM) was parameterized to forests of the same age in Poland. The EFDM was a so-called Markov chain described by factors, activities and transition probabilities. The projections made by the EFDM were constructed in an area-based matrix with a fixed number of states between which different proportions of forest area move in specific simulation steps [20]. For the simulation, management activities were defined based on Polish forest management practices, including no management activities, final felling and thinning. Then, the probability of occurrence was calculated for all of these activities, which allowed for the creation of a transition probability matrix for each activity and all combinations of factors (Figure 2). The program uses the Markov property, which calculates the next forest state based on the derivation of the area from the current state according to the transition probabilities specified by the modeler [7]. The activity probabilities were associated with the intensity of forest management activities in a given stratification group.

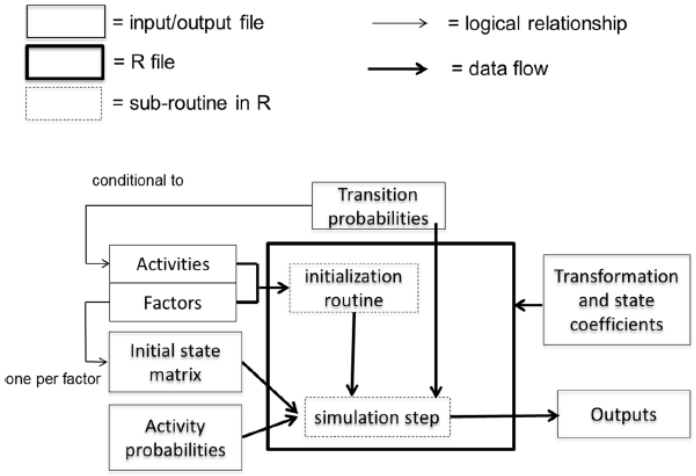


Figure 2. The parameter environment of the EFDM simulation runs [7].

In our case, the output matrices predicted the future state of the forest in a business-as-usual scenario. The volume of harvested timber was also estimated by this program. Table 1 summarizes the input data used for both models, since the same tree species with the same output characteristics were distinguished for both tools. The group "Other deciduous trees" consists of ash and aspen, while "Other conifers" includes silver fir and larch. The input

files were prepared based on the guidelines provided by the developers for the framework and the documentation included in the installation file [8].

2.6. Factors

The first step of the model application was the creation of the volume–age matrix by the modeler. Following the recommendation that 10–15 volume classes should be used in the model, 11 volume classes were derived. Volume classes were defined in units of m^3*ha^{-1} separately for each species and according to ownership type using quartiles (10th, 20th, 30th, . . . , 90th and 95th quartiles) to achieve an even distribution of volume classes [21]. Bare areas and regeneration areas were not considered. The 11th last class was defined as having no upper asymptote (Figure 3). Another descriptive parameter for forest condition was age class. It was assumed that the width of the age classes corresponded to the age classes reported by the NFI inventories and at the same time to the CBM-CFS3 age classes. Tree age was then divided into 13 classes, each 10 years in length. As in the case of volume, the final class, which starts at 120 years of age for all species and ownerships, has no upper limit (Figure 4).

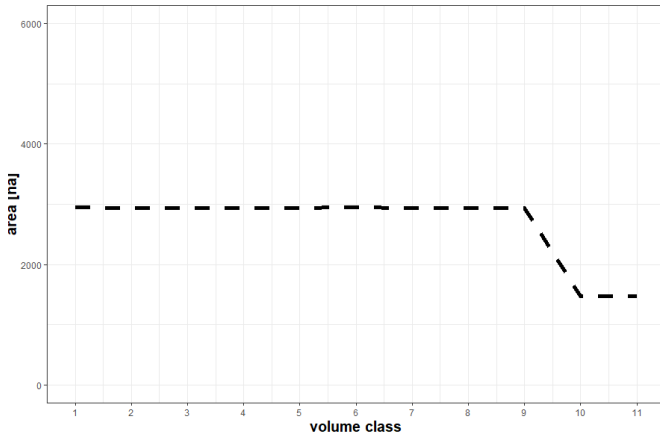


Figure 3. Distribution of the volume classes over the area (ha) used in EFDM.

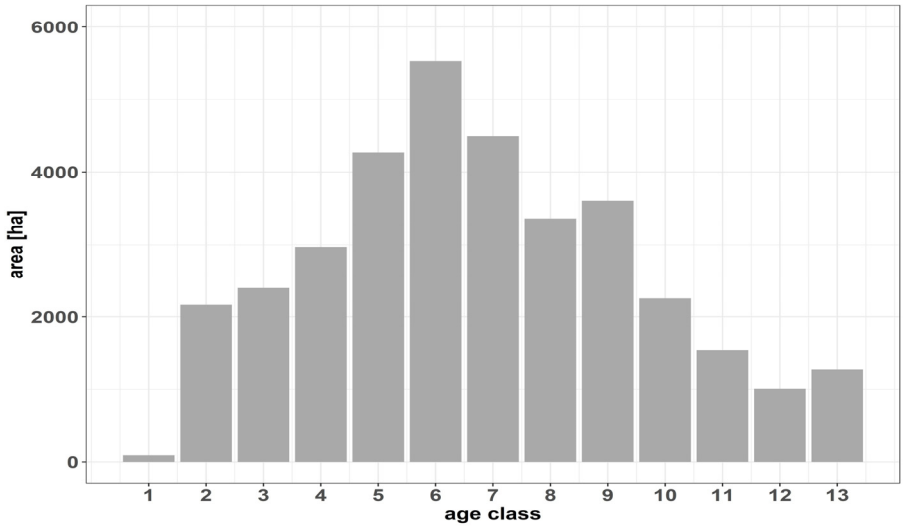


Figure 4. Distribution of age classes over the area (ha) used in EFDM.

2.7. Initial State

The next input file needed at the beginning of the simulation was the so-called initial state. The current state of the forest in our study was described by 2288 different cases. In the list of states, the data from the NFI were aggregated and classified by species and

ownership and summarized by age and volume classes with a corresponding area (ha), as shown in Figure 5.

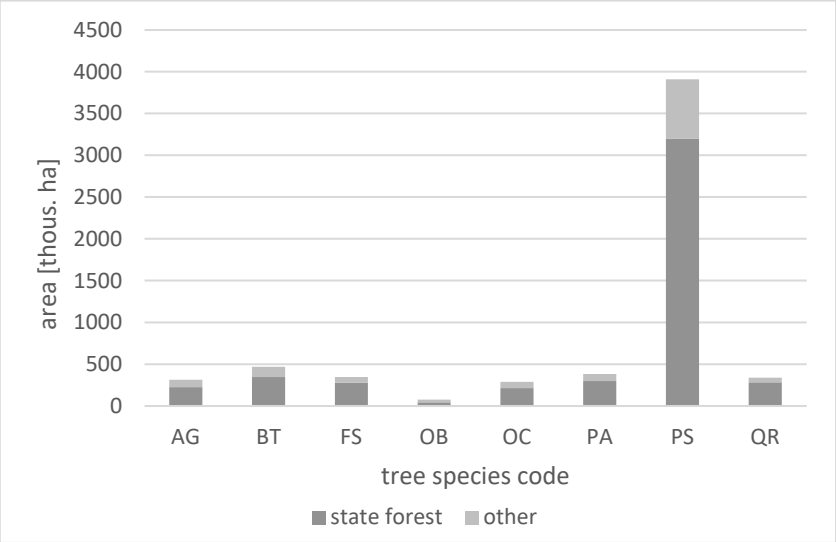


Figure 5. Distribution of leading species selected for EFDM according to the ownership.

2.8. Activity Probabilities

Activity probabilities were the proportions of area in each state cell (defined by volume and age class, site type, property type and species) on which a given activity was conducted in a simulation period [8]. In our case, the estimation of activity probabilities was carried out for each previously created combination of factors. These probabilities were based on national statistics produced by the Central Statistical Office for the period 2000–2015 [12], assuming a business-as-usual scenario. The following forest management practices were used as activities: clearcutting, thinning and no management probability. Proportional values were developed for all distinguished strata. Activity probabilities were estimated based on harvest intensity indicators as defined in the National Forestry Accounting Plan from 2019 [10].

Indicators were determined according to the age classes specified in the NFI and the harvest ratio determined by final cutting and thinning and compared to commercial volume (Ministry of Climate, 2019). The following equation was used to convert intensity indicators to activity probabilities (1):

$$Wi = U_i / V_i, \quad (1)$$

where Wi was the harvest intensity indicator for final felling and thinning in the given i-th age class, U_i was volume of harvested logs for final felling and thinning in the i-th age class, and V_i was volume of logs in the given i-th age class at the beginning of the period. When creating the probabilities, the indicators predicted for the period 2010–2019 were taken into account. It was assumed that final felling was increasingly often carried out in older than in younger stands, while thinning was mostly carried out in younger age classes.

The relationship between the intensity of activities in forests managed by state forests and private or other owners can be distinguished. It was assumed that final cutting was greater in state forests, while thinning was more intense in other forest types. This relationship can be seen in Figure 6. The input file was prepared so that the sum of probability activities in a row was 1.

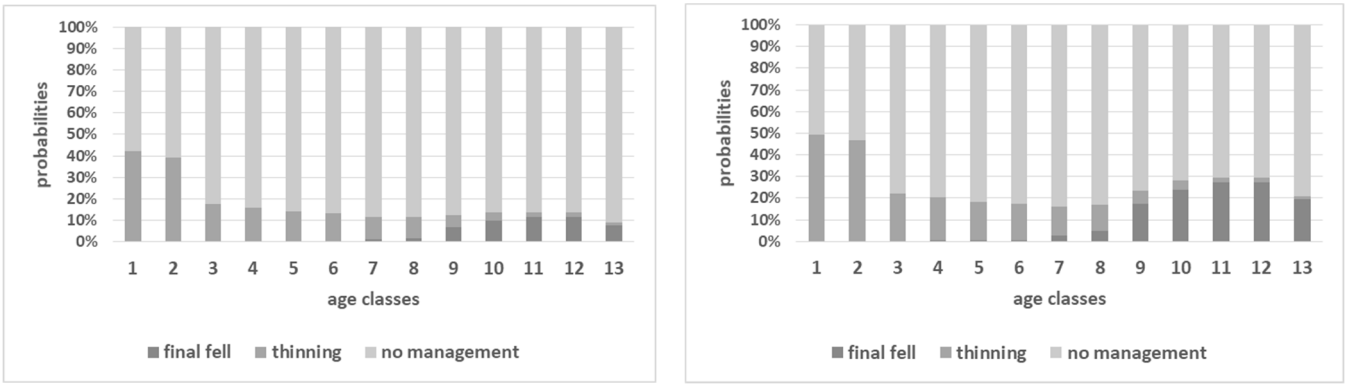


Figure 6. Activity probabilities according to the age classes—state forest (on the **right**) and other forest ownership types (on the **left**).

2.9. Transition Probabilities

Transition probabilities for thinning plots were created before the model was implemented but using features provided by EFDM developers. In the EFDM, thinning was performed at each simulation step corresponding to 10 years. For this purpose, the function makethinP() from the package hackfunctions.r was used and applied in the R—statistical environment. Since the most important argument of the function was the specification of the volume drop classes, it was decided to drop only 1 class starting from the second class. The final impact was prepared so that the entire area after the final impact would fall back to the first age–volume class (1–1). Thus, it was prepared without statistical estimation. There was no need to prepare a matrix for management activities. For the project, tree volume information was needed in two time periods. Since the information from the 2nd cycle of NFI only contains information about the current state of the forest, the previous (historical) data were needed. This information was derived by subtracting the annual increment volume multiplied by 10 years (equivalent to one simulation step) from the current measures. No management measures were prepared for strata younger than the 2nd class because the first class would have a negative number that could not occur. To implement these transitions in the dataset, the function estimatetransprobs() in the package efdmestim.r was prepared specifically for this purpose.

2.10. Output Generation

The results of the two programs were obtained at a given time step. In the case of the EFDM, one step corresponded to 10 years, which was an age class range. In the case of the CBM-CFS3, a simulation step was only 1 year. For a proper comparison, the results for a simulation period needed to be adjusted to the time frame of the NFI data. The results generated by the CBM-CFS3 focused on biomass and carbon in each forest ecosystem component, so cumulative results could also be obtained. In the case of the EFDM, the modeler must specify the output to be generated. The definition of the volume coefficient and the drain coefficients were created to obtain the desired results. In both cases, the coefficients were based on the volume class derived from the raw data and satisfied the equation $c_i = (vcl_i - vcl_{i-1})/2$, where c_i was the coefficient for a volume class i and vcl was the upper bound for the class. No upper limit was distinguished for the coefficient for the highest volume class, so it was defined as follows: 1.20 * vcl_{i-1}. The drain coefficients were given according to activity. For areas that were not managed, the drain value was set to 0 since there was no drain there. For areas that were finally logged, drain was assumed to be equal to the volume coefficients since all volume was removed. Calculation of the thinning coefficient depended on the number of volume drop classes specified in the probability matrix. In our case, only one drop volume class was assumed for thinning, so the thinning coefficients were calculated as follows: $cth_i = c_i - c_{i-1}$, where c_i and c_{i-1} were SMF in the middle class corresponding to the final impact coefficients. The output produced by the

EFDM was expressed in m^3 and then converted to m^3*ha^{-1} units. To convert biomass results to carbon units (t.C.), the total volume of growing stock (m^3) was multiplied by the biomass conversion and expansion factor in the case of the EFDM, which was specific to each species used in the model and was derived from input data from the CBM-CFS3. The conversion was carried out after obtaining the output from the volume of the growing stock. In contrast, biomass results from the CBM-CFS3 were reported in tons of carbon by default. For optimal comparison, the CBM-CFS3 results were converted back to m^3 with the reverse calculation using the biomass expansion factor and wood density for each species.

2.11. Validation of the Results

Since two carbon and biomass accounting frameworks were compared, the comparison was based on overall model performance, results obtained and reliability of results. Metrics such as growing stock volume (m^3*10^6 and m^3*ha^{-1}) and biomass of growing stock (t.C. and $t.C.*ha^{-1}$) calculated for the predominant species and ownership types were evaluated and compared. In addition, the degree of deforestation was calculated using the EFDM tool and validated with NFI and Central Statistical Office data for both forest tenure types. The basic results of the model were compared to ascertain the possible performance if more activities were added to the dataset.

3. Results

The simulations for both models were carried out for the period from 2010 to 2030. The results obtained were produced at a specific time step. In the case of the EFDM, the generated results had to be extrapolated in 5-year increments because the generated results used the width of the age class as the simulation interval. Data from the EFDM results are presented in Tables A1–A4 in Appendix A. The CBM-CFS3 was more flexible in this regard, as the results were generated for each modeling year (starting in 2010 and ending in 2030). The modeling results were displayed and compared together below, and the indices used for volume to biomass and biomass to volume conversions were also provided. Model results were produced at the national level with no breakdown by region or other forest site.

3.1. Species-Specific Growing Stock Volume (m^3*ha^{-1}), BEF, BCEF and Wood Density (WD) Factors

The comparison of growing stock volume was made using two models. Species-specific biomass expansion factor and biomass conversion expansion factor, as well as baseline wood density, were used to convert CBM-CFS3 results to growing stock volume. The equations used were described in more detail in a JRC document prepared by Pilli and Blujdea 2017 [22]. The results below (Table 2) show the average volume obtained for the period 2010–2014 after performing modeling with two programs. Even using the same BEF and WD factor, we did not get the exact same results for both models. For some species, differences between volume results were very high (even about 100% comparing EFDM to CBM-CFS3). The largest differences were between the "other broadleaves" and "other coniferous" groups.

3.2. Total Volume of Growing Stock (in m^3*ha^{-1})

From the first simulation step, the largest underestimation of the growing stock volume can be seen. This may be caused by conversions that must be made to adjust the calculation units for both programs. While the output of the EFDM was generated in m^3*ha^{-1}, this measure had to be converted back to input units for the CBM-CFS3 since the results of the program were generated in tons of carbon for each forest ecosystem element. Attention was also given to the growth trend calculated using the EFDM framework. After 2025, the EFDM shows an upward trend in forest growth. The decrease in total growth volume occurs only in state forests. In 2030, the decrease in volume was estimated to be about 20 m^3*ha^{-1}, which was probably related to the harvest intensity implemented in the parameters of

the program (Table 3, Figure 7). The results for the growing stock volume calculated in m^3*ha^{-1} of both programs show reasonably high agreement (about 70%–80%).

Table 2. Comparison of growing stock by species for the baseline condition and summary of indices derived from the CBM-CFS3.

Species	Code	Volume (m^3*ha^{-1}) EFDM	Volume (m^3*ha^{-1}) CBM-CFS3	BEF (CBM-CFS3)	BCEF (CBM-CFS3)	Basic Wood Density by Species
Beech	FS	358.22	356.33	1.362	0.760	0.68
Birch	BT	192.55	293.08	1.387	0.583	0.61
Oak	QR	277.14	244.51	1.511	0.893	0.65
Other broadleaves	OB	284.45	574.73	1.514	0.370	0.59
Other coniferous	OC	308.77	621.41	1.346	0.453	0.48
Black alder	AG	280.85	457.57	1.363	0.484	0.51
Scots pine	PS	298.18	372.50	1.279	0.414	0.49
Norway spruce	PA	297.28	276.31	1.282	0.528	0.43

Table 3. Growing stock volume (m^3*ha^{-1}): comparison between the two models EFDM and CBM-CFS3.

Growing Stock Volume (m^3*ha^{-1})	2015	2020	2025	2030
EFDM				
total	291.95	326.48	314.29	298.18
state forest	291.15	326.88	306.84	283.54
other	295.10	324.86	343.72	356.05
CBM-CFS3				
total	387.73	403.47	414.99	422.72
state forest	304.40	312.93	317.93	320.09
other	83.33	90.55	97.06	102.62
EFDM% CBM-CFS3	75.3%	80.9%	75.7%	70.5%

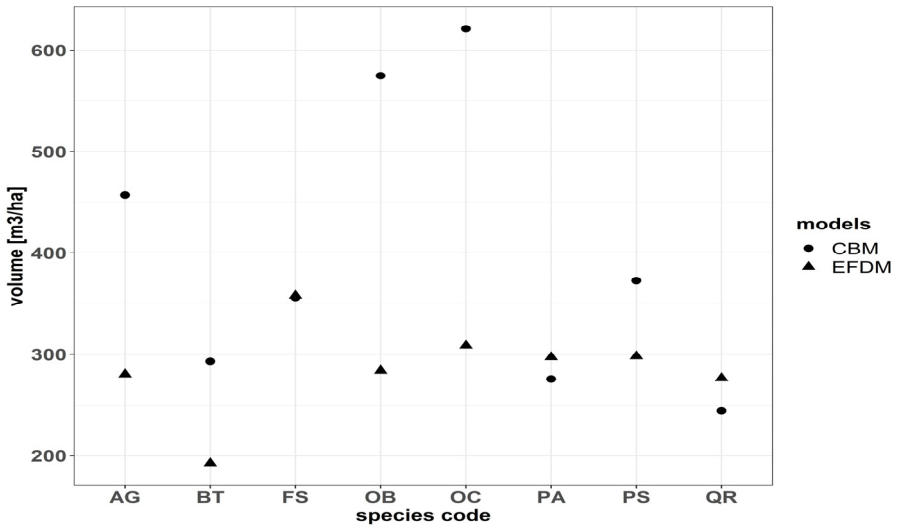


Figure 7. Growing stock volume (in 2030) by species, predicted by both models reported in m^3*ha^{-1}.

3.3. Growing Stock Biomass (t.C.10^6 *and t.C.*ha^{-1}*)*

Emergence biomass was calculated in tons of carbon, as this was the standard output of the CBM-CFS3 framework. The results from the EFDM could be adjusted to any unit. Due to its flexibility in generating outputs, it was decided to keep the units derived from the CBM-CFS3 as they could not be changed by the user. The biomass of the growing stock calculated by the EFDM was consistent with the CBM-CFS3 results in terms of the amount

of biomass. However, when we compare the growth trend line for the four simulated stages, it was not identical (Tables 4 and 5).

Table 4. Comparison of levels of growing stock biomass (t.C.*10^6).

Growing Stock Biomass (t.C.*10^6)	2015	2020	2025	2030
EFDM	993.39	1110.87	1069.41	1014.60
CBM-CFS3	985.79	1023.04	1051.95	1073.53
EFDM% CBM-CFS3	1.01%	1.09%	1.02%	0.95%

Table 5. Comparison of levels of growing stock biomass (t.C.*ha^{-1}).

Growing Stock Biomass (t.C.*ha^{-1})	2015	2020	2025	2030
EFDM	304.45	318.66	338.04	354.12
CBM-CFS3	228.69	240.20	249.87	257.62
EFDM% CBM-CFS3	1.33%	1.33%	1.35%	1.37%

3.4. Drain Values Compared to Country-Specific Data

Drain (from harvest) refers to management activities and timber use in the business-as-usual scenario used for the projections, as described in the Materials and Methods section. The results were obtained only from the EFDM framework and compared with the Central Statistical Office's Drain Volume Report and the projections based on it made by the team for the development of the national plans of accounting for greenhouse gas emissions and removals from forestry activities [10]. The obtained results were comparable. The agreement of results between the two forecasts obtained from the two sources was 90%, which was satisfactory (Table 6, Figure 8).

Table 6. Felling drain comparison received from EFDM.

Volume of Harvested Wood (m^3*10^3)	2016–2020	2021–2025	2026–2030
EFDM	39,385	41,746	43,351
Statistics Poland (GUS)	43,471	46,124	48,531
EFDM% Statistics (GUS)	91%	91%	89%

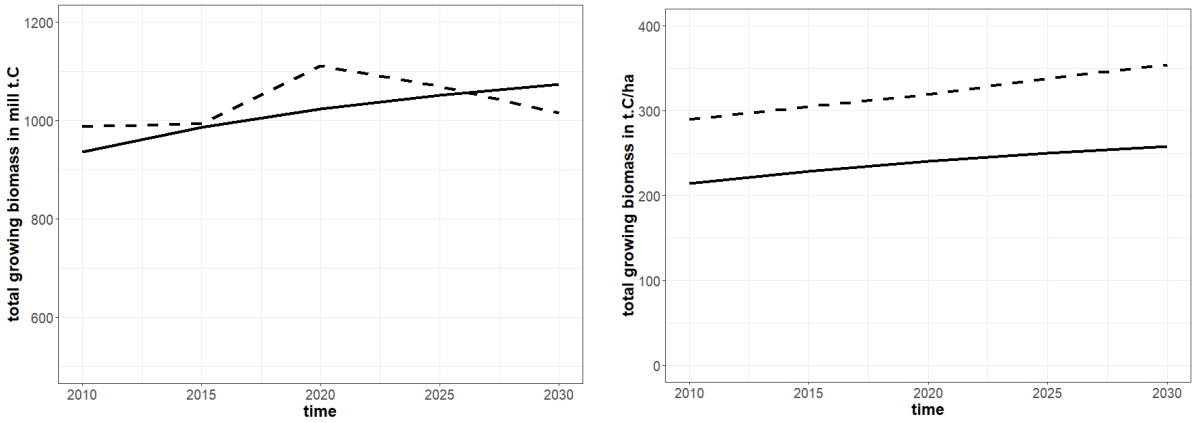


Figure 8. Total growing biomass calculated by both tools, reported in t.C. 106 (on the **left**) and t.C.*ha^{-1} (on the **right**). EFDM projections represented by dashed line, CBM-CFS3—solid line.

3.5. Changes in Age Classes over Simulation Periods

The age structure of the forest was dominated by forest stands of third class (40–59) and fourth (60–79), which occur in 24.9% and 19.4% of the total area, respectively [13]. For easier comparison, results from both frameworks were aggregated to 20-year age classes

and compared with area (thousand ha). Different colors of bars in a gray scale indicate simulation years, with the first year being the start year for the simulation (2010). It was important to emphasize that the CBM-CFS3 allows for the dynamic growth of the forest and changes in the class structure by automatically adding more classes according to the forest growth. This was not possible with the EFDM because the final age class has no upper limit unless the modeler creates additional classes to cover the future state of the forest as well. Based on the results, we can conclude that the CBM-CFS3 produces results that are more suited to real forest age structure than that of the EFDM. In all simulation steps, the modeling derived from the CBM-CFS3 provides a normal or near-normal distribution of age classes over the area. This cannot be claimed for the EFDM, as there was a significant decrease in third class (40–59) in 2025, which can be explained by the thinning performed in the EFDM. The EFDM also overestimates the area of classes VI (60–79) and V (80–99) compared to the CBM-CFS3 (Figure 9).

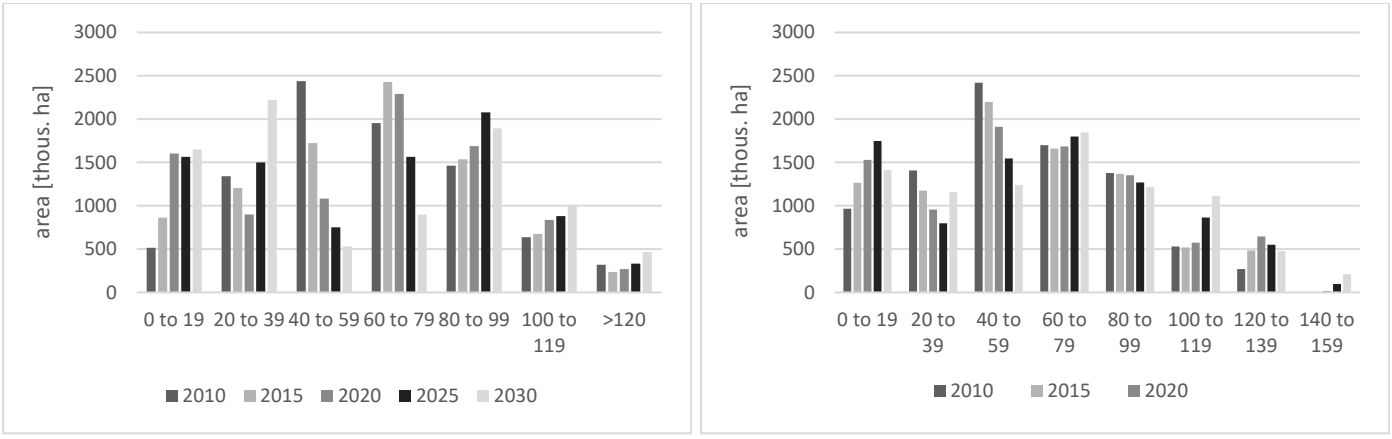


Figure 9. Age–class distribution over the area in the modelling years. Comparison between EFDM (on the **left**) and CBM (on the **right**) output results.

4. Discussion

The research conducted has demonstrated the potential of using two frameworks for forest resource accounting. The age and volume classes were organized to best reflect the Polish structure of a mixed, even-aged forest. The results of the EFDM framework were compared with the results of the CBM-CFS3, which was a national forest resource model used mainly for international forest carbon stock and biomass reports.

The results of the EFDM tool in its current form and with the settings proposed in this study can be used as an alternative to the CBM-CFS3, but only to a certain extent. From the obtained results, we can conclude that the EFDM with the selected age–volume classes and probabilities was not suitable for creating a complete model of the growth and development of the Polish forest area. The significant underestimation of stock increment by species was observed especially for other hardwoods and conifers. Of the eight tree species tested, only beech had almost identical stock volume in both frameworks. The EFDM also inaccurately developed the distribution of aggregate age classes over the entire plot. In the simulated stands, the age structure did not follow the growth pattern reported by NFI and adequately modeled by the CBM-CFS3. The bias between the frameworks was evident in the context of biomass of the growing stock. The growth trend was rather stable and positive in the case of the CBM-CFS3, while in the case of the EFDM, it reaches the same total growing biomass as the CBM-CFS3 in 2015. In 2020, the biomass had reached its peak of 1150 mill. t.C. and then decreased again to about 1000 mill. t.C.

The country-specific data from the Central Statistical Office were compared with the EFDM drain volume results. In this case, the simulation provided acceptable results. The agreement at the level of about 90% can be evaluated as equivalent for the framework.

The possible implementation of the EFDM framework was tested and compared with the CBM-CFS3 output. However, the results show that the tested accounting program (EFDM) needs to be further developed and adapted to the Polish-specific conditions. The tool can provide promising results in terms of crop volume projection.

The most challenging part was the preparation of the input files. Data received from the NFI had to be properly aggregated before they were loaded and processed by the EFDM and CBM-CFS3. The harvest data used as parameters for the activity probabilities based on the National Forest Inventory were not always adequate to model forest development. Several factors may cause the EFDM to underestimate forest resources, including (1) the number of volume classes (derived based on species and as quartiles), (2) the small number of age classes and (3) forest growth trends being derived from non-management conditions rather than from yield tables, as in the case of the CBM-CFS3, which may underestimate forest growth under Polish conditions. One of the major limitations was that the setup was based on the parameterization proposed in the EFDM documentation, which was prepared for Scandinavian forests, wherein silvicultural treatments were less frequent than in Poland. In the EFDM, thinning was assumed to occur in one simulation step, resulting in a decrease of one volume class per 10 years. In reality, two thinnings in 10 years are sometimes possible, which can be accounted for in the CBM-CFS3, but cannot be simulated in the EFDM.

Studies on similar topics can be found in the literature. Some focus more on modeling forest resources and others on calculating carbon stocks in the individual components of the forest ecosystem. A scientific article by Blujdea et al. [23] attempts to compare both tools with similar goals. The authors compared the CBM-CFS3 and the European Forest Information Scenario Model (EFISCEN) with data collected during two cycles of an NFI in Romania. The EFISCEN was one of the models proposed by the European Forest Institute. The model was fitted to the input data obtained from the NFI data and calculated the results over a period of up to 60 years. A comparison of the models in terms of area per age class showed that the CBM-CFS3 tends to overestimate the area of older stands in its model more so than the EFISCEN. In the last age class (>139 years), the CBM-CFS3 overestimated area by up to 55%. The volume of growing stock was similar for both tools in the study but slightly higher for the CBM-CFS3. There was an upward trend throughout the modeling period, with a difference of 6.8% in 2010 and 8.1% in 2060. The volume harvested during the simulation period was comparable for both tools in terms of final cut and thinning, with the CBM-CFS3 tool underestimating results for total harvest by 2% [23]. The present study yielded observations that confirm results and trends in other publications.

5. Conclusions

Two forest resource modeling frameworks were tested with the goal of successfully using NFI data to predict future forest health. This research partially confirmed the hypothesis that the EFDM can provide promising results in terms of forest resource and growth projections. In the case of the EFDM, the program demonstrates flexibility but at the same time simplicity and limited use. Further parameterization and model development was needed to obtain meaningful results. In contrast to the CBM-CFS3, it was not possible with the EFDM to obtain specific results—such as belowground biomass or carbon sequestration in each element of the ecosystem such as stumps, branches and foliage—unless the modeler has the specialized knowledge required to derive the necessary equations and transfer them to R code. Future work will require better parameterization of the EFDM, which must be agreed upon beforehand with forestry experts. For example, the Chapman–Richards function should be optimized and implemented to derive the volume classes. In addition, instead of predicting forest development based on the "no management" condition, yield tables can be used and applied to the EFDM to evaluate the performance of the system.

The EFDM approach developed allows us to simulate the capacity of forests to store carbon under varying scenarios of wilderness forest management at the national scale. The results can be easily compared with other projections at the level of European countries,

groups of countries or at the European level. The results on the predicted variability of biomass and carbon stocks under different forest management scenarios provide valuable information for making optimal decisions on forest management and ecosystem services and, consequently, on forestry-related policies.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Results from calculations conducted in EFDM software. Volume [m^3] by species and ownership type. Simulation in the time period (2010–2030), divided into 5-year simulation steps. Beech (FS), Birch (BT), Oak (QR), Other broadleaves (OB), Other coniferous (OC), Black alder (AG), Scots pine (PS), Norway spruce (PA).

Species	Owner	Step 0	Step 1	Step 2	Step 3	Step 4	Step 5
FS	state_forest	93,282,162.34	85,266,004.43	106,581,912.63	91,862,256.80	81,816,052.78	73,903,870.24
BT	state_forest	67,568,613.05	73,739,002.40	78,809,086.76	79,444,030.89	77,101,500.21	71,482,078.49
QR	state_forest	79,989,219.29	72,864,905.69	86,413,519.92	77,417,840.16	71,998,998.36	67,078,383.29
OB	state_forest	11,577,926.25	11,494,463.13	12,821,733.16	12,345,685.87	11,524,480.84	10,562,459.91
OC	state_forest	70,729,220.08	70,027,862.73	82,669,980.16	76,326,819.60	71,405,532.77	66,118,564.50
AG	state_forest	63,683,580.22	66,491,459.85	72,648,261.27	70,604,426.54	66,802,016.11	61,090,682.47
PS	state_forest	971,765,147.94	952,825,961.60	1,054,339,710.74	994,260,890.31	913,201,226.07	823,923,998.72
PA	state_forest	90,020,186.38	89,310,272.10	102,263,520.84	96,390,024.91	91,005,730.16	86,315,034.38
FS	other	28,950,229.70	32,887,446.22	37,444,039.45	40,398,371.15	43,331,498.55	45,603,890.31
BT	other	21,725,642.61	24,938,889.19	27,171,109.56	29,004,471.71	30,178,572.54	30,590,165.89
QR	other	12,353,693.68	17,398,780.12	20,600,685.96	22,802,060.48	24,537,845.73	26,017,101.06
OB	other	7,053,504.117	7,899,447.39	8,477,930.47	8,986,337.33	9,324,637.33	9,480,372.01
OC	other	24,786,952.84	27,276,174.46	29,663,572.26	30,847,631.98	31,376,557.34	31,398,693.37
AG	other	23,744,354.74	26,462,655.88	28,614,257.48	30,079,127.46	30,994,078.56	30,944,545.95
PS	other	184,809,439.06	200,095,451.32	217,016,260.27	226,072,555.24	230,405,948.31	229,888,492.71
PA	other	22,703,104.86	27,695,713.06	32,436,712.03	36,549,113.92	39,821,253.04	42,269,545.16

Table A2. Results from calculations conducted in EFDM software. Volume [m^3] aggregated by ownership type. Simulation in the time period (2010–2030), divided into 5-year simulation steps.

Owner	Step 0	Step 1	Step 2	Step 3	Step 4	Step 5
state_forest	1,448,616,055.55	1,422,019,931.94	1,596,547,725.49	1,498,651,975.08	1,384,855,537.32	1,260,475,072.01
other	326,126,921.60	364,654,557.65	401,424,567.49	424,739,669.28	439,970,391.39	446,192,806.46

Table A3. Results from calculations conducted in EFDM software. Drain volume [m^3] by ownership type and species. Simulation in the time period (2010–2030), divided into 5-year simulation steps.

Species	Owner	Step 0	Step 1	Step 2	Step 3	Step 4	Step 5
FS	state_forest	1,881,156.61	2,057,720.59	2,157,668.65	1,901,055.47	1,634,592.17	1,386,867.44
BT	state_forest	1,134,302.43	1,202,622.27	1,502,644.58	1,953,929.91	2,256,878.34	2,282,481.19
QR	state_forest	1,533,713.15	1,621,705.20	1,678,896.48	1,385,983.64	1,268,298.91	1,184,846.29

Table A3. *Cont.*

Species	Owner	Step 0	Step 1	Step 2	Step 3	Step 4	Step 5
OB	state_forest	230,205.25	253,252.11	278,789.55	305,937.61	315,464.39	331,846.53
OC	state_forest	1,500,577.03	1,652,434.96	1,713,149.43	1,730,135.06	1,792,199.79	1,739,793.59
AG	state_forest	1,272,890.32	1,410,002.34	1,617,166.95	1,798,541.96	1,891,014.67	1,821,860.35
PS	state_forest	19,186,598.71	22,639,455.47	24,823,082.68	26,858,013.93	27,859,521.46	27,037,470.84
PA	state_forest	1,933,409.94	1,984,122.15	1,979,263.83	1,964,739.56	2,078,274.20	2,153,856.10
FS	other	130,072.48	153,303.22	175,753.99	168,847.30	155,733.18	157,716.07
BT	other	161,997.50	132,935.37	109,698.09	88,979.27	75,534.57	67,311.23
QR	other	69,277.55	86,834.70	74,597.69	57,263.07	51,341.58	51,100.46
OB	other	56,174.79	47,851.46	39,707.14	32,190.81	26,674.77	23,548.45
OC	other	138,887.70	131,142.49	125,658.18	104,472.06	89,901.17	91,973.55
AG	other	159,391.08	133,854.06	107,143.26	91,434.54	82,476.51	83,343.06
PS	other	1,335,861.07	1,158,276.28	971,416.07	827,647.46	795,158.78	831,141.26
PA	other	128,546.25	123,004.06	108,026.28	88,539.34	86,679.68	89,983.79

Table A4. Results from calculations conducted in EFDM software. Drain [m^3] volume aggregated by ownership type. Simulation in the time period (2010–2030), divided into 5-year simulation steps.

Owner	Step 0	Step 1	Step 2	Step 3	Step 4	Step 5
state_forest	34,407,424.12	39,385,578.11	42,900,794.58	45,478,004.57	46,915,492.74	45,526,826.82
other	2,616,250.11	2,360,641.96	2,054,400.85	1,751,248.60	1,636,200.28	1,675,341.46

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