sciendo
Forestry Studies | Metsanduslikud Uurimused, Vol. 79, Pages 66–89

Research paper

Validation of saw log and technological wood assortment recovery and reduction predictions based on cut-to-length harvester data

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Padari, A., Kangur, A. 2023. Validation of saw log and technological wood assortment recovery and reduction predictions based on cut-to-length harvester data. – Forestry Studies | Metsanduslikud Uurimused 79, 66–89, ISSN 1406-9954. Journal homepage: http://mi.emu.ee/forestry.studies

Abstract. In this study, assortment yields were studied for Scots pine, Norway spruce, birch spp. (silver and downy birch), European aspen, black alder, and grey alder stand elements. Theoretical assortment yields were calculated using the Ozolinš' stem taper curve, incorporating tree diameters and heights. The modelled results were compared with actual yields provided by the State Forest Management Centre. During the study, differences in timber assortments and firewood yields were modelled compared to actual data. Changes in wood assortment yields, compared with undamaged and straight trees, depended on the tree species, stand site index, and stand element age. For Scots pine, depending on the stand site index and age, the reduction in log volume ranged from 7 to 28% of the total volume of all assortments. For Norway spruce, it was 5–30%, for birch spp. 30–70%, for aspen 50–90%, for black alder 20–50% and grey alder 5–30%. The increase in firewood volume according to the volume of all assortments was 3–4% for Scots pine, 5–14% for Norway spruce and birch spp., and 5–16% for European aspen. The difference between log and firewood changes represents the change in pulpwood. Over time, the need for new studies arises to adapt to evolving industry practices, including changes in log diameters and quality criteria. The appendix outlines steps that programmers can take to utilize the developed model.

Key words: assortment yield, Scots pine, Norway spruce, birch spp., European aspen, black alder, grey alder.

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Introduction

Accurate information regarding the volumes of growing stock and its wood properties is essential for effective forest management and wood obtainment planning (Malinen *et al.*, 2018). The assessment, based on pre-harvest spatially explicit growing stock assortments of standing wood volumes, becomes imperative in the selection of economically viable and spatially applicable cutting sites (Malinen *et al.*, 2010). It is also crucial in the planning of timber logistics to optimize the flow of raw materials (Kankare *et al.*, 2014). This information holds particular significance when employing the cut-to-length harvesting method (Kankare *et al.*, 2014).

DOI: 10.2478/fsmu-2023-0013

All decisions related to forest management depend on stand-level characteristics, such as species-specific mean diameter at breast height (DBH) or basal area, mean height, and age, as documented by Bravo *et al*. (2019) and Kangur *et al.* (2007). However, the foundation for bucking simulation-based calculations of timber assortment recovery lies in the application of species-specific tree stem form and corresponding taper models for assortment distinction, as described by Malinen *et al.* (2018). Typically, these taper models are developed based on stem measurements of actual analysis trees (Bravo *et al*., 2019; Eastaugh *et al*., 2013). In this context, bucking involves the theoretical simulation of corresponding timber assortment diameters (either the minimal diameter or acceptable diameter range). Actual bucking, where analysis trees are cut to assortment length, occurs only in practical implementation. Literature sources indicate that assortment recovery is influenced not only by tree species but also by its specific average diameter, height, and various other factors, including diameter distribution (Siipilehto & Rajala, 2019), assortment length (Puumalainen, 1998), wood properties, defects (Malinen *et al*., 2018), and harvester operators (Malinen *et al*., 2007).

In the evaluation of standing wood volumes, which is based on pre-harvest stand growing stock assortments, bucking is executed using species-specific generalized assortment calculation models. In these models, the differences between assortments, arising from damage or defects, are either incorporated based on inventory information or through an age-dependent reduction function (Padari *et al*., 2009). However, the validation of these functions relies on real cut-to-length assortment measurement data. The widespread use of harvesters and thereafter the cut-to-length harvest methods has facilitated the availability of high-precision large datasets for this purpose.

In the Baltic countries, the current methodology for dividing standing wood volume into roundwood timber assortments (including log, small-dimension log, pulpwood, firewood, and logging residues) has been in use since the adoption of the cut-to-length system in the 1990s, a practice implemented in Scandinavia over a decade earlier. The initial cut-to-length assortment functions in Finland were developed and published in 1982 (Nyyssonen & Ojansuu, 1982). In Estonia, the bucking models applied were documented in the analysis of growing stock assessment for comparing allowable stand-replacing cuttings (Padari & Muiste, 2003).

Enhanced bucking models, also employed in the current study, (Kinnisasja erakorralise hindamise kord, 2023) have been utilized for assessing wooden biomass availability in Estonia since 2009 (Padari *et al*., 2009). This bucking method has been consistently applied in various analyses, including estimating wood availability for substituting oil shale-based raw material with low-quality wood for energy production in power plants in the Narva region (Kask *et al*., 2011). The method has also been employed in comparing different management regimes under various nature protection scenarios (Sirgmets *et al*., 2011), analysing pulp and paper assortment recovery, and predicting reductions for roundwood market pricing studies (Sirgmets *et al*., 2011). Additionally, it has been used to assess management scenarios for hybrid aspen and silver birch plantations established on abandoned agricultural lands (Tullus *et al*., 2012) and to estimate the potentials and revenue loss of managed forest sites considered for new nature protection areas (Adermann *et al*., 2015).

In the present day, approximately 98% of the cuttings conducted by the Estonian State Forest Management Centre (RMK) involve the use of harvesters (Kaivapalu, 2017). The implementation of the cut-to-length harvesting method in the 1990s has revealed a gradual realization that the existing volume correction-based bucking model does not accurately represent the practical bucking activities carried out in the field (Kangur *et al.*, 2007). Notably, systematic deviations, either below or above the estimation, have been observed in the case of spruce and birch when comparing pre-harvest bucking with post-harvest cut-to-length data.

In the contemporary context, obtaining actual assortment bucking information is facilitated by real harvest measurements collected from cut-to-length harvester data. RMK has introduced a certified harvester for validating the machinery and operators of partners. Concurrently, a harvester data collection database has been implemented to compile genuine bucking data from across Estonia. For the current study, a dataset comprising real bucking data from RMK was utilized, covering clear-cuts conducted from 2011 to 2017 and encompassing pre-harvest conditions from over 27.5 thousand stand elements. While studies based on harvester bucking data are limited, some case studies, such as the one conducted in Finland by Siipilehto & Rajala (2019), using seven clear-cut sites, have explored comparisons between theoretical bucking and actual bucking.

The objective of this study is to analyse and validate the prevailing methodology employed in predicting saw log assortment recovery and reduction, utilizing cut-to-length harvester data.

Material and Methods

The current tree assortment model

The current method for timber assortment recovery, extensively elucidated by Padari *et al.* (2009) in their article on woody biomass calculation in Estonia, involves the following stages in assorting based on stand data:

1. Timber is categorized into diameter classes, determined as the ratio of a diameter class to the square mean diameter of a stand element (d/D). A relevant Finnish study emphasized the impact of diameter distribution on saw log and pulpwood recovery (Siipilehto & Rajala, 2019). However, due to the unavailability of diverse diameter distribution data, a uniform distribution was employed for all cases.
2. Height is computed for each diameter class using a height curve derived from Prodan's book (1965) and referred to as the Levakovic II function (Kiviste *et al.*, 2002).
3. Assortment recovery is then calculated for each diameter class based on diameter and height values. The taper curve equation developed by Latvian researcher Ozolinš (2002; Silava, 1988), commonly used in Estonia for growing forest volume calculation, is employed. Padari (2020) has presented a mathematical algorithm for utilizing this taper curve to determine volumes of wood assortments.
4. Subsequently, the bark proportion equation is applied to compute the diameters of assortments under the bark (Padari *et al.*, 2009).
5. For saw log assortments, a selected length ranging from 3.1 to 6.1 m (0.3 m increment) is chosen, while pulpwood and firewood assortments are set at a fixed length of 3 m. Assortment distribution is carried out based on the small end diameter under the bark, determined using the taper curve equation. The specified assortment lengths and diameters are detailed in Table 2. Assorting begins with the widest assortment of the respective tree species and proceeds in descending order until the last assortment (Table 2). The assorting process initiates at stump height (one-third of the diameter at breast height, but not below 10 cm). The determination of a single assortment length involves the following considerations:
   a) calculating the diameter at the height of the end of the last assortment (stump in the first case) to which the minimum length of the assortment was added;

b) if the diameter was larger than the minimum diameter of the respective assortment, calculations with this assortment were continued (otherwise, the next assortment was selected, and step a) was repeated);

c) performing a calculation cycle in which stem diameters were calculated by incrementing assortment length by assortment step until the stem diameter was shorter than the minimum diameter of the log. In this case, the assortment length applied in the diameter calculation that preceded the last calculation was used. If the stepwise increase in length reached the maximum assortment length, but the diameter still remained larger than the minimum diameter of the assortment, the calculation cycle was restarted. The minimum length applied was the twofold minimum length of the assortment, and the maximum length was the twofold maximum length of the assortment. If necessary, the cycle made use of multiple log minimum and maximum lengths until the stem diameter was smaller compared to the log minimum diameter.

6. In accordance with the taper curve presented above, the volumes of the assortments were computed utilizing the integral method, as outlined by Ozolinš (2002) and Padari (2020).

The previously outlined methodology has been retained in the new model. However, as part of this project, the segment addressing the correction of assortment volume resulting from damage and bending underwent revision and replacement.

Historically, theoretical models for correcting assortment recovery in the context of damage and bending were employed. These models, as published by Padari *et al.* (2009) in their work on woody biomass calculation in Estonia, were utilized until now. The graphical representation of the proportions of damaged trees calculated through the provided equation is presented in Figure 1.

Following the determination of the propor-

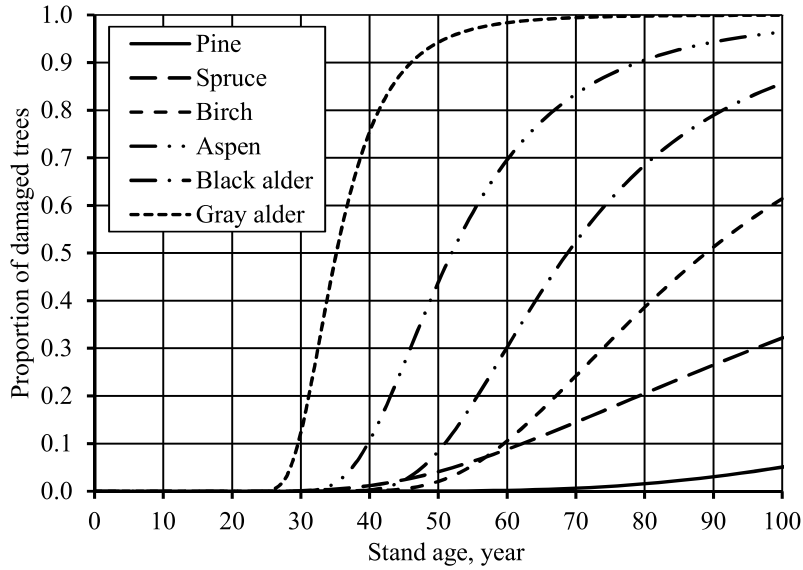

Figure 1. Proportion of damaged trees depending on tree species and age.

tion of damaged trees, assortment damage was rectified according to the methodology outlined by Padari *et al.* (2009):

1. The volumes of saw logs and pulpwood were both multiplied by the proportion of damaged trees (depicted in Figure 1), resulting in theoretical volumes for the saw logs of the damaged trees (Vdam_log) and pulpwood (Vdam_pulp).
2. The obtained results (Vdam_log and Vdam_pulp) underwent further adjustment by multiplying them by the coefficient 0.5, denoted as 0.5Vdam_log and 0.5Vdam_pulp, respectively. These adjusted volumes were then subtracted from the saw log or pulpwood assortment and added to the firewood assortment.
3. The saw log assortment volumes of the remaining damaged trees (0.5Vdam_log) underwent additional modification. Specifically, for pine, a multiplication factor of 0.5 was applied; for spruce, a factor of 0.75 was used, and for broadleaf trees, a factor of 1.0 was employed. The resulting volumes were subtracted from saw log assortments and added to pulpwood assortments.
4. To account for trunk curvature, 5% of pine and spruce saw logs, 10% of aspen saw logs, and 25% of birch saw logs were adjusted, being transferred from the log assortment to the pulpwood assortment. Similarly, 25% of black alder and 50% of grey alder saw log volumes were relocated from the log assortment to the firewood assortment.

Table 1. General data on felled elements included in the analysis. Site index class and site index H_{100} relationship are described in Table 2.

Tree species	No. of elements	Age, years		Site index class	
		minimum	maximum	maximum	minimum
Scots pine (*Pinus sylvestris* L.)	14,013	21	219	1A	5A
Norway spruce (*Picea abies* (L.) H. Karst.)	3,045	16	177	1A	5
Silver and downy birch (*Betula pendula* Roth, *Betula pubescens* Ehrh.)	7,145	22	153	1A	5
European aspen (*Populus tremula* L.)	1,862	23	140	1A	3
Black alder (*Alnus glutinosa* (L.) Gaertn.)	679	37	138	1A	4
Grey alder (*Alnus incana* (L.) Moench)	770	18	75	1A	4
Total	27,514	16	219	1A	5A

Actual data of the State Forest Management Centre on assortment recovery

Data on assortments felled from clear-cutting areas were retrieved from the RMK for analysis. Clear-cuttings were carried out from 2011 to the first half of 2017. Only stand elements from the first layer were selected for analysis. However, the stand elements that included tree species represented also in the second layer or single-tree layer were neglected. This was done due to the fact that assortments of the same tree species were aggregated and thus, distributing obtained roundwood data between different layers proved impossible. All stand elements which had stand data but lacked felled assortments were also excluded from the analysis. Firewood was considered by tree species in several stands, but aggregated in a group named 'mixed species'. Firewood volumes of the mixed tree species were weighted by a composition coefficient and divided to the stand elements.

In total, 27,514 felled stand elements were analysed, comprising 14,013 pine elements, 3,045 spruce elements, 7,145 birch elements, 1,862 aspen elements, 679 black alder elements, and 770 grey alder elements (Table 1). Only firewood was salvaged from stand elements of other tree species. These 27,514 analysed stand elements were distributed across 21,057 stands. The geographical distribution of the felled stands is depicted on a map (Figure 2).

To identify the assortments mentioned above, a table compiled based on roundwood parameters sourced from the RMK database was utilized, as presented in Table 3.

Table 2. Site index classes and site index H_{100} relationship.

Site index H_{100}, m	Site index class	Site index class in calculations
< 11.5	5A	6
11.5...15.5	5	5
15.5...19.5	4	4
19.5...23.5	3	3
23.5...27.5	2	2
27.5...31.5	1	1
> 31.5	1A	0

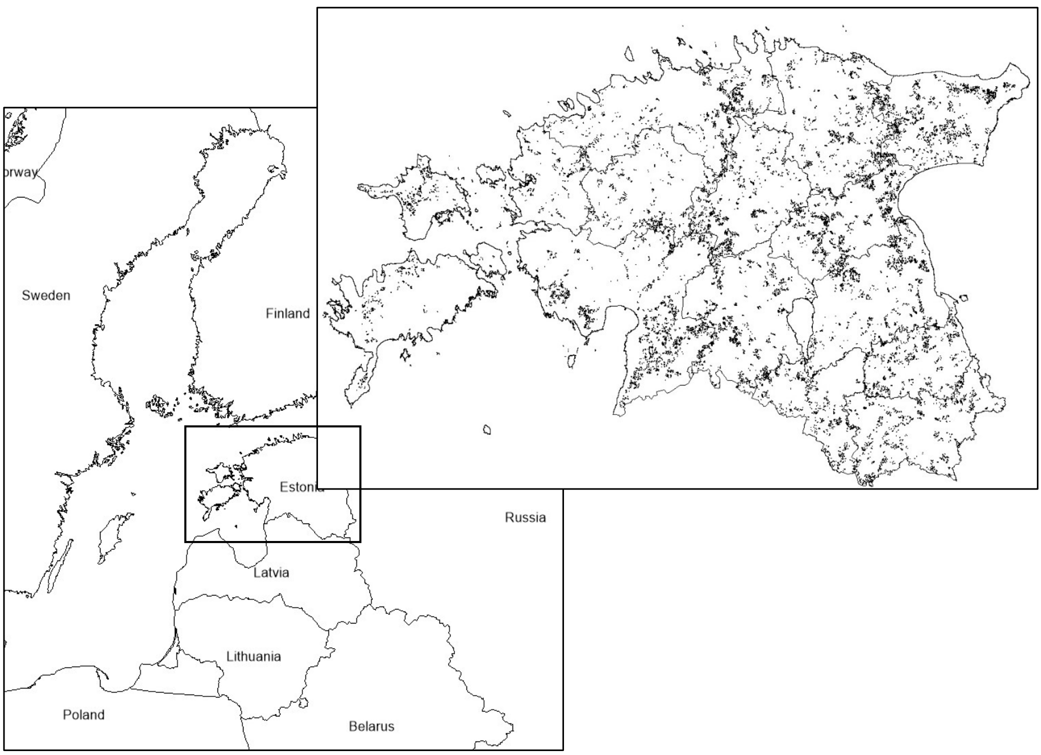

Figure 2. Locations of cutting areas.

Table 3. Parameters of timber assortments (roundwood) used in the analysis.

Tree species	Assortment	Top diameter, cm	Length, m		
			minimum	step	Maximum
Scots pine	Log	28–...	3.1	0.3	6.1
	Log	23–28	3.1	0.3	6.1
	Log	18–23	3.1	0.3	6.1
	Log	13–18	3.1	0.3	6.1
	Log	10–13	3.1	0.3	6.1
	Pulpwood	5	3.0		3.0
	Firewood	3	3.0		3.0
Norway spruce	Log	25–...	3.1	0.3	6.1
	Log	18–25	3.1	0.3	6.1
	Log	13–18	3.1	0.3	6.1
	Log	10–13	3.1	0.3	6.1
	Pulpwood	5	3.0		3.0
	Firewood	3	3.0		3.0
Silver and downy birch	Log	14–...	3.1	0.3	6.1
	Pulpwood	5	3.0		3.0
	Firewood	3	3.0		3.0
European aspen	Log	14–...	3.1	0.3	6.1
	Pulpwood	5	3.0		3.0
	Firewood	3	3.0		3.0
Black alder	Log	18–...	3.1	0.3	6.1
	small log	14–18	3.1	0.3	6.1
	Firewood	3	3.0		3.0
Grey alder	Log	18–...	3.1	0.3	6.1
	small log	14–18	3.1	0.3	6.1
	Firewood	3	3.0		3.0

In order to ensure comparability of the data, the results of all elements were converted to percentages, ensuring that the total of logs, pulpwood, and firewood equalled 100. This conversion was applied both to the results obtained through the described methodology and to the actual felling volumes obtained from RMK.

Additionally, the minimum diameters of spruce and pine logs in use at the respective felling areas were monitored. Theoretical assortment volumes for each stand were calculated based on the dimensions of assortments cut in the corresponding stand. For instance, if pine assortments in the database had a minimum diameter of 18 cm, smaller diameter log assortments were categorized as pulpwood to enable a comparison between actual and theoretical assortment volumes.

Correction model compilation

Two correction models were formulated for each tree species: 1) a firewood increase model and 2) a log volume reduction model.

Initially, an appropriate form for the regression equation was sought to conduct the modelling. The following equation was selected as the primary equation for regression:

$$\Delta m = e^{a} \cdot \left(\frac{A}{A+1}\right)^{b} \cdot \left(\frac{Si+d}{Si+f}\right)^{c} - i, \quad (1)$$

where Δm – volume difference, %;
A – stand element age, year;
Si – site index class;
d, f – coefficients the values of which were found so that the statistical indicators (standard error, coefficient of determination and/or significance probability) of the regression equation were the best;
i – variable that was used for equation logarithming (the argument of the logarithm can only be a positive number);
a, b, c – coefficients found by linear regression.

To find coefficients a, b and c, the equation was converted to linear form:

$$ln(\Delta m + i) = a + b \cdot ln\left(\frac{A}{A+1}\right) + c \cdot ln\left(\frac{Si+d}{Si+f}\right). \quad (2)$$

In the process of refining this equation, it was noted that the constants derived from the original dataset delineate volume differentials solely within the delineated ranges of ages and site index classes. Consequently, a secondary modelling phase was conducted with the objective of formulating an equation applicable across all age and site index class variations. For leveraging the equations derived from the original dataset, computations were performed for site index classes ranging from 0 to 6, corresponding to H_{100} values of 33.5 m, 29.5 m, 25.5 m, 21.5 m, 17.5 m, 13.5 m, and 9.5 m (refer to Table 2), and for ages spanning from 1 to 200 years. Anomalies emerged in the equation for younger ages, resulting in occasional negative outputs. These anomalies were rectified by truncating negative outputs to zero during subsequent analysis. Conversely, at advanced ages, the curve converged towards a limiting value, devoid of any inconsistencies. The computed results underwent regression analysis categorized by site index classes, with age being the sole independent variable. The ensuing equation employed in this analysis is as follows:

$$\Delta m = e^{a + b \cdot \ln\left(\frac{A}{A+1}\right) + c \cdot \left[ln\left(\frac{A}{A+1}\right)\right]^{n}}, \quad (3)$$

where Δm – volume difference, %;
A – stand element age, year;
n – exponent the value of which was found so that the statistical indicators (standard error, coefficient of determination and/or p-value) of the regression equation were the best;
a, b, c – coefficients found by linear regression.

To find coefficients a, b and c, the equation was converted to linear form:

$$ln(\Delta m) = a + b \cdot ln\left(\frac{A}{A+1}\right) + c \cdot \left[ln\left(\frac{A}{A+1}\right)\right]^{n} \quad (4)$$

The values of the constants a, b, and c in the equation were predominantly influenced by the site index class. Typically, a quadratic parabola was employed as the equation; however, in the case of constant c for birch veneer logs, the natural logarithm was utilized as the dependent variable (y). Multiple regression analyses were conducted to determine the exponent n. Subsequently, following a comparison of the regression analysis data, the equation exhibiting the most favourable statistical outcomes was chosen, and the corresponding value of the exponent n was incorporated into this equation.

Results

The equation parameters derived from the regression analysis conducted using the data collected from RMK are presented in Table 4. Equation 2 was utilized in the regression analysis.

The error encountered in the regression equations stemmed from instances where certain young stand ages (where initial data were absent) led to the production of negative results. Consequently, a novel model was devised to yield logical outcomes even for young stands, replacing negative results with zeros. This involved utilizing Equation 1 to compute results separately for each site index class across ages ranging from 1 to 200 years. Subsequently, all negative values were adjusted to zero. Regression analysis was then conducted for each age class (Equation 4). While the specifics of the regression results are not elaborated upon here, it is noteworthy that the determination coefficients approached unity ($R^2 > 0.99$) across all cases. The following relationships between the model coefficients (a, b, c) and the site index class were established, employing a square parabolic function to depict the association:

$$a, b, c = k + l \cdot Bn + m \cdot Bn^2, \qquad (5)$$

where *a, b, c* – Equation 1 coefficient (one of them depending on the formula);
Bn – site index class;
k, l, m – Equation coefficients (Table 5).

Table 4. Equation parameters obtained by comparing roundwood assortment volumes.

Tree species	Assortment	*a*	*b*	*c*	*d*	*f*	*i*	R^2	p-value
Scots pine	Log volume reduction	-0.4560	-6.7947	-46.8016	99	100	1	0.0356	< 0.0001
	Firewood increase	2.7817	1.0015	267.0156	99	100	1	0.0233	< 0.0001
Norway spruce	Log volume reduction	0.2145	6.7871	-0.0656	1	20	1.1	0.0158	< 0.0001
	Firewood increase	-3.1086	17.2571	-91.9444	49	50	0.1	0.0195	< 0.0001
Silver and downy birch	Log volume reduction	1.0622	9.1595	0.3487	10	50	1	0.0945	< 0.0001
	Firewood increase	0.1733	3.2363	0.0063	0,1	1	1	0.0052	< 0.0001
	Veneer log	-3.6396	10.4272	-2.6481	10	20	0.1	0.1445	< 0.0001
European aspen	Log volume reduction	1.0522	12.6587	15.8415	49	50	1	0.1991	< 0.0001
	Firewood increase	-1.0607	28.4761	-0.0969	0.1	0.2	0.1	0.0381	< 0.0001
Black alder	Log volume reduction	0.6106	22.1975	-0.0837	1	2	1	0.0789	< 0.0001
Grey alder	Log volume reduction	-6.106	12.485	-61.485	90	100	1	0.0353	0.0257

Note. *a, b, c, d, f* and *i* are constants of Equations 1 and 2.

Table 5. The parameter *n* of the volume change Equation 3 and the parameters of the Equation for calculating its coefficients *a*, *b* and *c* (Equation 5).

Tree species	Formula	Con-stant	Equation coefficients			
			k	*l*	*m*	*n*
Scots pine	log volume reduction	a	-2.259	0.24693	-0.01345	3
		b	11.35752	-2.10076	0.1712	
		c	894.235	-304.766	28.869	
	firewood increase	a	-3.3503	0.0159	-0.0013	2
		b	1.5375	-0.0271	0.0022	
		c	1.5328	-0.0261	0.0021	
Norway spruce	log volume reduction	a	-0.89371	-0.13886	0.01049	4
		b	29.4603	4.36432	-0.33114	
		c	-366800	-228124	-4093	
	firewood increase	a	-1.66542	-0.06081	0.0012	4
		b	29.59224	0.27817	0.09189	
		c	-115756	-24063	89.533	
Silver and downy birch	log volume reduction	a	-0.39607	0.06595	-0.0032	5
		b	28.784	-1.088	0.042	
		c	3829316	885112	80082	
	firewood increase	a	-1.67591	0.01012	-0.00097	4
		b	25.21899	-0.21777	0.02076	
		c	-211985	7782.9	-749.88	
	veneer block recovery	a	-2.7282	-0.2457	-0.0683	4
		b	30.281	12.921	-1.639	
		ln(-c)	12.655	0.8226	0.2254	
European aspen	log volume reduction	a	0.09015	0.01429	-0.00061	4
		b	27.49482	-0.06593	-0.01049	
		c	-150369	7285	-387	
	firewood increase	a	-1.34789	-0.01386	0.0011	5
		b	46.31225	0.04688	-0.00447	
		c	10507971	920148	-82200	
Black alder	firewood increase	a	0.1209	-0.09111	0.01198	10
		b	73.66109	-4.70172	0.78866	
		c	$-2.703 \cdot 10^{15}$	$-5.258 \cdot 10^{15}$	$6.974 \cdot 10^{14}$	
Grey alder	firewood increase	a	-0.82187	-0.30129	0.00434	7
		b	58.03680	-0.13325	5.87003	
		c	$3.048 \cdot 10^{11}$	$-2.887 \cdot 10^{11}$	$4.242 \cdot 10^{12}$	

Consequently, the site index class serves as the basis for determining coefficients a, b, and c when applying Equation 5. Subsequently, volume variation is calculated using Equation 3, which is contingent upon age.

Figures 3 to 5 describe the results of the equations obtained with regression analyses. Figure 3 graphically illustrates the models created for correcting the stand element assortment of pine, spruce, birch and aspen, and Figure 5 that of black alder and grey alder. The parts A, C, E and G of Figure 3 are for log volume reduction (by considering injuries, curvatures and other defects) and the parts B, D, F and H are for increasing the volume of firewood. The amount of pulpwood is obtained by subtracting the volumes of logs and firewood from the total volume of the assortments.

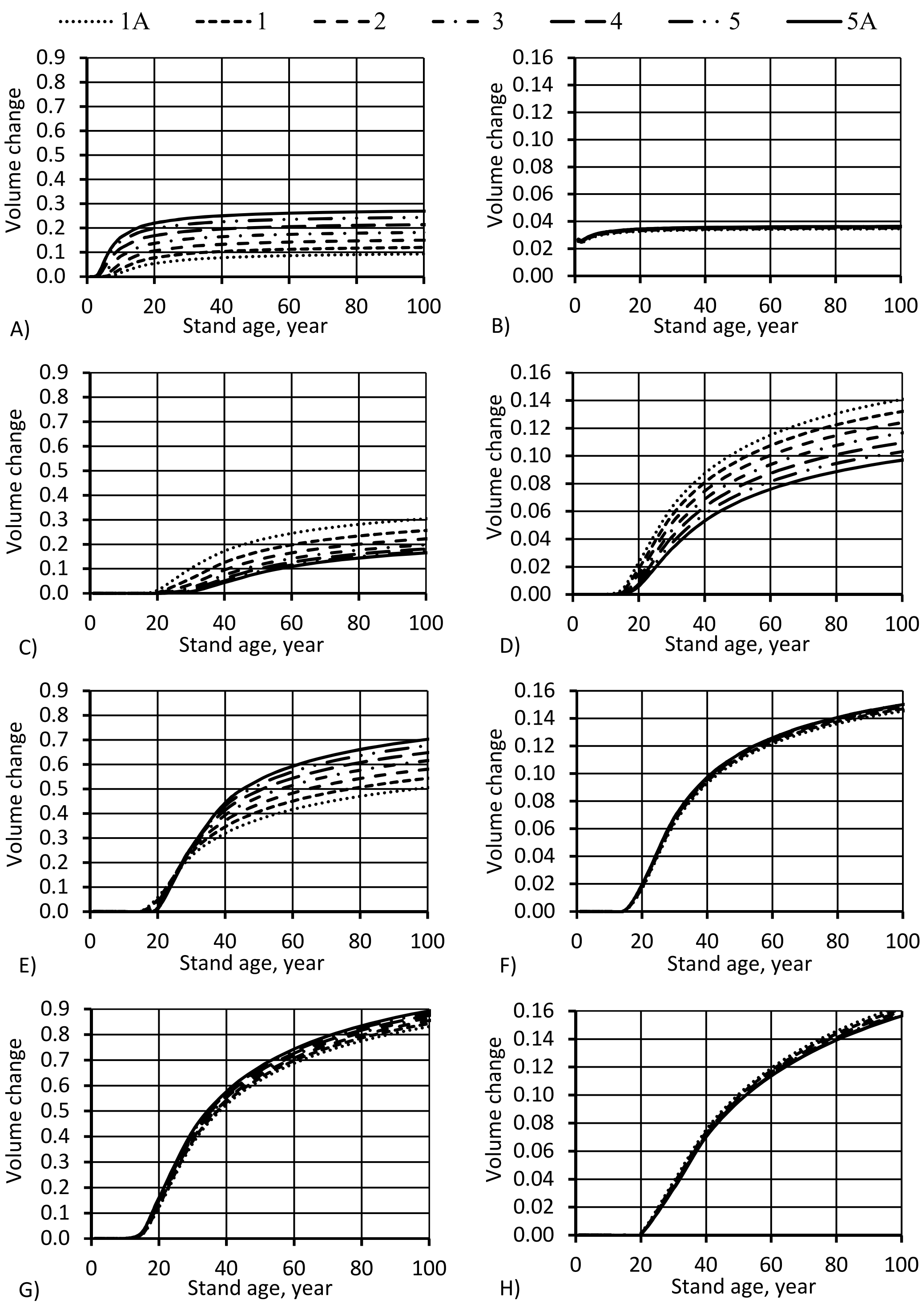

Figure 3. Log volume reduction (A, C, E and G) and firewood volume increase (B, D, F and H) depending on stand age and site index class (A, B – Scots pine; C, D – Norway spruce; E, F – Birch spp.; G, H – European aspen).

Although log assortments are reduced after removing defects, not all of them qualify for firewood. In addition, there is Figure 4 which describes the birch veneer log recovery. The veneer logs were mostly cut from IA site index class forests, but also to a small extent from I and II site index class birch forests. Thus, it is not reasonable to calculate veneer logs for birch forests of the site index class III or lower.

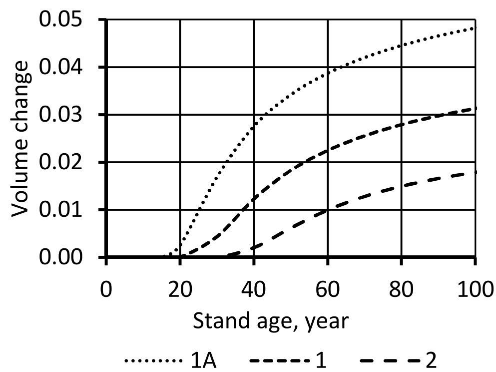

Figure 4. Birch veneer log recovery depending on site index class and stand element age.

In the application of correction equations, the variable H_{100} may be substituted for site index class, as it can be converted into a site index class using the equation provided in Annex 10 to the Forest Inventory Instruction (Metsa korraldamise juhend, 2009):

$$Bn = \frac{33.5 - H_{100}}{4}, \quad (6)$$

where Bn – site index class;
H_{100} – stand height if it were 100 years old.

In this context, employing integer values for site index class becomes redundant; instead, it is advisable to utilize site index class, preferably as decimal numbers.

Based on data from RMK, only firewood had been harvested from all stand elements where other tree species were present; hence, this study did not develop the correction equation for other tree species.

In order to compare the old and new assortment models, both were compared against actual logging data, utilizing stand elements with a minimum volume of 25 m^3/ha in the sample. Assortment volumes and the discrepancies between these volumes and the actual assortments were computed for both models. The outcomes of the three scenarios (actual, old model, and new model) are depicted in Figures 6–11 for Scots pine, Norway spruce, birch species, European aspen, black alder, and grey alder, respectively. These figures delineate the results by diameter class, incorporating the distribution of diameters, as well.

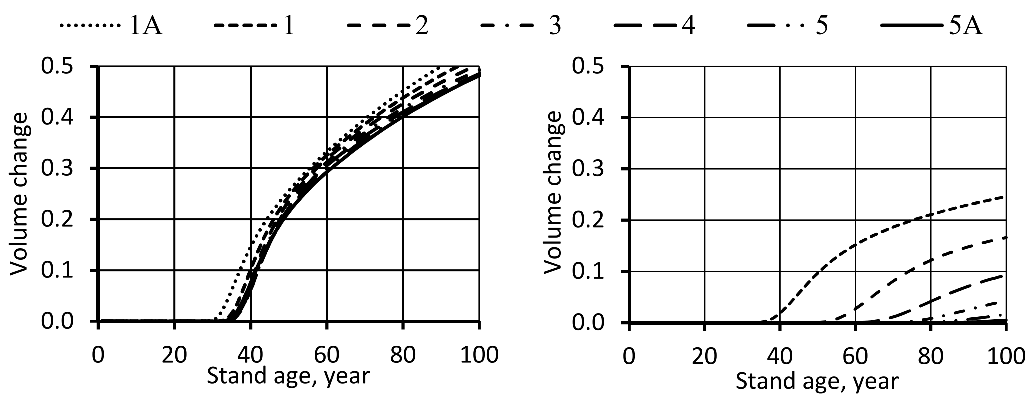

Figure 5. Black alder (left) and grey alder (right) firewood increase, and log volume reduction proportion depending on site index class and stand element age.

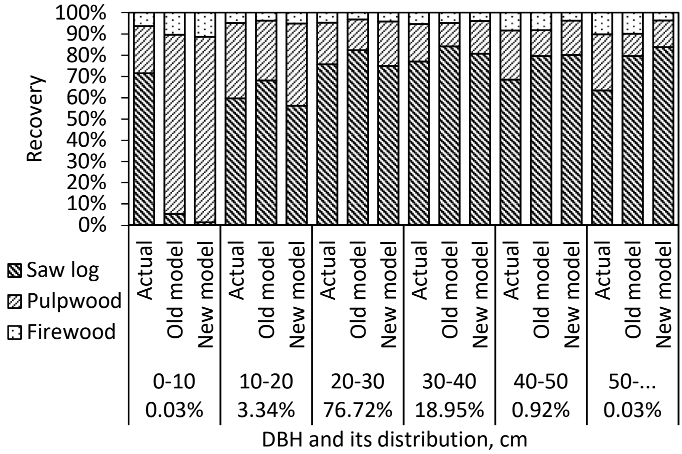

Figure 6.

Distribution of Scots pine assortments calculated by diameter classes according to actual data, the old model and new model.

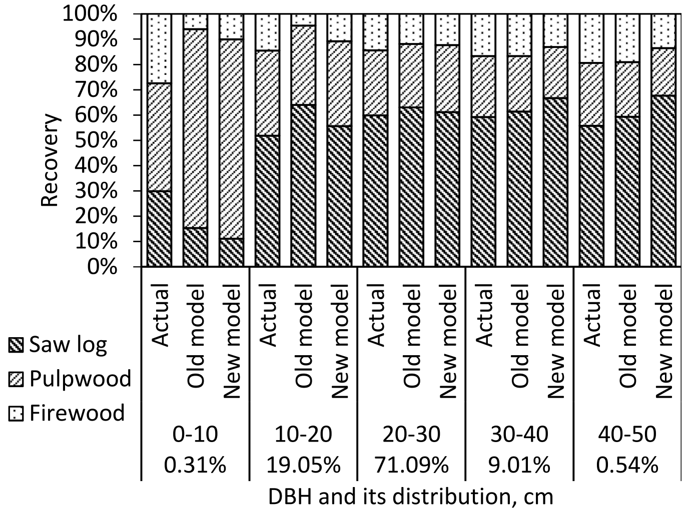

Figure 7.

Distribution of Norway spruce assortments calculated by diameter classes according to actual data, the old model and new model.

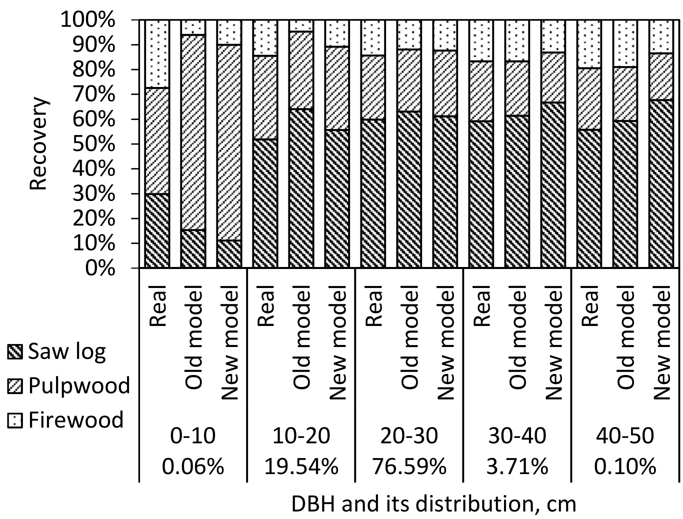

Figure 8.

Distribution of birch species (silver and downy birch) assortments calculated by diameter classes according to actual data, the old model and new model.

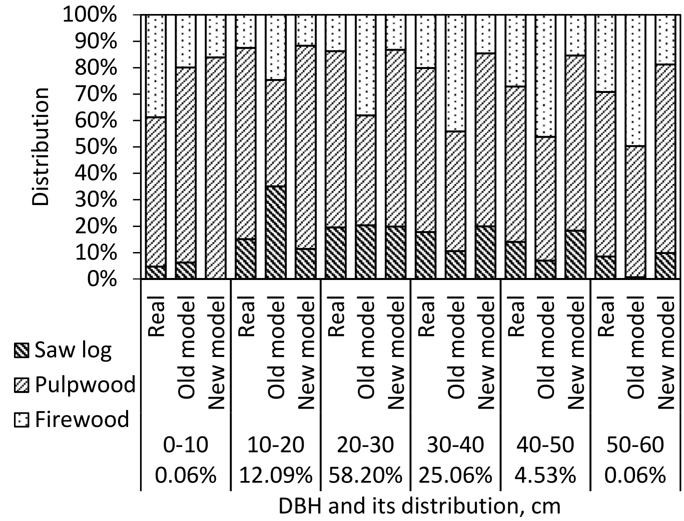

Figure 9.

Distribution of European aspen assortments calculated by diameter classes according to actual data, the old model and new model.

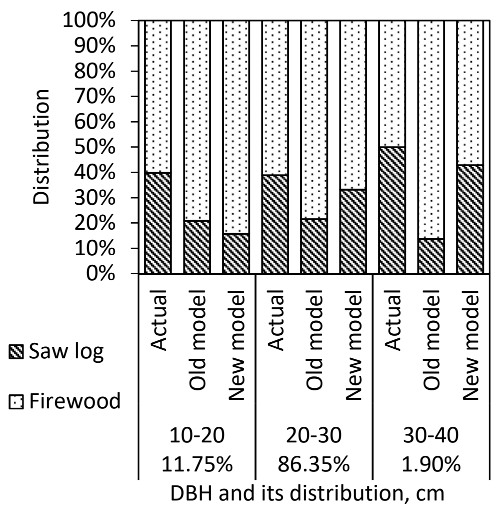

Figure 10. Distribution of black alder assortments calculated by diameter classes according to actual data, the old model and new model.

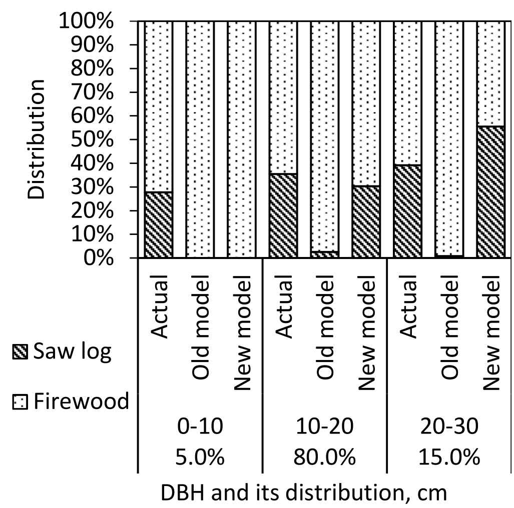

Figure 11. Distribution of grey alder assortments calculated by diameter classes according to actual data, the old model and new model.

Figure 12 presents a comparison of log, pulpwood, and firewood assortment outputs calculated using both the old and new models for Scots pine and Norway spruce species, while Figure 13 illustrates the comparison for birch species and European aspen using the initial dataset. Additionally, Figure 14 depicts the disparities in log and firewood volumes of assortments calculated using both the old and new models from the initial dataset for black alder and grey alder.

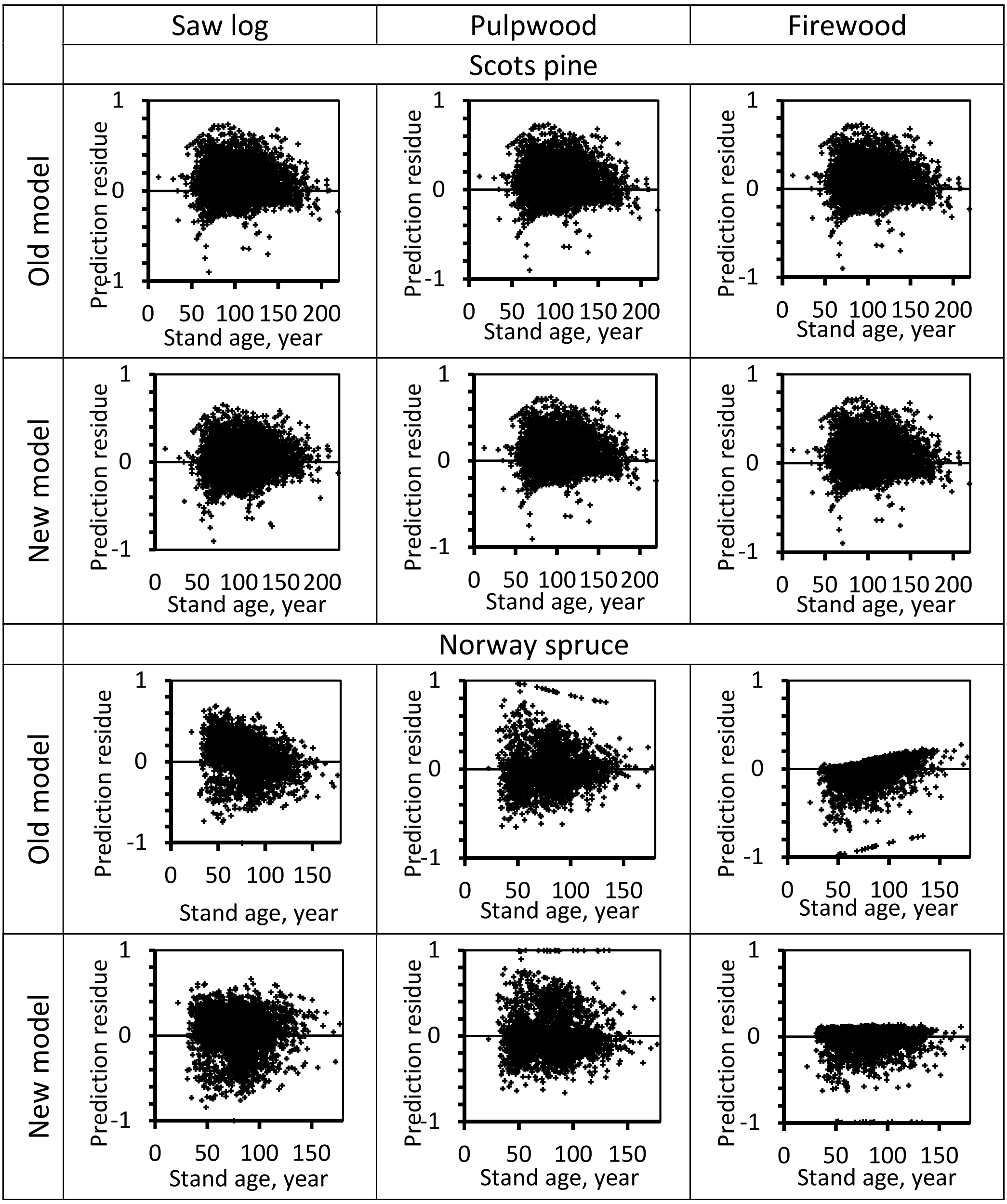

Figure 12. Old and new model prediction comparison residuals for volumes of Scots pine and Norway spruce assortments.

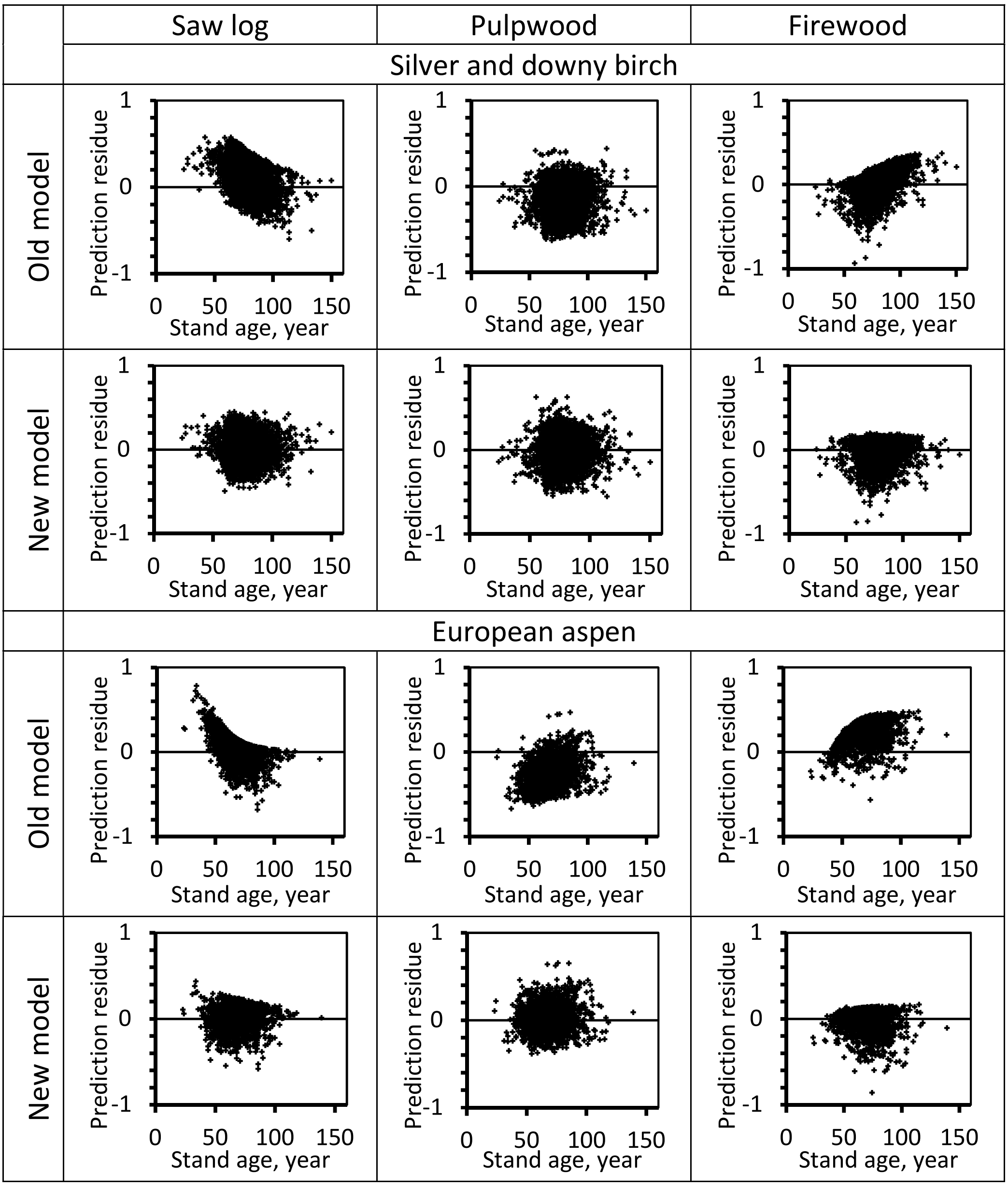

Figure 13. Old and new model prediction comparison residuals for volumes of silver and downy birch, and European aspen assortments.

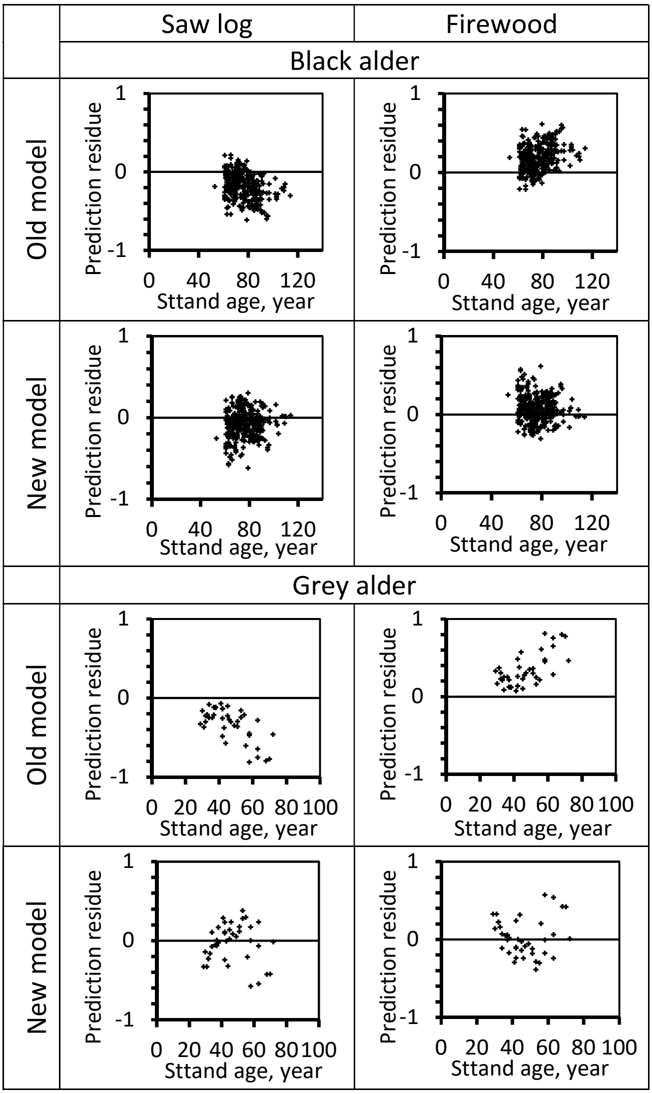

Figure 14.

Old and new model prediction comparison residuals for volumes of black and grey alder assortments.

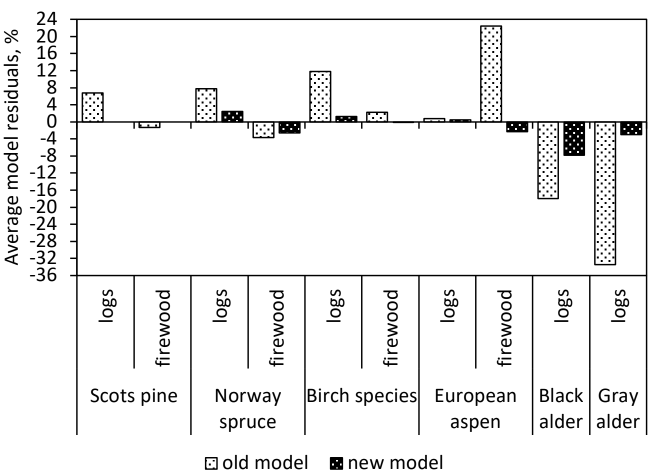

Figure 15.

Average model residuals by tree species.

Table 6. Average model residuals for different models for calculating assortment volumes by tree species.

Tree species	Assortment	Average model residuals, %	
		old model	new model
Scots pine	saw log	6.74	-0.01
	firewood	-1.33	-0.82
Norway spruce	saw log	7.78	2.40
	firewood	-3.67	-2.55
Birch species	saw log	11.83	1.23
	firewood	2.21	-0.16
European aspen	saw log	0.75	0.42
	firewood	22.48	-2.34
Black alder	saw log	-17.98	-7.84
Grey alder	saw log	-33.45	-2.99

In the analysis, model prediction residuals were computed for both the old and new model. The arithmetic means of these residuals, expressed as percentages, are presented in Table 6, and the same information is graphically depicted in Figure 15.

The comparative data in Table 6 and Figure 15 clearly demonstrate that the new model provides better description of the actual assortment outcomes when compared to the old model.

Discussion and Conclusion

Figures 6–11 provide a comparison of models for different tree species, namely Scots pine, Norway spruce, birch spp. (downy and silver birch), European aspen, black alder, and grey alder. In Figure 6, it can be observed that the new model for pine yields more accurate results in assortment distribution when the stand diameter ranges from 10 to 40 cm. Below 10 cm, both models significantly underestimate log output, but the old model provides slightly more accurate estimates. Conversely, for stand diameters exceeding 40 cm, the models overestimate log output, with the old model overestimating less than the new model.

The comparison of models for spruce (Figure 7) and birches (Figure 8) assortment output indicates that the new model provides more accurate estimates for log output in the 10–30 cm diameter range. Similar trends are observed for other diameter ranges, as seen with pine. The comparison of models for aspen assortment output (Figure 9) reveals that the distribution calculated by the new model is much more accurate than that obtained from the old model, and closely aligns with actual results for stand diameters ranging from 10 to 60 cm. For stands with diameters below 10 cm, the old model overestimates log and pulpwood output, while the new model underestimates log output and overestimates pulpwood output.

The comparison of output for black alder assortments (Figure 10) demonstrates that the new model underestimates log output for stand diameters between 20 and 40 cm, whereas the old model underestimates log output even more. For stands with diameters between 10 and 20 cm, the new model underestimates log output more than the old model. In the case of grey alder (Figure 11), the new model overestimates log output for stands with diameters between 20 and 30 cm, performs reasonably well for diameters between 10 and 20 cm, and underestimates output for diameters below 10 cm. The old model yields almost negligible log output for all stand diameters.

Given that the mean diameter of mature stands generally lies within the 20–40 cm range, the novel model yields more precise assortment output calculations in comparison to its predecessor. Additionally, as illustrated in Table 6 and Figure 15, the new model more effectively characterizes the real assortment outcomes than the outdated model.

Several scientific articles, including the current work, have focused on stand diameter and height data analysis. This study aims to calculate the proportion of sawlog output in relation to the sum of all assortments, allowing for a comparison with a previous Finnish study by Nyyssonen & Ojansuu (1982) (Figure 16). The figure illustrates differences between the Estonian and Finnish models, particularly in the diameter range of 20–25 cm, where the Estonian model estimates higher log output for smaller diameter stands and lower for larger diameter stands compared to the Finnish model.

Siipilehto & Rajala (2019) conducted a study adjusting diameter distributions for each stand individually, resulting in precise saw log and pulpwood recoveries. The comparison with the Estonian model (Figure 16) indicates higher pine and spruce saw log recoveries in the Finnish study. These differences may originate from stem defects and rots more prevalent in Estonia.

In a 75-year-old 3 ha *Vaccinium myrtillus* pine forest in Finland (stand diameter 29.8 cm and height 24.7 m), Vastaranta *et al.* (2014) found a proportional recovery of 85.5% for saw logs and 14.5% for pulpwood. The results placed Vastaranta *et al.* (2014) findings between Siipilehto & Rajala (2019) and the Estonian model. However, the study focused on a single sub-compartment, limiting the generalizability of the results. Kankare *et al.* (2014) tested terrestrial laser scanning (TLS) and a combination of TLS and airborne laser scanning (ALS) on the same Finnish area, but despite promising results, these methods still lacked accuracy compared to the current methods.

Puumalainen (1998) studied the theoretical dependence of assortment recovery on minimum diameter and length values. They found that shortening the minimum saw log length had a greater impact on saw log recovery than reducing diameter. The new Estonian model represents actual saw log recovery, considering variations in saw log lengths based on orders. For most data, it is unknown which cuttings were carried out according to which orders. This is the reason why using different saw log lengths is a supplementary factor increasing recovery divergence.

Malinen *et al.* (2010) studied cutting scenarios and observed different results for assortment recoveries. Figure 16 shows average saw log recovery for pine, spruce, and birch (a total of 1,399 pines, 2,061 spruces and 26 birches were measured in sample plots) according to Malinen *et al.* (2007), with detailed stem data producing reliable estimates (Table 7).

The stem quality database employed in Finland contains dimensional and quality information regarding trees harvested in specific thinning and final cutting stands (Malinen *et al.*, 2018). In a previous study (Malinen *et al.*, 2018), external tree defects were estimated, while internal quality was not assessed, resulting in a significantly smaller total saw log reduction of 11.7% for spruce. This current study incorporates actual log recoveries from cutting stands and considers internal defects, as depicted in Figure 3 (C) and Table 7.

For context, a brief comparison with

Table 7. Saw log proportion reduction.

Tree species	Age used in the Estonian model	Malinen *et al.* 2007			Estonian model (Figure 3)
		MELA-96	MELA-05	Bucking simulation	
Pine	60–100	16.04	24.25	18.17	9–28%
Spruce	60–80	2.35	17.79	6.38	10–29%
Birch	50–70	30.27	29.35	41.46	38–64%

tree species from other regions is presented. A study in Brazil examined 30 Japanese cedars in a plantation, revealing saw log, pulpwood, and firewood recoveries of 66.1%, 32.0%, and 1.9%, respectively, out of all roundwood assortments (Sanquetta *et al.*, 2018). Despite testing stem taper curves, this study did not provide model tree dimensions. The absence of diameter values prompted the illustration of saw log recovery in Figure 16 with a red dotted line.

In another analysis, a dataset of 1,038 trees was utilized to fit taper models and estimate saw log and firewood volumes in 273 plots within eight-year-old *Tectona grandis* L.f. stands in Brazil (Pelissari *et al.*, 2017). This dataset represents the second thinning stage, enabling commercial volumes. The saw log recoveries observed in Brazil were found to be lower than those in Estonian conifers and grey alder but surpassed the saw log recoveries of other broadleaf trees. The result is presented in Figure 16 with a red plus sign.

It would be intriguing to compare developed models with practical bucking outcomes. However, owing to variables impacting the actual assortment recovery, the dataset should encompass a representative sample of diverse stand types, harvester operators, and wood buyers. Acquiring such extensive data poses significant challenges (Malinen *et al.*, 2010). While this study delved into the impact of age and quality, it omitted an analysis of the correlation between the assortment recoveries under investigation and site type, harvester operators, and wood buyers. Concurrently, the influence of all these factors remains obscured within the resultant models.

In conclusion, the practical applicability of the assortment recovery model devel-

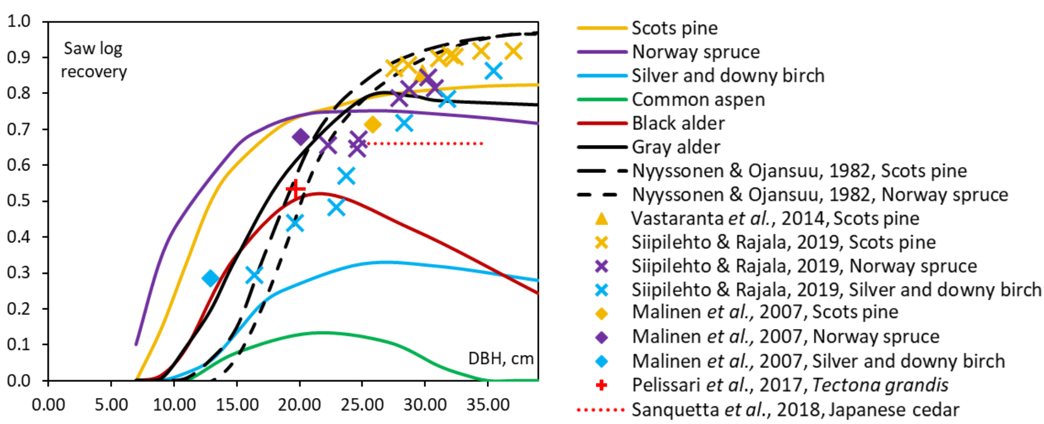

Figure 16. Saw log proportions of the total volume of all roundwood assortments by tree species and sources.

oped in this study can be assessed. However, it is essential to acknowledge that over time, the dimensions of timber and veneer log have undergone changes. With the adoption of newer technologies, the diameters of timber logs have progressively decreased. Sawmills now purchase logs with diameters as small as 8–10 cm, while the plywood industry starts from 16-cm-wide logs. Additionally, quality criteria for logs have been reduced. Some sawmills, for instance, cut boards from curved logs, with saws following the curvature of the log. The boards obtained through this method, known as curve sawing, straighten during stacking and drying. All such changes impact the output of logs from the forest. Therefore, periodic studies are necessary to calculate the proportions of log assortments under these evolving conditions.

In modern harvesting operations, the diameters, lengths, and assortment names of all trees are measured. It would be wise to compile detailed data and use it not only for assortment recovery studies but also for various other data analyses.

The steps for programmers to utilize the developed model are outlined in the Appendix 1.

Acknowledgements. This study was supported by the project of the Environment Agency of the Republic of Estonia No. 4-1/17/32.

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Appendix 1. Using the algorithm.

The successful implementation of the algorithm is contingent upon the availability of inventory data. Predictions for forest roundwood assortments are made based on the following steps utilizing inventory data:

1. Trees are categorized into diameter classes, determined by the diameter of the stand element, utilizing the diameter distribution:

Relative diameter of a tree in relation to the diameter of a stand element	Number of trees, per mille
0.4	11
0.5	34
0.6	59
0.7	96
0.8	131
0.9	154
1.0	154
1.1	132
1.2	96
1.3	64
1.4	35
1.5	18
1.6	10
1.7	4
1.8	2

2. Height is assigned to each diameter class, considering the height, diameter of the stand element, and tree diameter (size of the diameter class) as outlined by Padari (1999) and Padari *et al.* (2009).
3. Assortments for each diameter class are identified using Ozolinš' stem taper curve, in accordance with assortment dimensions (Ozolinš, 2002; Padari, 2020). Assortment volumes are calculated excluding bark.
4. The volume of the entire tree with bark is computed, starting from 0 and extending to the height of the tree.
5. Assortment volumes for an individual tree are multiplied by the occurrence of trees in the respective diameter class. The same procedure is applied to the total tree stem volume.
6. The volumes of assortments across different diameter classes are aggregated. Quantities of assortments are determined for the stand element under the assumption of all trees being healthy and defect-free. Total tree stem volumes are also summed.
7. A ratio is derived by dividing one of the stand elements by the sum of the assortments (saw logs + pulpwood + firewood).

8. This ratio is used to scale all assortments and the sum of total tree stem volumes.
9. The ratio for saw log volume reduction is calculated using Equation 5 and 3. If required, the site index class is computed beforehand using Equation 6.
10. Similarly to section 9, the ratio for firewood increase is determined.
11. The ratio from the previous step is added to the firewood ratio.
12. Due to potential variations in log assortments, an additional variable is introduced for log correction. This variable is computed by dividing the ratio from section 9 by the sum of log assortment ratios (calculated in section 8). If the result exceeds 1, the additional variable is set to 1.
13. For all log assortments, the log assortment ratios from section 8 are multiplied by the expression 1 minus the additional variable from section 12.
14. The pulpwood ratio is determined by subtracting the log assortment ratios (results from section 13) and the firewood ratio (calculated in section 11) from 1.
15. Actual quantities of assortments are obtained by multiplying the ratios from sections 11, 13, and 14 by the quantities of assortments from section 6 (saw logs + pulpwood + firewood) divided by total tree stem volumes from section 6.