Modeling of the assortment structure of spruce tree trunks in the Kostroma region, European Russia

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Abstract.. The issue of using the equations of the stem taper to develop new standards for the assortment of the forest stands is relevant and is widely presented in local and foreign industry sources. The values of trunk diameters for assortment assessment were determined using the O. Garcia stem taper equation. A method for modeling the assortment structure of spruce tree trunks using the stem taper model is proposed. A comparison of the obtained data with current forest inventory standards showed that the use of the stem taper model made it possible to increase the accuracy of accounting for large commercial timber of the highest height quality class by up to 27%. Adjusting the yield values of large, medium, small wood commodity, volume of firewood and waste will help to rationalize the use of trunks and increase the profitability of forestry in the region. The application of the proposed methodology will help to simplify the procedure for sorting forest resources and reduce the costs of its implementation.

1 Introduction

Kostroma Region is the second largest region in the Central Federal District of the Russian Federation. The forest cover of this territory is 74.1%. One of the main forest-forming species of the region is spruce (*Picea* sp.). The wood of this species is widely used in industry and is of great economic importance. The environment-forming properties of spruce also play a significant role [1-2]. Therefore, standards are needed, the application of which will allow us to assess the stock of mature standing timber and analyze its assortment structure to optimize the use of stem wood in obtaining sawn timber of the established standard and reduce the volume of waste.

Since 1908, assortment tables have been used to determine the output of timber commodity categories in the Kostroma region, which have a number of shortcomings. The shortcomings of the height quality class rank scales, expressed by the discrepancy between the graph of the heights of the forest stand and the level of the heights of the curves in the rank tables, which leads to significant inaccuracies in determining the reserve and justifying

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the region of permissible application of the existing tables, as well as to an incorrect assessment of the assortment structure of the forest stand.

Assortment tables must be compiled for each species, for forest taxation areas. They must be an integral part of the system of general and regional standards for determining the volumes of trunks and forest stands, timber yields for individual technical categories when assessing the forest felling fund. The tables must ensure the accuracy of determining the volumes of trunks and reserves during enumerative taxation of at least ±4%.

It is most rational to estimate the volume of tree trunks and its distribution by wood commodity, firewood and waste that have commercial demand using standards based on mathematical equations. This method provides the opportunity to conduct a high-quality analysis of the expected benefits and costs of timber harvesting, automated classification of the volume of the same tree into different assortments based on current demand [3-6]. The basis for such standards can be the equations of the stem taper, which with great accuracy reflect changes in the diameter and shape of any part of the tree trunk with height [7-9]. With the help of such equations, it is possible to estimate both the volume of the entire trunk and output values of large, medium, small wood commodity, volume of firewood and waste of different lengths by obtaining information about the diameter in the bark or without bark at any height [10]. The stem taper equations can be used to compile assortment tables based on individual stem lengths or specific diameter thresholds [11-13].

The aim of this study is to evaluate the application of the stem taper equation for modeling the assortment structure of spruce trunks in the Kostroma region.

2 Materials and methods

2.1 Data

The data was the results of the analysis of 1686 tree trunks of spruce trees from the Kostroma region. The obtained sample characterizes the dominant and co-dominant trees of spruce forests with wood sorrel, blueberry and fern. In the conditions of the studied region, spruce stands are predominantly formed by hybrid forms of spruce (Picea × fennica) with varying degrees of manifestation of morphological characteristics of Norway spruce (*P. abies*) and Siberian spruce (*P. obovata*)

The diameters of the segments into which the trunks in question were bucked were installed only in the bark. An empirical function $y = 0.9647x - 0.2466$ was used to find the values of diameters without bark (y – diameter without bark, cm; x – diameter with bark, cm). Calculations of the output of large, medium and small wood were performed in Microsoft Excel and in Python. For comparison we used assortment and commodity tables for forests of the central and southern regions of the European part of the RSFSR (1987).

According to the stem taper, commodity wood, firewood and waste were distinguished. Commodity timber included with a diameter of 6 cm in the upper section. Firewood included non- commodity parts of the trunk with a diameter of 3 cm. The remaining parts of the trunk were classified as waste. According to the thickness in the upper cut, commodity timber in accordance with GOST 9463-88 (Round timber of coniferous species) was distributed into size categories. Small wood included timber from 6 to 13 cm inclusive, medium wood from 13.5 to 25.0 cm, and large wood from 25.1 cm.

2.2 Model

Prediction of the values of the diameters from the butt to the tip for calculating the yield of different output of large, medium, small wood commodity, volume of firewood and waste s and sizes was made using the O. Garcia equation [13], which showed good quality of modelling the stem taper [13]:

$$d_i = \sqrt{D^2\left(\frac{H - h_i - b_0 + b_0 \exp\left(-\frac{(H - h_i)}{b_0}\right) + b_1(H - h_i)\exp\left(-\frac{h_i}{b_2}\right)}{H - 1{,}3 - b_0 + b_0 \exp\left(-\frac{(H - 1{,}3)}{b_0}\right) + b_1(H - 1{,}3)\exp\left(-\frac{1{,}3}{b_2}\right)}\right)} \quad (1)$$

Where d_i – diameter at height h_i, cm; D – diameter at height 1.3 m, cm H – tree height, m; b – model parameters.

2.3 Model evaluation

The conformity of the predicted values of the output of wood commodity, firewood and waste with the actual data was assessed using generally accepted criteria: root mean square error (*RMSE*), mean absolute percentage error (*MAPE*), mean absolute error *(MAE*), mean bias error (*MBE*) and coefficient of determination (R^2) [12]. Calculations were performed in Microsoft Excel.

3 Results and discussion

3.1 Model estimation results

The actual and predicted values of the yield of large wood commodity (in m^3) from spruce trunks (Figure 1a) are characterized by a trend line with the equation y = 1.0148x + 0.0054; for medium wood commodity (Figure 1b) y = 1.0009x + 0.0056; for small wood commodity (Figure 1c) y = 0.9951x – 0.0021; firewood and waste (Figure 1d) y = 0.9914x + 0.0018. All comparisons are characterized by uniform distribution of points along the trend line. A small left-side asymmetry is noted only for the feature volume of firewood and waste. The minimum spread of points of actual and predicted values is characteristic of the feature volume of large wood commodity.

The differences between the actual and predicted values of the sizes of wood commodity, firewood and waste in volume units were determined by calculating the indicators generally accepted in mathematical statistics. (Table 1). The analysis of the metrics revealed that the *RMSE* values for all considered indicators range from 0,008 to 0,064. The proximity of the *MBE* and *MAE* values to zero indicate a good fit of the model to the data set and the presence of a small proportion of overestimated and underestimated values. The R^2 values of the considered features range from 0.883 to 0.980, indicating sufficient modeling quality. The *MAPE* values ranged from 6.637 to 50.701%. Such significant discrepancies are explained by the presence of an artifact in this conformity metric, which manifests itself in a significant overestimation of values when comparing the volumes of trunks close to zero and having no economic value. The comparison of actual and predicted values showed that the use of the equation of the stem taper of spruce trees made it possible to obtain the yield of large, medium and small wood commodity, as well as firewood and waste with sufficient accuracy in both volumetric and relative quantities.

The obtained values of the metrics of conformity between the considered indicators in relative values are presented in Table 2. Compared with the results of calculating the metrics for volumetric values, the *RMSE* values increased and were located in the range from 3,612 to 5,649. The *MBE* values indicate the presence of a slight overestimation of the predicted values for the output of large and small wood commodity, as well as firewood and waste. The *MAPE* values for the large and medium wood commodity, firewood and waste decreased by 2,213 to 3,838%; for small wood commodity they increased slightly. The calculated R^2 values for economically significant wood commodity range from 0,954 to 0,982.

The comparison of actual and predicted values showed that the application of the equation of the stem taper of the spruce tree trunk made it possible to obtain the yield of large, medium and small commercial timber, as well as firewood and waste with sufficient accuracy in both volumetric and relative values. Using the proposed equation, a material assessment table was compiled for pine trees in the Kostroma region, reflecting the yield of large, medium and small commercial timber, as well as firewood and waste. The input to the table is the diameter at a height of 1.3 m and the height of the tree. The proposed table can be used for trees with taxation diameters from 8 to 80 cm and a height from 8 to 40 m.

3.2 Modelling of material assessment

The values of the volumes of output of wood commodity, firewood and waste obtained using the equation of the stem taper were compared with the volumes given in the assortment table for spruce trees (Figure 2a). An analysis of the figure allows us to note that with a volume of large wood commodity of 3 m^3 for height quality classes 1a, 1, 2, the values calculated using the stem taper model exceed those found from the assortment tables by up to 0,4 m^3. For the volume of medium wood commodity (Figure 2b) up to 0.4 m^3, the tabulated and predicted values of the yield have the smallest differences, which then increase. For height quality classes 1a, 1 and 2 an underestimation of the calculated values of the yield of average commercial timber is noted compared to the tabulated ones. The yield of small wood commodity (Figure 2c) is characterized by the presence of maximum discrepancies between the values of the feature. The volumes calculated by the model for higher height categories are significantly less than the tabulated ones after 0.05 m^3. The yield of firewood and waste (Figure 2d), calculated using the model, in most cases corresponds well to the tabulated data. Small differences begin to appear for higher height categories after 0.3 m^3.

To obtain information on the magnitude of variation between the values of the volumes of output of commodity timber, firewood and waste, established by applying the equation of the generator and assortment tables, the calculation of conformity metrics by height quality classes was performed. For all timber, the volumes calculated using the tree stem generatrix equation and those taken from the tables have significant differences. The values of the yield of large wood commodity are characterized by a high proportion of explained variance for all height quality classes. The *MBE* values for large commercial timber indicate an overestimation of the predicted values compared to the tabulated ones for all height quality classes except 4. The magnitude of the differences for higher height classes is up to 27.818%. The average yield of large wood commodity is characterized by the values of the coefficient of determination, located in the range from 0.033 to 0.835. The *RMSE* values do not exceed 0.199. In general, the predicted values were lower than the tabulated ones by up to 36.245%. The calculated values of small wood commodity yield were lower than the tabulated values by up to 43.720%, with *RMSE* not exceeding 0.062. The obtained values of the yield of firewood and waste for the 1a and 1 height categories exceed the data in the tables by 15.806–25.471%, respectively. For the 2, 3, 4, 5 and 5a height categories, an underestimation of the predicted volumes by up to 43.327% was noted.

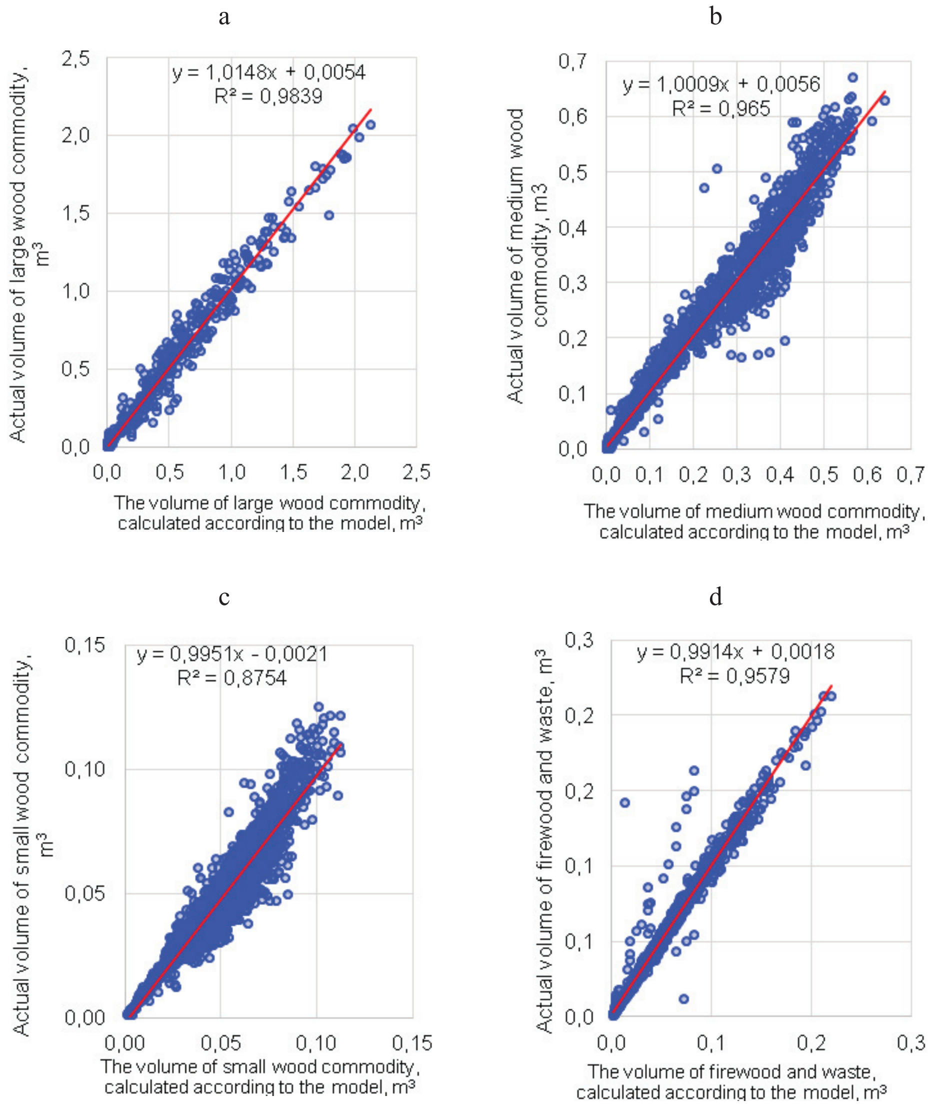

Fig. 1. Ratio of calculated and actual values: a) volume of large wood commodity, b) volume medium wood commodity, c) volume of small wood commodity, d) volume of firewood and waste.

Table 1. Metrics of compliance of actual and predicted values of timber yield of various commodity categories and sizes in volumetric quantities.

Indicator	*RMSE*	*MBE*	*MAE*	*MAPE*	R^2
Volume of large wood commodity, m^3	0.064	0.017	0.040	50.701	0.980
Volume medium wood commodity, m^3	0.038	0.007	0.026	21.871	0.954
Volume of small wood commodity, m^3	0.008	-0.002	0.006	14.415	0.883

Volume of firewood and waste, m^3	0.008	0.001	0.003	6.637	0.958

Table 2. Metrics of compliance of actual and predicted values of timber yield of various wood commodity, firewood and waste and sizes in relative values.

Indicator	***RMSE***	***MBE***	***MAE***	***MAPE***	R^2
Volume of large wood commodity, m^3	4.896	2.183	3.670	48.488	0.972
Volume medium wood commodity, m^3	5.649	1.253	4.146	18.348	0.954
Volume of small wood commodity, m^3	4.804	-1.874	3.071	16.659	0.982
Volume of firewood and waste, m^3	3.612	0.204	0.695	2.799	0.590

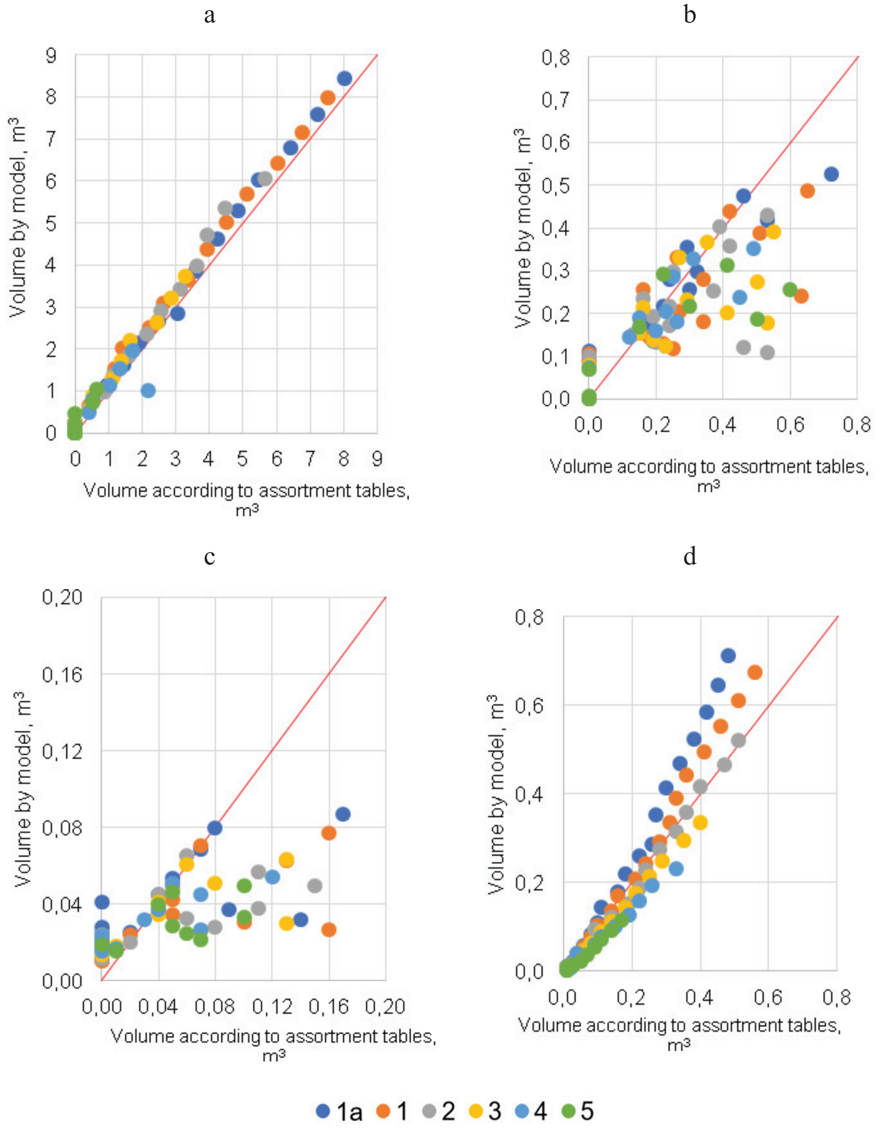

Fig. 2. Comparison of the values of the volumes of timber output of various wood commodity, firewood and waste from the assortment tables and established using the equation of the stem taper a)

large wood commodity, b) medium wood commodity, c) small wood commodity, d) firewood and waste.

3.3 Discussion

Thus, for spruce stands of the Kostroma region, the application of the equation of the stem taper allowed to increase the accuracy of accounting for wood commodity of 1a, 1, 2, 3 height quality class by up to 27% compared to the current standards, which will increase the receipt of funds at the rates of payment from tenants to the regional budget. The ensured accuracy and adjusted approach to determining the output of wood commodity, firewood and waste will contribute to the rationalization of the use of spruce trunks and the receipt of more valuable assortments.

4 Conclusions

For spruce stands growing in the Kostroma region, an algorithm for determining the assortment structure using the equation that forms the tree trunk is proposed. The values of the quality metrics indicate the advantage of the proposed sorting method over the use of classical tables. The application of the tree trunk-forming equation for sorting will allow you to increase the profitability of forestry in the Kostroma region due to the receipt of previously unaccounted funds from the sale of up to 27% of large commercial timber belonging to the highest altitude categories. The use of the proposed methodology will facilitate the simplification of the forest resource sorting procedure and the reduction of costs for its implementation. Further research is required, aimed at introducing the considered model of the assortment structure into the automated algorithm of taxation of the logging fund. The proposed method of modeling the assortment structure of spruce tree trunks using the tree trunk forming equation can be reproduced for other species and forestry conditions.

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