The Siberian spruce (Picea obovata L.) stem formation in the Yenisei Range

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Abstract. The present research investigated the Siberian spruce stem formation features, basing on materials from 15 sample plots, where we cut and measured 160 model trees. We indicated that the stem form factor is 12-17% less than the average in current volume tables, which entails errors in determining stem and growing stock volumes. We established features of the spruce bark formation at different relative lengths. We did not reveal any influence of bark on the stem shape. We also made some recommendations for the inventory assessment of spruce stands in the study area.

1. Introduction

The Yenisey Range is a range of mountains located between the Kan River valley and the Stony Tunguska, representing the elevated southwestern edge of the Central Siberian Plateau.

The climate is continental due to the hampered access of humid air currents from the Atlantic Ocean.

The mean annual precipitation within the most elevated watersheds reaches 700 mm. The average annual temperature is about -5 °C. Snow depth exceeds 1 m.

The Yenisei Ridge's uplands are characterized by winter temperature inversions; winter temperatures there are higher than in the underlying basins and river valleys. Sometimes the temperature difference reaches 10 °C.

Thus, the study area's climate is rather harsh and largely depends on the relief of the Yenisei Range. The region is characterized by several types of terrain: the central drainage basin – a slightly eroded massif with prevailing heights of 700-900 m (the highest point is 1,104 m high Yenashimsky Polkan); western, southern, and northern low ridges isolated from each other by river valleys, made up of metamorphic rocks, which usually have dome-shaped peaks covered with a stone run; deep (up to 200-250 m) river valleys: the Velmo, the Big Pit River, the Teya, etc.

The most common parent rocks in the study area are dense bedrocks – shales, sandstones, less often igneous rocks – alkaline and acidic.

Taiga acidic non-podzolized soils were formed on shales. Rendzina was formed from carbonate- or occasionally sulfate-rich parent material. Soil formation is largely conditioned by permafrost.

A characteristic feature of the study area's vegetation is the transient mountain-lowland plant community and not pronounced vertical zonation [1-4].

In the central and northern parts of the region, the main forest-forming tree species are pine (Pinus sylvestris L.) and larch (Larix sibirica L.), which form relatively low-productivity low-density stands. The most common forest type is mossy pine forests.
The southern part of the study area is occupied by dark coniferous forests composed of Siberian fir (Abies sibirica L.), Siberian spruce, and Siberian pine (Pinus sibirica Du Tour). Along with dark coniferous stands, there also grow pine and larch forests of mossy, lichen, herb-rich, and sphagnum types. Pure spruce forests are rarely observed; low-productivity stands prevail.

Spruce stands establishment in different regions [5-10], and forest inventory standards for their assessment have been studied for a relatively long period. When developing volume tables, V.K. Zakharov [5] established boundaries of the spruce stem form factor: the highest – 0.8; medium – 0.7; the lowest – 0.6. The basis for this classification was the materials collected in spruce stands of the European part of Russia.

The study of spruce stands inventory attributes in Yenisei Siberia has not yet received sufficient attention, probably because pure spruce stands occupying large territories are relatively rare in the region. At present, two volume tables were being used for spruce forests of this region – a table compiled in 1974 by E N Falaleev [11] for spruce forests of the Krasnoyarsk Krai and a table created in 2002 by A S Smolyanov and G K Subochev [12] for the southern taiga spruce forests of Central Siberia.

Such an inadequate forest inventory does not correspond to a vast region that includes several forest sites with different environmental conditions.

The tables’ analysis showed that current volume tables were based on the breast height form factor 0.47-0.53, which corresponds to the average spruce stem according to VK Zakharov [5].

The present study aimed to establish spruce stem formation features in low-bonitet mountain spruce forests of the Yenisei Range and assess the volume tables’ correspondence to the inventory object.

2. Methods and Materials

The research was based on materials from 15 sample plots, where we cut and measured 160 model trees. The characteristics of the sample plots are given in table 1.

| No | Stand composition | Mean | Density | Stock, m³/ha | Bonitet class | Forest type | Model trees, pcs. |
|----|-------------------|------|---------|-------------|--------------|-------------|--------------------|
| 1 | 6S2F1P1B          | 19.7 | 25.3    | 163         | 0.62         | 198         | IV a               | 10 |
| 2 | 6S1P1F2B          | 18.9 | 25.5    | 166         | 0.61         | 179         | IV b               | 11 |
| 3 | 5S2P1F2B          | 20.1 | 26.8    | 166         | 0.72         | 228         | IV b               | 11 |
| 4 | 6S3F1B+P          | 19.3 | 26.3    | 169         | 1.2          | 354         | IV a               | 10 |
| 5 | 4S3F1P2B          | 22.0 | 30.9    | 169         | 0.74         | 269         | IV c               | 13 |
| 6 | 5S2P1F2B          | 19.2 | 25.7    | 174         | 0.51         | 149         | IV a               | 10 |
| 7 | 4S3P1F2B          | 18.8 | 23.6    | 158         | 0.59         | 174         | IV c               | 9  |
| 8 | 5S2F1P2B          | 22.0 | 28.3    | 184         | 0.66         | 240         | IV d               | 12 |
| 9 | 5S2P1F2B          | 17.8 | 23.7    | 196         | 0.63         | 170         | V c                | 9  |
| 10| 7S2F1BfewP        | 21.9 | 29.6    | 160         | 0.54         | 198         | IV d               | 12 |
| 11| 6S2F1P1B          | 19.3 | 26.4    | 153         | 0.88         | 259         | IV b               | 10 |
| 12| 7S2F1B+P          | 21.0 | 28.9    | 156         | 0.51         | 176         | IV d               | 12 |
| 13| 7S2F1BfewP        | 22.3 | 31.4    | 169         | 0.71         | 259         | IV b               | 13 |
| 14| 5S3P2F fewB       | 19.2 | 24.0    | 157         | 0.68         | 200         | IV a               | 9  |
| 15| 6S1F3B+P          | 19.7 | 25.5    | 177         | 0.48         | 153         | IV c               | 9  |

a – Siberian spruce (Picea obovata), b – Siberian fir (Abies sibirica L.), c – Siberian pine (Pinus sibirica Du Tour), d – birch (Betula sp.); a–Bilberry spruce forest, b–Mossy spruce forest, c – Mossy and bilberry spruce forest, d – Herb-rich spruce forest.
The establishment of sample plots was carried out following the industry standard – OST 56-69-83 “Sample plots. Establishment methods” [13]. We measured model trees by the “model tree card” scheme, dividing stems into sections, describing defects, and conducted stems specification. We used the proportional stepwise representation method for selecting model trees. After their processing, we obtained series of shape coefficients and breast height form factor and conducted their statistical assessment (table 2).

3. Results and Discussion
It turned out that the average values of the second shape coefficient (q₂) and the breast height form factor (F) correspond to the lowest spruce stem following the classification of V K Zakharova [5]. Comparison of the data obtained showed that the use of outdated volume tables is associated with significant systematic errors. In current volume tables, the spruce stem form factor is on average 12-17% higher than in Yenisei Range spruce stands, which entails overestimated stem volumes and growing stock when conducting forest inventory.

Table 2. Statistical indicators of the series of form coefficients and factors.

| Statistical indicator                  | Stem shape indicator |
|----------------------------------------|----------------------|
|                                        | q₀      | q₁      | q₂      | q₃      | F       |
| Mean                                   | 1.33    | 0.85    | 0.63    | 0.37    | 0.45    |
| Standard error                         | 0.01    | 0.005   | 0.01    | 0.01    | 0.01    |
| Standard deviation                     | 0.12    | 0.06    | 0.07    | 0.09    | 0.07    |
| Minimum                                | 1.04    | 0.68    | 0.44    | 0.17    | 0.29    |
| Maximum                                | 1.73    | 0.97    | 0.84    | 0.72    | 0.75    |
| Coefficient of variation, %            | 9.2     | 7.1     | 11.7    | 23.9    | 15.0    |
| Experimental accuracy, %               | 0.7     | 0.6     | 0.9     | 1.9     | 1.2     |

Notably, E N Falaleev volume tables [11] are more consistent with the Yenisei Range spruce stands.

Figure 1 illustrates the relationship between the form height (Hf) and the spruce height (H). The following equation displays it, with the coefficient of determination (R²)=0.85 and the standard error (S)=0.94:

\[
Hf = \frac{31.789 \times H}{(50.819 + H)}
\] (1)

The average form height value is 8.84±0.19 with the variability of a characteristic of 27.8% and an experimental accuracy of 2.2. Correlation analysis showed a reasonably high degree of form height (Hf) mediation by characteristics of the tree inventory. The correlation coefficient between form height and tree age (r) is 0.649. The correlation coefficient between form height and tree height is 0.921. The correlation coefficient between form height and stem diameter at the height of 1.3 m (D₁.₃) is 0.847.

We calculated the average form height values for separate diameter classes (table 3), enabling making calculations when compiling inventory standards.

Several studies have established that in thick-barked species (such as larch or pine), bark significantly influences the stem shape [14-16], which entails some changes in the timber assortment and species structure and redistribution of the commercial and fuelwood parts of a trunk.

Analysis and comparison of shape and form factor indicators for spruce stems in bark and without bark showed no significant differences. Only a 5.7% decrease in the average shape factor value q₃ was noted, which can be explained by an increase in the series variability.
Figure 1. Correlation between form height (Hf) and spruce tree height.

Table 3. Form heights of various diameter spruce stems.

| Statistical indicator | Form height distribution by diameter classes, m |
|-----------------------|------------------------------------------------|
|                       | 8      | 12     | 16    | 20    | 24    | 28    | 32    | 36    | 40    | 44    | 48    | 52    |
| Mean                  | 4.6    | 6.3    | 7.2   | 8.1   | 9.1   | 9.3   | 9.9   | 10.5  | 10.9  | 11.5  | 11.8  | 11.8  |
| Standard error        | 0.21   | 0.29   | 0.37  | 0.18  | 0.22  | 0.25  | 0.29  | 0.53  | 0.35  | 0.44  | 0.40  | 0.45  |
| Coefficient of variation, % | 18.9  | 16.9   | 17.6  | 9.6   | 8.2   | 11.7  | 11.9  | 17.8  | 13.5  | 13.3  | 6.7   | 6.6   |
| Experimental accuracy, % | 4.6   | 4.7    | 5.1   | 2.2   | 2.4   | 2.7   | 2.7   | 5.4   | 3.3   | 3.8   | 3.3   | 3.8   |

Besides, Siberian spruce bark, being of complex chemical composition, is a raw material for valuable products. It is used in folk medicine, serves as a raw material for tannins, etc. [17-20]. To date, there is a significant amount of studies, which mainly consider the peculiarities of bark formation in spruce growing in the European part of Russia [21-23].

Figure 2 demonstrates the bark volume in spruce stems in different regions.

Figure 2 shows changes in the volume of bark in spruce stands in the Leningrad Oblast [16], Arkhangelsk Oblast [21], Krasnoyarsk Krai [11], the southern taiga forests of Central Siberia [12], and data obtained in the present study. The most significant regional variability in bark volume is observed in relatively small spruce trees; further, the differences are minimizing.

The following equation displays the relationship between stem diameter in the bark at 1.3 m height (D_{1.3}) and percentage of bark volume relative to stem (V_k) in the Yenisei Range spruce forests:

\[
V_k = 1/(a \times x + b)
\]  

where:  
\(a=0.001164\), \(b=0.035249\)
The percentage of bark volume relating to stem in spruce stands in the study region is significant. It exceeds similar indicators for other regions, which is a likely consequence of harsh growing conditions and forest stands' low productivity. A V Tyurin [24], N P Anuchin [25] and others indicated this feature of bark formation.

The following linear equation reflects the relationship of double bark thickness ($2T_{1.3}$) at 1.3 m height with the stem diameter with a sufficient degree of reliability ($R^2 = 0.74$):

$$2T_{1.3} = 0.028 \times D_{1.3} + 0.887 \quad (3)$$

The average percentage of bark volume relative to stem diameter was 92.5±0.2%, with a variation coefficient of 3.1%.

Table 4 shows the bark growth dynamics ($\Delta 2T_{1.3}$) in the average increase in bark diameter ($\Delta D_{1.3}$).

Table 4. Dynamics of the proportion of bark growth in the average stem diameter growth at 1.3 m height.

| Age, years | 20 | 40 | 60 | 80 | 100 | 120 | 140 | 160 | 180 |
|------------|----|----|----|----|-----|-----|-----|-----|-----|
| $\Delta 2T_{1.3}$, % | 23.9 | 14.2 | 10.7 | 9.0 | 7.9 | 7.2 | 6.8 | 6.4 | 6.2 |

Figure 3 illustrates the change in bark thickness in stems of different diameters by relative lengths.

Figure 3. Average double bark thickness ($2T$) distributed by the relative stem lengths.
Table 5 demonstrates the relative spruce bark sizes for the Yenisei Range.

**Table 5.** Relative bark thickness distributed by the relative stem lengths.

| Data                  | Relative stem lengths |
|-----------------------|-----------------------|
|                       | 0         | 0.1       | 0.25      | 0.5       | 0.75      |
| obtained data         | 139.3     | 100       | 91.9      | 77.8      | 62.1      |
| according to Gusev    | 141.5     | 100       | 87.4      | 73.2      | 57.1      |

Comparing the obtained results with II Gusev’s data [21] for spruce stands in the north of the European part of Russia, we revealed region-determined features in spruce bark formation in the study area.

In conclusion, we would like to point out one more aspect of the ecological and economic assessment of the Yenisei Range forest stands. At present, according to the state-approved forest zoning, the Yenisei Range is assigned to the Priangarskiy taiga region, together with territories of more favorable conditions for forest vegetation growth. The established features of spruce stem formation in the study area can serve as one of the factors confirming the need to distinguish this region as an independent zoning unit.

4. **Conclusion**

The Yenisei Range is characterized by specific conditions that are harsh for forest growth, which differ from the Lower Angara region bordering the Yenisei Range and other Yenisei Siberia areas. Such conditions have formed due to the Yenisei Range location, relief, and climate.

The Yenisey Range low-productive forest stands are characterized by certain developmental features. As a result of the present study, we managed to achieve the goal formulated in the introduction – the features of the Siberian spruce stem formation have been established.

According to the results obtained, the following conclusions can be drawn:

- in the Yenisei Range, the Siberian spruce stem form factor is 12-17% less than values used in the current volume tables;
- volume tables used in determining the spruce stands growing stock in the study area require adjustment or processing;
- when adjusting the tables, data on the change in the spruce form heights obtained in frames of the present research may be applied;
- in the low-productive spruce forests of the study area, trees with a relatively high bark volume are formed, which should be taken into account when adjusting the stand assortment tables;
- the obtained data indicate the presence of regional features of the bark formation in the studied stands on different parts of the stem;
- the study results allow us to assert a need to discuss the forest zoning revision to distinguish the Yenisei Range into a separate forest area.

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