Interrelations of size and weight parameters of Norway Spruce tree branches

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Abstract. Studying the crown structure is an important element of both ecological and silvicultural research. Intensive reforestation involves regular thinning and multiple pruning to produce high-quality knot-free timber. At the same time, the work productivity is associated with the quantitative parameters of the crown: the number of living and dry branches in a whorl, size and weight of the branches, etc. The size and weight parameters of Norway spruce (Picea abies) branches were studied in artificial stands of trees. It was found that the intensity of branch growth, as well as the process of clearing the trunk from branches, largely depends on the biosocial position of trees.

1. Introduction
Studying the structure (architectonics) of a tree crown is an important facet of ecological research since it largely predetermines the process of competition between species in a forest ecosystem. Many scientists have studied the biological productivity of the assimilation apparatus of tree species [1-3]. From a practical point of view, the crown structure is of interest in intensive forestry, especially in terms of the production of high-quality wood by pruning. This is due to the dependence of the work productivity and the resulting wood characteristics on the number of living and dry branches in a whorl, their size, the distance between the whorls, etc.

Another important component of the proposed study is the establishment of the relationship between the size and weight of the branches and trunks of Norway spruce (Picea abies), which can be further used in assessing the phytomass of their aboveground part in order to analyze the carbon pools of forest ecosystems.
2. Methods and Materials

The formation of tree crowns occurs under the influence of a number of factors, the key ones of which are tree species and growing conditions. This led to the choice of spruce plantations, located in Gatchina forestry unit (Leningrad region, Russia), as an object of study. Due to the same planting scheme and high safety of crops, the distances from each of the considered model trees to the neighboring ones were approximately the same. Thus, it can be said that the formation of crowns took place in conditions similar in terms of competitive relationships and without significant damaging effects that sometimes arise due to overflow in mixed stands with the participation of deciduous species. The compactness and location of the experimental plot, whose area is 2.0 hectares, ensured the similarity of microclimatic and soil conditions. At the same time, despite the indicated similarity in the conditions of growth, the formed plantation contains trees that differ in their size, life state, and biosocial position. To characterize the latter, back in the 19th century, Gustav Kraft introduced five growth classes: class I includes trees that occupy a dominant position in the stand, and class V – strongly oppressed and drying trees located exclusively under the canopy [4]. Within the framework of the study, the trees of Kraft class I and IV were considered. This choice was made to obtain the maximum contrast in the position of the considered trees in the canopy of the stand. In the studied trees, the following were determined: the number, length, and diameter of the base of the branches in whorls, the wet weight of the whorl and the middle branch in it, as well as the needles air-dry weight obtained as a result of its drying under laboratory conditions.

Subsequently, the data obtained became the basis for studying the relationship between the size and weight parameters of the branches of Norway spruce trees. For this purpose, we carried out the statistical analysis of the measurement results including the regression analysis with the aim of:

- studying the age dynamics of the size and weight of branches;
- assessing of the dynamics of the number and ratio of living and dry branches when moving from the top of the tree to its base;
- evaluating the relationship between the size and weight of branches and their dependence on the size of the trunk at the attachment point.

3. Results and Discussion

The analysis of the size and weight parameters of the branches was carried out taking into account the biosocial position of the trees. Differences in characteristics of the branches of Norway spruce trees of Kraft class I and IV are presented in figure 1, which shows the dependence of the lengths and diameters of the branches base on the serial number of the whorl, which also demonstrates the time elapsed since the beginning of its formation.

![Figure 1](image-url). Changes in branch base diameter (a) and length (b) from the top to the butt part in Kraft class I and IV trees.
As can be seen in figure 1, there is an increase in branch base diameter and length from the top to the butt part caused by the growth process. Withal the noted increase is manifested unevenly since it is largely influenced by weather conditions in the year of whorl formation. Despite the noted unevenness, in general, the dynamics of the dimensional parameters in the branches of Norway spruce can be described by the Verhulst logistic model [5]:

\[ y = \frac{K}{1 + Ee^{-rt}} \]  

(1)

where \( K \) – capacity of the medium, the maximum possible value of the studied parameter under the given conditions; \( E \) – the multiplicity of growth; \( r \) – the relative growth rate; \( t \) – time in years elapsed from the beginning of branch growth and determined by the number of whorls, when counting from the top of the tree to its base.

This model and its modification were repeatedly used when describing the growth process, both of individual trees and stands in general [6, 7].

The values of the logistic model parameters describing the dynamics of the branch base diameter and length, as well as the determination coefficients \( R^2 \) are presented in table 1, where it can be seen that in most cases the used model showed a high accuracy of a branch size description. Wherein for the branch length as a less volatile parameter than the diameter of their base, the approximation is more accurate and the variability of the model parameters is lower.

**Table 1.** Parameters of the logistic model describing the age dynamics of branch base diameter and length.

| Characteristics       | Kraft class | Logistic model parameters (1) | \( R^2 \), % |
|-----------------------|-------------|-------------------------------|--------------|
| Branch base diameter  | I           | 22.34 1.59 0.33              | 83.54        |
| (mm)                  | IV          | 57.49 10.6 0.07               | 73.19        |
| Branch length         | I           | 2.32 6.09 0.31               | 97.26        |
| (m)                   | IV          | 1.73 4.72 0.2                | 87.77        |

It should be noted that due to being asymptotic the logistic model does not take into account delimbing of the trunk, which limits its application to an area not actively affected by this process.

The dynamics of the proportion of dry branches in whorls, considered in the framework of the proposed study, are of interest to assess the intensity of clearing the trunk from branches. It was found that the average number of branches in whorls in the crown part, where the process of drying out and shedding has not yet begun, is 6 pieces for the Kraft class I and 5 pieces for the Kraft class IV with the coefficients of variation ± 19.0% and ± 18.0%, respectively.

Due to the difference in the number of branches in whorls, the proportions of dry and living branches were used to analyze the process of cleaning the trunk. As can be seen from figure 2, in the upper part of the crown, the proportion of living branches is 100%, but upon reaching a certain level (for trees of Kraft class I – the 12th whorl and for class IV – the 9th whorl) it starts decreasing. This allows us to conclude that in class IV trees, the delimbing process begins earlier.

For the trees of both Kraft classes I and IV, the total length of the crown is 28 whorls. However, due to the different intensity of tree growth in height, there is an almost two-fold difference in the length of the crown, which averaged 13.0 m for trees of the Kraft class I and 6.4 m for class IV.
Figure 2. Dependence of the branches number (a) and the proportion of living branches (b) on the number of whorls in Kraft class I and IV trees.

A modification of the logistic model described above can be used to describe the distribution of the proportions of live and dry branches depending on the whorl number. In this case, the coefficient $K$, which is the asymptote of the curve, can be taken equal to 100:

$$y = 100 \cdot \left(1 - \frac{1}{1 + a \cdot e^{-b \cdot n}}\right),$$

where, $a$ and $b$ –model parameters, given in table 2.

Table 2. Parameters of the logistic model describing the dynamics of the proportion of live branches when moving from the top to the base of the trunk.

| Kraft class | Logistic model parameters (2) | $R^2$, % |
|-------------|-------------------------------|----------|
| I           | $a = 1.69$, $b = 0.94$       | 99.73    |
| IV          | $a = 1.89$, $b = 0.88$       | 98.23    |

Establishing the internal relationships of the branch parameters plays an important role in their studying. For this reason, the study examined the interrelations between the size and weight of Norway spruce tree branches.

When analyzing the dependence of the branch length on the diameters of their bases, it was found that these parameters are characterized by high variability (figure 3) due to the individual characteristics of trees, competitive relationships, position relative to the cardinal points, and many other factors. At the same time, if we operate with values averaged over whorls and model trees, the dependence of the branch length on their base diameter can be described by a multiplicative function:

$$y = a \cdot x^b$$

where, $y$ – dependent variable; $x$ – independent variable; $a$ and $b$ – model parameters.

The parameters of this model are shown in table 3 and the theoretical values of the branch length of the trees with different Kraft classes, based on them, are demonstrated in figure 3, where it can be seen that with equal base diameters, class IV trees are characterized by a longer branch length. This pattern can be explained by the fact that being in a depressed state trees striving to maximize the absorbing surface develop primarily the length of the branches.
Figure 3. Relationship between base diameter and length of individual branches in Kraft class I and IV trees.

Using the multiplicative function (3), the dependence of the branch size on the trunk diameter at the attachment point can also be described. In this case, the positive values of parameter $b$ shown in table 3 indicate a direct relationship between the listed parameters. Different dynamics are observed if we consider the relationship between the size and weight of branches, as well as the dependence of weight on the number of whorls.

Table 3. Parameters of a multiplicative model describing the relationship between the dimensions of the branches of Norway spruce.

| Characteristics                                           | Kraft class | Multiplicative model parameters (3) | $R^2$, % |
|-----------------------------------------------------------|-------------|-------------------------------------|----------|
| Dependence of the branch length (m) on the base diameter (mm) | I           | 0.0026 2.149                       | 89.58    |
|                                                            | IV          | 0.0232 1.691                       | 85.19    |
| Dependence of the branch base diameter (mm) on the trunk diameter at the attachment point (mm) | I           | 3.053 0.395                       | 81.20    |
|                                                            | IV          | 0.956 0.579                       | 92.74    |
| Dependence of the length of the branches (m) on the trunk diameters at the attachment point (mm) | I           | 0.019 0.940                       | 95.40    |
|                                                            | IV          | 0.018 1.025                       | 90.18    |

When considering the dynamics of needles and branches mass, both separately and as a whole in the whorl, it was found that in the direction from the top of the trunk to its base, these parameters first increase and then decrease (figure 4). This pattern is due to the previously mentioned process of clearing the trunk from branches. At the same time, since the lifespan of the branches of the second and higher order is 2-3 times lower than that of the branches of the first [2], even with an increase in branch base diameter and length, a decrease in their weight is seen in the lower part of the crown.

To describe this dependence, an exponential function can be used:

$$y = a \cdot e^{-\frac{(n-b)^2}{c}}$$

where $a$, $b$, and $c$ – model parameters, given in table 4; $n$ – whorl number.
Figure 4. Dependence of the whorls weight (a) and needles air-dry weight in them (b) on the number of whorls in Kraft class I and IV trees.

Model parameter $a$ is the maximum value of the estimated characteristic, and parameter $b$ is the ordinal number of the whorl, below which it begins to decrease. As can be seen, in trees of both Kraft classes I and IV, a decrease in the mass of branches and needles is observed below 8-10 whorls, which allows us to say that the greatest photosynthetic activity occurs in the crown section located above them, characterized by younger needles and a relatively higher illumination. Interestingly, there is also a significant difference in the mass of whorls and needles of different Kraft class trees, particularly due to the different sizes of their constituent branches.

Table 4. Parameters of the exponential model describing the distribution of the mass of branches, needles, and branch diameters along the crown length.

| Characteristics                          | Kraft class | Exponential model parameters (4) | $R^2$, % |
|------------------------------------------|-------------|----------------------------------|---------|
|                                          |             | $a$ | $b$ | $c$ |               |
| Middle branch weight (kg)                | I           | 0.84 | 10.08 | 44.02 | 79.32 |
|                                          | IV          | 0.11 | 10.40 | 63.96 | 55.69 |
| Needles air-dry weight in the middle     | I           | 201.00 | 8.95 | 31.48 | 88.24 |
| branch (g)                               | IV          | 31.28 | 8.66 | 28.53 | 62.15 |
| Whorl weight (kg)                        | I           | 5.82 | 9.85 | 28.54 | 96.34 |
|                                          | IV          | 0.54 | 8.51 | 32.82 | 83.81 |
| Needles air-dry weight in a whorl (g)    | I           | 204.92 | 9.03 | 30.19 | 88.41 |
|                                          | IV          | 35.08 | 8.77 | 30.96 | 77.19 |

4. Conclusion
The studies carried out in spruce plantations grown in order to obtain high-quality knot-free wood made it possible to estimate the size and weight parameters of the branches in different Kraft class trees, to characterize the relationships between them, and to describe the dynamics when moving from the top of the trunk to its base. It was found that the intensity of branch growth, as well as the process of clearing the trunk from branches, largely depends on the biosocial position of the trees.

At the same time, it should be noted that since the studies were carried out in forest plantations growing in similar conditions, it was impossible to analyze the dependence of these processes on the age of trees and growing conditions. In addition, it is necessary to consider similar patterns regarding the interwhorl branches widely presented in the crowns of spruce trees, which will improve the accuracy of their phytomass assessment. All this necessitates further research in this direction.
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