Biological productivity of pine stands growing in southern mountain dark taiga of Krasnoyarsk krai

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Abstract. The research is devoted to studying the biological productivity of modal Siberian pine stands of the Siberian taiga zone (southern ecoregions). Forest stands of the IV bonitet class, including Bilberry- and Bergenia-dominated forest types, were studied. The study was based on mathematical modeling of the forest stand growth combined with the conversion-volumetric method for determining the amount of phytomass converted to sequestered carbon. Tables were proposed that reflect the quantitative characteristics of the age dynamics in phytomass and the carbon contained in it. The range of changes in the phytomass in modal Siberian pine stands throughout all age classes in the Bilberry-dominated forest type was from 40.2 to 297.7 t m\(^{-3}\), in the Bergenia-dominated forest type - from 52.6 to 292.1 t m\(^{-3}\). In Siberian pine forests of the IV bonitet class, carbon pools were concentrated in the Bilberry-dominated type from 37.5 to 147.6 t C ha\(^{-1}\), in the Bergenia-dominated type - from 48.1 to 147.2 t C ha\(^{-1}\). The results supplemented the existing database on the biological productivity of taiga forests and can be used in organizing forest monitoring and implementing regional environmental programs, including calculating the carbon cycle.

1. Introduction

Forests provide a wealth of goods and services needed for human well-being. Ecosystem services provided by forests include storing 250 billion tonnes of carbon, restoring atmospheric carbon dioxide (CO2) concentration, water purification, climate regulation, and maintaining biodiversity. Despite the importance of forests, they are still being destroyed by annual logging, fires, various emergencies, including insect pests outbreaks.

Since forests play a key role in the global carbon cycle [1, 2], they act as both carbon sinks [3-5] and carbon sources [6-8]. According to the FAO Global Forest Resources Assessment 2020, the total global carbon stock in forests decreased from 668 Pg C in 1990 to 662 Pg C in 2020 [1]. Deforestation and forest degradation due to inefficient forest management are the primary causes of increased carbon dioxide emissions [7-9]. For example, Pearson and colleagues [7] reported emissions of 0.99 to 2.33 Mg C per cubic meter of timber extracted in tropical forests. Notably, emissions were dominated by damage from timber harvesting and logging infrastructure. In addition, according to Putz [10], in forests subjected to conventional logging, carbon emissions were over 100 Mg C per hectare.

By absorbing the carbon dioxide during photosynthesis, forest ecosystems transfer atmospheric carbon into an inactive state for a long time. By storing carbon dioxide in phytomass, forests remove it from the cycle [11, 12].
When assessing forest carbon storage, three main pools are usually considered: living phytomass, detritus, and humus [12]. The active living phytomass carbon pool is formed in a multidirectional flow of gas exchange for the processes of photosynthesis and respiration, growth and phytomass formation, and destruction of plant residues. The transformation of the main incoming and outgoing fluxes (photosynthesis and respiration) is reflected in dynamics in the phytomass fractions at the individual-tree level and, apparently, in stands of different ages and species composition. For regional forest ecosystems, the study of the transformations of carbon in photosynthesis at the phytomass fractional composition level is essential for understanding sink self-regulation and phytomass formation mechanisms. It is advisable to conduct a stand-level dynamics study performed for these processes, reflecting the statistical indicators of the forest growth and development within a particular territory or region. Such an approach provides detailed information for environmental monitoring at the local level.

In the southern mountain forests of Siberia, mixed dark taiga dominated by the Siberian pine is of great resource and ecological potential. These stands are disturbed by logging, forest fires and weakened after defoliation by the Siberian silk moth, which affects both forest stability and carbon sequestration capacity. A database reflecting the stand development is necessary to analyze the carbon balance in these forests. The database should include information on phytomass and its fractional composition and carbon pools in modal Siberian pine stands of the given region.

2. Objects and methods of research

In the present research, we studied the biological productivity of Siberian pine stands in forests growing within the southern mountain dark taiga of the Eastern Sayan Mountains (Krasnoyarsk Krai, Irbeyskoye forestry, Kunguskoyskoye district forestry). The landscape complex geographically belongs to the South Siberian mountain forest zone, Sayan Mountain Conifer Forests bioregion. Siberian pine stands of the IV bonitet class dominate the study area. These stands are modal, meaning they mainly concentrate resource and ecological potential of the region. At the same time, these stands face an increased risk of external factors impact (fires, logging, insect pests). The stands are mixed-species; their composition involves Siberian fir, Siberian spruce, Scots pine, birch, aspen. Modal forest stands are represented mainly by two types of forest (identified according to dominant field-layer vegetation) – Bilberry (Vaccinium myrtillus L.)-dominated and Bergenia-dominated. Forest type was an additional criterion for determining the biological productivity of Siberian pine stands within the study area.

The present study was based on the forest inventory data for 495 inventory units. Table 1 shows the results of standard statistical processing of the series of the average inventory indicators of the selected stands.

| Table 1. The average forest inventory indicators of the Siberian pine stands of the IV bonitet class. |
|-----------------------------------------------------------------------------------------------|
| Forest type            | Age, years | Height, m  | Diameter, cm | Density | Growing stock, m³/ha |
|------------------------|------------|------------|--------------|---------|---------------------|
| Bilberry-dominated     | 185 ± 3.5  | 20.6 ± 0.1 | 29.4 ± 0.4   | 0.57    | 238 ± 4             |
| Bergenia-dominated     | 178 ± 2.5  | 20.6 ± 0.1 | 30.6 ± 0.3   | 0.62    | 287 ± 4             |

We stratified the experimental data by age classes to detail the processes under study. The following age classes were accepted: young stands – up to 80 years old, middle-aged – 81-160, ripening – 161-200, mature – 201-240, overmature – over 241 years [13].

Tree height growth, stem diameter growth, and increment of cumulative timber volume in modal Siberian pine stands were modeled using the Curve Expert 1.4 software.

We calculated the amount of phytomass produced by a Siberian pine stand at different ages using the conversion-volumetric method (Ph/M conversion). The method implies an assessment of phytomass
reserves using conversion coefficients, which are the ratio of phytomass fractions (Ph, t/ha) to the standing stock (stem-wood only) (M, m$^3$/ha). Appropriate coefficients were applied, allowing the transition from the stem stock (M, m$^3$/ha) to individual fractions of phytomass (Ph, t/ha) (trunks, branches, needles, roots) [14, 15].

Phytomass carbon pool of trees (dry matter) was calculated using conversion coefficients based on the following parameters - 1 kg of the dry mass of the woody parts wood, bark, branches, twigs, stumps, and roots contains 0.50 kg of carbon, 1 kg of needle dry mass - 0.45 kg [14, 15].

3. Results and discussion
Firstly, we studied the dynamics of the main inventory characteristics that determine the stem wood increment in modal Siberian pine stands (IV bonitet class), considering the forest growth conditions of the study area. Statistical analysis of the experimental data showed the following pattern for naturally developing forest stands: the older stand is, the less variable indicators are. Thus, the accuracy of the experiment increases with the increase of stand age.

The results of modeling age-related changes in average height, diameter, and standing stock in the studied modal Siberian pine stands showed an adequate approximation of these growth processes using an exponential function (1):

$$y = a(1 - \exp^{-bx})$$  \hspace{1cm} (1)

Where: $a$, $b$ – constant coefficients of the equation (table 2); $x$ – stand age, years.

Table 2 shows the coefficients in the equations and indicators of their adequacy. The equation works for the 60 to 180 years age class.

| Parameter          | Coefficients in the equation | Standard error (S) | Coefficient of determination ($R^2$) |
|--------------------|------------------------------|--------------------|--------------------------------------|
|                    | a                            | b                  |                                      |
| **Bilberry-dominated forest type** |                              |                    |                                      |
| Height, m          | 22.201                       | 0.015              | 0.51                                 | 0.99                     |
| Diameter, cm       | 36.840                       | 0.008              | 1.60                                 | 0.99                     |
| Stock, m$^3$/ha    | 375.824                      | 0.007              | 17.20                                | 0.75                     |
| **Bergenia-dominated forest type** |                              |                    |                                      |
| Height, m          | 22.597                       | 0.013              | 0.88                                 | 0.99                     |
| Diameter, cm       | 44.436                       | 0.007              | 2.20                                 | 0.98                     |
| Stock, m$^3$/ha    | 341.442                      | 0.011              | 10.36                                | 0.86                     |

Table 3 shows the age series of the inventory characteristics of modal Siberian pine stands transformed using the exponential function.

The analysis revealed some differences in the standing stock in different forest types at certain ages in modal stands. These differences also influence the amount of phytomass production.

Following the adopted method (Ph/M conversion), the initial parameter for determining the fractional amount of phytomass was the stem wood stock. The stand phytomass was calculated only for trees, excluding other vegetation. Tables 4 and 5 illustrate the biological productivity of modal Siberian plant stands of the IV bonitet class for Bilberry- and Bergenia-dominated forest types, respectively.

Comparative analysis of the calculations showed that the total phytomass from young stands to overmature stands increased in the Bilberry-dominated forest type by 7.3 times, in the Bergenia-dominated forest type - by 5.6 times (tables 4-5). The proportion of stem wood in Bilberry-dominated forest type stands varied from 49.9% in mature, and overmature stands to 61.7% in ripening ones. The proportions of branches of the total phytomass varied from 8.2% in middle-aged to 12.9% in young
stands (tables 4-5). The increase in the proportion of individual fractions of phytomass by age classes followed a distinct pattern. The weight of all fractions increased sequentially with the age of the stand.

Table 3. Indicators of the course of growth of Siberian pine stands of different age classes.

| Age, years (age class) | Average height, m | Average diameter, cm | Stock, m³·ha⁻¹ | Stock dynamics, m³·ha⁻¹·year⁻¹ |
|-----------------------|-------------------|----------------------|-----------------|--------------------------------|
|                       |                   |                      |                 | average                      |
| Bilberry-dominated forest type |
| 40 (young)            | 10.0              | 10.5                 | 96              | 2.4                           |
| 120 (middle-aged)     | 18.5              | 23.3                 | 220             | 1.8                           |
| 180 (ripening)        | 20.7              | 28.7                 | 276             | 1.5                           |
| 220 (mature)          | 21.4              | 31.0                 | 301             | 1.4                           |
| 280 (overmature)      | 21.9              | 33.3                 | 328             | 1.2                           |

| Age, years (age class) | Average height, m | Average diameter, cm | Stock, m³·ha⁻¹ | Stock dynamics, m³·ha⁻¹·year⁻¹ |
|-----------------------|-------------------|----------------------|-----------------|--------------------------------|
|                       |                   |                      |                 | current                        |
| Bergenia-dominated forest type |
| 40 (young)            | 9.4               | 10.5                 | 123             | 3.1                           |
| 120 (middle-aged)     | 18.1              | 24.7                 | 252             | 2.1                           |
| 180 (ripening)        | 20.6              | 31.3                 | 296             | 1.6                           |
| 220 (mature)          | 21.4              | 34.4                 | 312             | 1.4                           |
| 280 (overmature)      | 22.1              | 37.8                 | 327             | 1.2                           |

Table 4. Dynamics of biological productivity in modal Siberian pine stands of Bilberry-dominated forest type.

| Age, years (age class) | Stands phytomass, t·ha⁻¹ | Current stand growth, t·ha⁻¹·year⁻¹ | Carbon, t·C·ha⁻¹ |
|-----------------------|--------------------------|-------------------------------------|-----------------|
|                       | Stem | Crown branches | Needles | Total aboveground biomass | Roots | Total | Current stand growth | Carbon, t·C·ha⁻¹ |
| 40 (young)            | 22.0 | 5.2           | 3.5     | 30.7                      | 9.6   | 40.2 | 1.7               | 37.5 |
| 120 (middle-aged)     | 90.9 | 12.3          | 5.9     | 109.2                     | 41.0  | 150.2 | 0.8               | 75.0 |
| 180 (ripening)        | 108.3 | 16.8         | 7.4     | 132.6                     | 43.0  | 175.6 | 0.5               | 87.8 |
| 220 (mature)          | 135.2 | 31.9         | 13.6    | 180.7                     | 90.1  | 270.8 | 0.5               | 135.5 |
| 280 (overmature)      | 147.2 | 34.7         | 14.8    | 196.7                     | 98.0  | 294.7 | 0.4               | 147.6 |

The indicators ratio in age classes

| Age, years (age class) | 40 / 40 | 120 / 40 | 180 / 40 | 220 / 40 | 280 / 40 |
|-----------------------|---------|----------|----------|----------|----------|
| 40 / 40               | 1.0     | 1.0      | 1.0      | 1.0      | 1.0      |
| 120 / 40              | 4.1     | 2.4      | 1.7      | 3.6      | 4.3      |
| 180 / 40              | 4.9     | 3.2      | 2.1      | 4.3      | 4.5      |
| 220 / 40              | 6.2     | 6.2      | 3.9      | 5.9      | 9.4      |
| 280 / 40              | 6.7     | 6.7      | 4.2      | 6.4      | 10.3     |

The main share of the carbon stock (tables 4-5) in modal Siberian pine stands was concentrated in the mature and overmature forests. Variations in the total carbon stock throughout all age classes in the Bilberry-dominated forest type varied from 37.5 to 147.6 t·C·ha⁻¹, in the Bergenia-dominated forest type - from 48.1 to 147.2 t·C·ha⁻¹.

However, it should be borne in mind that the presented results are preliminary and may change if the stands are affected by various external factors. Fires and intensive timber harvesting affect phytomass accumulation and carbon sequestration most.
### Table 5. Dynamics of biological productivity in modal Siberian pine stands of Bergenia-dominated forest type.

| Age, years (age class) | Stands phytomass, t ha\(^{-1}\) | Current stand growth, t ha\(^{-1}\) year\(^{-1}\) | Carbon, t C ha\(^{-1}\) |
|------------------------|-----------------------------------|-----------------------------------------------|--------------------------|
|                        | Stem | Crown branches | Needles | Total aboveground biomass | Roots | Total |                        |
| 40 (young)             | 29.3 | 6.9            | 3.6     | 39.8                      | 12.7  | 52.6  | 2.1                      | 48.1                     |
| 120 (middle-aged)      | 104.2| 14.1           | 4.6     | 122.9                     | 46.9  | 169.8 | 0.8                      | 85.9                     |
| 180 (ripening)         | 116.3| 18.1           | 5.1     | 139.4                     | 47.2  | 186.5 | 0.4                      | 94.1                     |
| 220 (mature)           | 140.2| 33.1           | 12.6    | 186.0                     | 93.4  | 279.3 | 0.4                      | 140.4                    |
| 280 (overmature)       | 146.6| 34.6           | 13.2    | 194.4                     | 97.6  | 292.1 | 0.2                      | 147.2                    |

| The indicators ratio in age classes | 40 / 40 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
|-------------------------------------|---------|-----|-----|-----|-----|-----|-----|-----|
| 120 / 40                            | 3.6     | 2.0 | 1.3 | 3.1 | 3.7 | 3.2 | 0.4 | 1.8 |
| 180 / 40                            | 4.0     | 2.6 | 1.4 | 3.5 | 3.7 | 3.6 | 0.2 | 2.0 |
| 220 / 40                            | 4.8     | 4.8 | 3.5 | 4.7 | 7.3 | 5.3 | 0.2 | 2.9 |
| 280 / 40                            | 5.0     | 5.0 | 3.6 | 4.9 | 7.7 | 5.6 | 0.1 | 3.1 |

### 4. Conclusion

The current normative and informational support of forestry (both scientific and practical) makes it challenging to solve global and regional ecology issues. Expansion of knowledge of the ecological functions of forests and assessment of their resource potential is required.

In frames of the present research, we analyzed the dynamics of phytomass fractions and their ratios in various age classes basing on studying the dynamics of the inventory indicators of Siberian pine stands in the southern mountain dark taiga of the Eastern Sayan Mountains. A uniform increase in phytomass of all fractions and carbon reserves from young stands to overmature ones was revealed. According to the observations, the maximum amount of carbon was concentrated in the mature and overmature stands.

The proposed tables of biological productivity of modal Siberian pine stands of the Siberian taiga zone give a detailed quantitative characteristic of the age dynamics of changes in phytomass and the carbon contained in it, representing a toolkit for ecological forecasting and monitoring of taiga forest ecosystems.

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