Modeling of growth and development of modal fir and spruce stands in Middle Siberia

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Abstract. At present, a significant area of Siberian dark coniferous forests is characterized by a significant decrease in resistance due to recurrent forest fires, mass reproduction of insect pests and diseases, which leads to their natural degradation and death. However, the intensity of the growth processes of the coniferous stand under certain forest conditions persists in the long term. Therefore, the creation of regression models of the course of forest growth with the identification of forest conditions is very important both from the point of view of practice and environmental monitoring. The object of the study was the stands of Siberian fir (Abies sibirica Ledeb) and Siberian spruce (Picea obovata Ledeb) of bonitet classes III-IV, growing in the conditions of the West Siberian southern taiga plain forest region on the territory of the Yenisei forestry of the Krasnoyarsk Territory. The initial data for studying the processes of natural growth of fir and spruce plantations were the materials of the mass inventory of 11097 units. As a result of the work carried out for modal fir-spruce stands, concentrated in the territory of Central Siberia (Yenisei forestry of the Krasnoyarsk Territory), regression models of the growth course have been developed, which make it possible to predict the dynamics of taxation indicators and reproduce the succession picture of the development of stands.

1. Introduction
Siberia is one of the main reserves of Russia's forest resources. The Siberian Federal District has concentrated on its territory about half of the country's forest area (about 370 million hectares). Of these, the share of dark coniferous plantations accounts for one sixth (62 million hectares). However, within the framework of an extensive model of forestry in conjunction with climate change, periodic outbreaks of mass impact of pests and diseases, as well as forest fires, natural forest degradation is observed [1].

Thus, in most regions of Russia, there is a negative tendency towards the accumulation of dead forest plantations remaining on the vine, which is caused by insufficient volumes of sanitary and health-improving and other forestry activities aimed at developing dead forest plantations. Thus, as a result, forest areas are losing their important ecological and economic component.

The vulnerability of the dark coniferous forest formation to negative impacts in comparison with the light coniferous one has been scientifically substantiated and proven by many researchers [2, 3, 4, 5, 6, 7]. At present, a significant area of dark coniferous forests in Central Siberia is characterized by a significant decrease in resistance due to the impact of the above factors. For example, more than 5% (> 3 million hectares) of all dark coniferous plantations in Siberia over the past decade have been damaged to some extent by dangerous pests. And during the last century, due to outbreaks of mass reproduction of the Siberian silkworm (Dendrolimus sibiricus Tschetv.), At least 20 million hectares have died in the...
dark coniferous forests of Siberia [8]. As practice shows, most of these forests will be left for natural development and self-restoration, since the modern forest management system does not allow timely implementation of sanitary and recreational activities properly.

It is generally known that more often the succession processes occur through the change of species, which takes whole decades, or through successful natural reforestation with coniferous species, without a period of replacing the forest space with birch and aspen. However, in both cases, the patterns of development, the intensity of growth processes in coniferous stands in certain forest conditions persist in the long term. Therefore, the creation of regression models of the course of forest growth with the identification of forest conditions is very important both from the point of view of practice and environmental monitoring.

Modeling the growth of stands is used to analyze and assess various relationships in their development [9, 10]. Modeling is a research method that replaces the object of study with its mathematical model, working with which allows you to better understand the object itself.

There are various approaches to their compilation and classification basis. Recently, due to the availability of mass inventory materials and climatic changes, the typological approach to the study of the growth and development of plantations has received additional interest [11].

Within the framework of the presented work, a study of the growth rate of the most common types of forest of dark coniferous (fir-spruce) forest plantations of Central Siberia, growing within the boundaries of the Yenisei forestry of the Krasnoyarsk Territory, was carried out. On the basis of mathematical analysis, regression models of growth processes have been developed, which can be useful for adjusting and improving forest inventory standards and diverse work in terms of environmental monitoring.

2. Objects and methods of research
Bonitet was taken as the basis for identifying forest growing conditions as a universal indicator of habitat quality [11]. The object of the study was the stands of Siberian fir (Abies sibirica Ledeb) and Siberian spruce (Picea obovate Ledeb) of the III - IV quality classes, growing in the conditions of the West Siberian southern taiga plain forest region on the territory of the Yenisei forestry of the Krasnoyarsk Territory. Within a given forest stand productivity, the most common forest types are the green moss group.

The research methodology is based on the developments of N.V. Tretyakov, supplemented by I.V. Semechkin [12, 13]. The work is based on the materials of the mass inventory of 11097 stands, with 6428 stands of Siberian fir (Abies sibirica Ledeb), and 4669 stands of Siberian spruce (Picea obovate Ledeb). In the process of sampling, stands were selected with a predominance of the main forest element with a share of Siberian fir or Siberian spruce at least five units in the total composition of the plantation.

The series of the average inventory indicators of the populations of the selected stands were subjected to standard statistical processing, the results of which are shown in table 1.

| The group of forest types | Age, years | H, m | D, cm | fullness of the stand | Stock, m$^3$/ha |
|--------------------------|------------|------|-------|----------------------|----------------|
| Siberian fir (Abies sibirica) |            |      |       |                      |                |
| III bonitet class        | 99 ± 0.8   | 18.7 ± 0.2 | 20.2 ± 0.1 | 0.67 | 194 ± 1 |
| IV bonitet class         | 99 ± 0.6   | 16.3 ± 0.1 | 17.8 ± 0.1 | 0.64 | 162 ± 1 |
| Siberian spruce (Picea obovate) |        |      |       |                      |                |
| III bonitet class        | 145 ± 0.4  | 23.3 ± 0.1 | 26.7 ± 0.1 | 0.58 | 221 ± 1 |
| IV bonitet class         | 145 ± 0.6  | 20.6 ± 0.1 | 23.6 ± 0.1 | 0.58 | 187 ± 1 |

Analyzing the volume of the initial data, we can talk about their sufficient number, since the indicator of the accuracy of the experiment, which characterizes the discrepancy between the average values of the general population and the average value of the sample population, for fir stands lies in the range from 0.34% to 0.87%, for spruce stands - from 0.12% to 0.39%.
In addition, the variability of fir forests ranges from 22.0% to 40.3%, spruce forests, these values are from 8.6% to 20.4%. Moreover, the greatest variability of traits is observed in forest stands belonging to the II, III, VIII and IX age classes, i.e. young and over-mature plantations.

The processes of growth and development of fir stands were modeled using the Curve Expert 1.4 application program.

3. Research results and their discussion

When considering the course of growth of dark coniferous stands, it should be noted immediately that in the absence of a stress factor (forest fire, an outbreak of insect pests, weather conditions), as a result of which mass death of trees occurs, in other cases, during their natural development, significant age differences are characteristic. All transitions from self-seeding and undergrowth to the oldest overmature trees are found here. With the natural dying off of the latter, their place is taken by young ones that have developed from undergrowth, which is always present in one or another quantity under the canopy of the plantation. The forest-forming process in the stands is carried out continuously, however, its intensity in certain periods of time is not the same, since it depends on a number of constantly changing factors. Hence, the entire external appearance of dark coniferous forests is also constantly changing: at some stages of development, relatively young trees under the age of 50-60 years prevail in the stands according to the number of trunks, on others - older ones - up to 80-120 years. At the same time, the taxation indicators of the stand change, which in turn affects other components of the plantation. Thus, it follows that in their development all plantings go through certain stages or stages of development [14].

However, despite the fact that one dark-coniferous stand, be it fir or spruce, can include several generations of trees, in general, the regularity of their development, productivity, as well as taxation characteristics, on average, persist throughout its life, since they are due to the quality of forest conditions.

Based on the data of various sources [14, 15], it can be assumed that the stands under study arose from the regeneration undergrowth preserved and survived in the process of logging or after the natural decay of birch and aspen forests.

According to the results of the study, the statistical analysis of the main taxation characteristics showed a characteristic pattern for naturally developing forest stands, namely, with increasing age, the variability of indicators decreases and the ac

\[ H = ab^x \cdot x^c \]

\[ D = ab^x \cdot x^c \]

\[ M = ab^x \cdot x^c \]

...
From the data in the table it can be seen that the indicators of the adequacy of the obtained equations are quite high. Thus, the coefficient of determination of fir stands is in the range from 0.887 to 0.978, for spruce - from 0.419 to 0.637.

The most important taxation indicator used in forestry practice is the growing stock (or stem wood) per unit area, measured in cubic meters per hectare (m$^3$/ha). Figure 1 shows the change in the stock of modal dark coniferous stands of the study area with age.

**Figure 1.** Change in stock of modal dark coniferous stands.

The analysis of changes in the stock of forest stands with age allows us to conclude that the productivity of green moss fir trees is somewhat higher than that of spruce forests. Thus, the stock of fir forest stands of the III quality class at the age interval from the stage of young growth to the overripe...
The state varies from 10 to 255 m³/ha, while the stock of spruce stands from 9 to 219 m³/ha, respectively, the indicators for the stock of the IV class of quality also differ.

4. Conclusion
As a result of the work carried out for modal fir-spruce stands, concentrated in the territory of Central Siberia (Yenisei forestry of the Krasnoyarsk Territory), regression models of the growth course have been developed, which make it possible to predict the dynamics of taxation indicators and reproduce the succession picture of the development of stands.

The practical importance of the selected growth patterns, which characterize the features of the development of modal stands in certain forest conditions, is indisputably important. In addition to the above advantages, with the help of them, it becomes possible to detail environmental observations related to the identification of the accumulation of the total growing stock per unit area, including during forest pathological monitoring, in terms of places for determining a favorable forage base for insect pests.

In addition, the obtained regression models will make it possible to adjust the taxation standards of the study area.

Acknowledgement
The research was carried out within the State Assignment (theme «Fundamental principles of forest protection from entomo- and phyto- pests in Siberia» No. FEFE-2020-0014) supported by the Ministry of Education and Science of the Russian Federation.

References
[1] Soldatov V V, Astapenko A S, Golybev D V, Vaganov E A, Pyzhev I P and Ibe A A 2018 Weakening factors of boreal forests of Siberia IBFRA Conference «Cool forests at risk?» Book of Abstracts (Laxenburg, Austria) 47-44
[2] Gleason K E, Bradford J B, Bottero A, D’Amato A W, Fraver S, Palik B J, Battaglia M A, Iverson L, Kenefic L and Kern C C 2017 Competition amplifies drought stress in forests across broad climatic and compositional gradients Ecosphere 8(7) July 2017 e0184
[3] Dekkov N 2019 Natural regeneration in Siberian fir (Abies sibirica Ledeb.) forests subjected to invasion of the four-eyed fir bark beetle (Polygraphus proximus Blandf.) Forestry Studies|Metsanduslikud Uurimused 70 44–57
[4] Kharuk V I, Shushpanov A S, Petrov I A, Knorre S T, Fir A A 2019 (Abies sibirica Ledeb.) Mortality in Mountain Forests of the Eastern Sayan Ridge, Siberia Contemporary Problems of Ecology 12(4) 299-309
[5] Pavlov I N, Litovka YA, Golubev D V, et al. 2020 Mass Reproduction of Polygraphus proximus Blandford in Fir Forests of Siberia Infected with Root and Stem Pathogens: Monitoring, Patterns, and Biological Control Contemp. Probl. Ecol. 13 71–84
Retrieved from: https://doi.org/10.1134/S1995425520010060
[6] Vertui F 1998 Scots pine (Pinus sylvestris L.) die-back by unknown causes in the A’osta (Valley, Italy) Chemosphere 36(4-5) 1061-5
[7] Woodward S 2006 Causes of decline in United Kingdom broadleaved stands Possible Limitation of Decline Phenomena in Broadleaved Stands (Warsaw) pp 21-7
[8] Ginenko Yu I 2003 Outbreaks of mass reproduction of forest insects in Siberia and the Far East in the last quarter of the XXth Forestry information 1 46-57
[9] Deal R L, Orlikowska E H, D’Amore D V and Hennon P E 2017 Red alder-conifer stands in Alaska: an example of mixed species management to enhance structural and biological complexity Forests 8 131 Retrieved from: https://doi.org/10.3390/f8040131
[10] Perin J, Claessens H, Lejeune P, Brostaux Y and Hébert J 2016 Distance-independent tree basal area growth models for Norway spruce Douglas-fir and Japanese larch in Southern Belgium Europ J For Res 1–12 Retrieved from: https://doi.org/10.1007/s10342-016-1019-y
[11] Anuchin NP 1982 *Forest taxation: a textbook for universities* (Moscow: Lesn. Prom-st) p 552

[12] Semechkin I In 1962 Experience of using data from eye taxation to study the dynamics of plantations *Proceedings of the Institute of Forest and Timber* 8 119-31

[13] Batvenkina T In 2001 Study of the rate of change in the average taxation indicators of pine stands of different completeness and density *Forest inventory and forest inventory* Intern. Scientific-Practical Journal 1(30) 33-6

[14] Falaleev E N 1964 *Fir forests of Siberia and their complex use* (M.: Timber industry) p 213

[15] Andreev G V and Ivanova N S 2008 Natural regeneration of Siberian spruce and fir under the canopy of dark coniferous forests of the Southern Urals *Forest inventory and forest inventory* 2(40) 25-8