Bioenergy potential of mature pine and spruce stands in the boreal zone of Russia

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Abstract. In the article, we discuss some issues of the stem phytomass formation and energy potential of stands with different proportions of pine and spruce growing in Northwest Russia. The objects of study were mixed coniferous stands of natural origin not affected by economic impact. On the basis of biometric characteristics and wood sampling, the balance of stem phytomass and bioenergy potential of stands with different proportions of pine and spruce were calculated. The largest growing stock and stem mass are formed in plantations with a share of pine of 70-90\%, and spruce, 80-90\%. The analysis of variance showed a statistically significant difference between plantations with a predominance of pine and spruce. The energy balance of stands with different proportions of pine and spruce is directly related to the stem biomass of these species. Plantations with a predominance of up to 70\% of the main species are characterized by high energy potential. The results of the calculation of the energy component of forest stands with different proportions of pine and spruce allow us to optimize species composition in order to obtain a possible effect both for the needs of thermal power engineering and for compiling the energy balance of forest communities.

1. Introduction

Forest, as a natural system, can be a renewable resource of energy only if its management methods are sustainable and ecologically balanced [1-3]. This means that the conditions for the future forests must be such as to allow future ecosystems to survive. A reliable indicator of a thriving forest is its high biomass. The biomass of woody plants depends on the species. The quantitative expression of material-energy flows can serve as a basis for assessing the efficiency of production processes and environment-forming functions of the cenosis [4-8].

According to current estimates, biomass is the second dominant, after the sun, renewable and environmentally friendly energy source. The global annual increase in biomass is equivalent to 20-30 billion tons of standard fuel, i.e. it exceeds the annual oil production [9-11]. The interest in biomass stems from the need to solve environmental problems. Unlike other types of fossil fuels, the combustion of biomass and products of biomass processing does not lead to an increase in carbon dioxide in the atmosphere and does not cause its pollution with sulphur dioxide. Wood biomass is one of the few renewable raw materials on Earth. The International Biological Program (IBP), a long-term program for studying biological productivity of natural and man-made plant and animal communities on a global scale, has been in existence since 1964 [12, 13]. The ultimate goal of IBP is to identify the
main patterns of distribution and reproduction of organic substances with the purpose of their most rational use by humans and obtaining maximum productivity per unit area in natural or artificial conditions. In accordance with this, IBP studies all natural factors that determine biological productivity of plant and animal organisms and their communities. The IBP Committee's recommendation is that quantitative data on biomass be expressed in terms of the amount of energy stored in it [12, 13].

There is an ever-increasing demand for renewable energy and preservation of the natural environment [14-16]. In many countries, scientific research is expanding and practical measures are being taken to increase the role of wood raw materials in fuel and energy supply. The use of wood and its waste for this purpose, as well as the creation of special energy plantations of woody species are considered as the most important economic measures. The experience of some countries shows the possibility of creating heat-generating plants using wood waste with an efficiency of 85–90%. A cubic meter of dry wood can replace up to 200 liters of oil, or up to 200 cubic meters of natural gas [17]. Wood energy is also of solar origin, but unlike oil, coal and gas, wood is a renewable resource.

Wood biomass as an energy source is the object of many research programs in various countries of the world, including Russia, which holds 22% of the world's forest resources and 2/3 of the world's boreal forests [9, 18, 19].

Russia in general and Northwest Russia in particular have a huge raw material potential for the development of bioenergy. In Northwest Russia, mixed modal stands of pine and spruce occupy up to 30% of the forested area, and in the most common series of forest types – green moss – up to 70% of forest lands [9, 17].

Stand composition is an integral indicator reflecting inventory characteristics of a stand. Depending on this factor, quantitative and qualitative characteristics of a stand are formed, which form the dendrocnosis, growing stock and wood density and, as a result, its phytomass as a whole. In these stands, depending on the share of pine and spruce, different amounts of stem phytomass are formed, because wood density varies with the share of individual species' participation in the forest stand composition. The biomass of a growing tree is unevenly distributed: wood makes 82%, bark, 15%, and tree greenery, 3%. The largest share (up to 65%) is made by the trunk, which is the main object of logging industry [6].

The objective of the study was to determine the bioenergetic efficiency of mixed forest stands with different proportions of pine and spruce in the most common green moss series of forest types in the conditions of the Leningrad Region.

2. Methods and Materials

2.1. Objects of research

The study objects were 90–100 year-old mixed pine and spruce stands not affected by economic activities. They were growing in the conditions of the Luzhsko-Oredezhsky landscape, on a flattened moraine plain on two-member soils – sandy loam on boulder red-colored loams, which are underlain by Devonian rocks, in the Gatchina district of the Leningrad Region. These landscape and soil types occupy up to 40% of the forest fund of the study region [17]. The data on mixed pine and spruce stands (table 1) show that, depending on the share of the species, stands with different biometric characteristics are formed in homogeneous soil-hydrological conditions. This makes it possible to determine the stand composition for the formation of qualitative and quantitative characteristics of forest stands with different contribution of pine and spruce and, ultimately, the bioenergetic potential of stands.
2.2. Methods
Forest inventory and wood sampling were carried out on 23 sample plots according to generally accepted silvicultural methods [18]. The share of a species’ participation was calculated as the ratio of its growing stock to the total growing stock of a stand. For compiling conversion equations for calculating wood density, model trees were selected in stands with different proportions of pine and spruce. Twelve to twenty cores were taken from trees of all classes of pine and spruce tree diameters. The basic wood density was used as an indicator of the mass per unit volume of wood. The basic wood density was measured by the method of maximum moisture capacity using the selected wood samples. The basic wood density is expressed by the ratio of the mass of an absolutely dry sample ($m_0$) to its volume at a moisture content equal to or higher than the saturation limit of the cell walls ($V_{\text{max}}$):

$$\rho_b = \frac{m_0}{V_{\text{max}}}, \text{ kg/m}^3$$  \hspace{1cm} (1)

Based on the analysis of samples from model trees, the equations for the relationship between the basic density at a height of 1.3 m and the average density of the trunk wood were built [18]. This made it possible not to cut model trees in a study area located in similar mixed coniferous stands, but to use wood cores instead.

Despite the difference in calorific value, wood of all species without exception has the same elemental composition. These elements are the basis of organic compounds: cellulose, hemicellulose, lignin and relatively small amounts of resins, fats, and gums. The gross calorific value of 1 kg of wood depends little on the species; in principle it is equal to the gross calorific value of the wood substance and corresponds to $\approx 4752.9$ kcal / kg or 19.9 MJ of energy [1, 7].

3. Results and Discussion
A comparative analysis of the growing stock and mass indicators of stem phytomass in stands with a predominance of pine showed that the largest stock and stem mass is formed in plantations with a share of 90%P 10%S-70%P 30%S (figure 1).
Figure 1. Distribution of the growing stock (a) and stem mass (b) per ha in stands with a predominance of pine.

In stands with a predominance of spruce, the largest stock and stem mass are formed in the stands with 90%S 10%P and 80%S 20%P (figure 2).

Figure 2. Distribution of growing stock (a) and stem mass (b) of wood per hectare in stands with a predominance of spruce.

A distinctive feature of stands with a predominance of pine, in contrast to forest stands with a predominance of spruce, is a more uniform decrease in growing stocks and stem mass with a decrease in the proportion of pine in the stand composition. However, it should be noted that the highest productivity of stands with a predominance of spruce is observed when its share is 80-90%, and the lowest productivity, in stands where spruce contributes 40-70%.
The correlation analysis performed for stands with a predominance of pine and spruce showed a linear relationship between the growing stock and stem mass. The assessment of the influence of the stand composition on the formation of wood mass and volume using analysis of variance showed a statistically significant difference (according to Fisher's criterion) between stands with a predominance of pine and spruce (table 2). Based on this, we can conclude that the share of coniferous species has a strong influence on the formation of these indicators.

Table 2. Analysis of variance of the influence of the composition of the stand on the formation of growing stock and phytomass.

| Variance  | Sum of Squares | Degrees of Freedom | Squared mean | Fisher's actual criterion Ff | Fisher's theoretical criterion Ft p = 1% | Probability of accepting the null hypothesis |
|-----------|----------------|--------------------|--------------|----------------------------|------------------------------------------|---------------------------------------------|
|           | for the growing stock |                     |              |                            |                                          |                                             |
| Total     | 315137         | 23                 |              |                            |                                          |                                             |
| Variants  | 294030.5       | 11                 | 26730.05     | 15.86                      | 4.46                                     | 3.41E-05                                    |
| Replicates| 2570.94        | 1                  | 2447.05      |                            |                                          |                                             |
| Residual  | 18535.57       | 11                 | 1685.052     |                            |                                          |                                             |
|           | for the stem mass of stands |                     |              |                            |                                          |                                             |
| Total     | 69807.48       | 23                 |              |                            |                                          |                                             |
| Variants  | 66415.34       | 11                 | 6037.758     | 28.67                      | 4.46                                     | 1.69E-06                                    |
| Replicates| 1075.402       | 1                  | 1075.402     |                            |                                          |                                             |
| Residual  | 2316.733       | 11                 | 210.6121     |                            |                                          |                                             |

There was a positive correlation between energy balance of stands with different proportions of pine and spruce and stem biomass of these species. Stands with a predominance of the main species of up to 70% are characterized by high energy potential (figure 3). Stands with a predominance of pine have a high bioenergetic potential when the share of the species in the stand composition is lower. Forest stands with 90-80% of spruce form a greater energy component than pine stands with the same proportion of the species.

4. Conclusions
The results of the study show that at the experimental sites, highly productive coniferous stands currently grow, which can serve as a prototype for growing mixed pine and spruce stands.

In the green moss series of forest types, the development of mixed stands can be multidirectional, and the final available growing stock and phytomass of stem wood can differ substantially by the age of maturity.

The results obtained for calculating the energy component of forest stands with different proportions of pine and spruce allow us to optimize the species composition in order to obtain a desired result, both for the needs of thermal power engineering and for compiling the energy balance of forest communities for environmental purposes.
Figure 3. The amount of energy accumulated in the stem mass in stands with a predominance of pine (a) and spruce (b).

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