Soil factors affecting the growth and sustainability of spruce stands in the north-eastern Moscow region

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Abstract. Forests located around large urban areas belong to the protective category of the system of Russian forestry. On the one hand, this status defines limitations in the forest management and use; on the other hand, it does not require specific treatments related to the restoration of forests considering their recreational potential, and encouraging the creation of stands sustainable to natural and anthropogenic factors’ influence. This research was conducted in the north-east of Moscow region on the territories where spruce stands were seriously affected by the 2010-year drought. Using distance methods, forest areas with spruce stands of different productivity and level of damage were identified. In these areas, a soil survey was conducted and soil series forming various growth and development conditions for spruce stands were obtained. Quantitative constraint equations for soil factors closely related to the spruce stands productivity were gained. It is shown that the sustainability of averagely-productive stands to unfavorable factors (drought) turned to be higher than that of highly-productive ones. That is why the increase of stand productivity class in recreation forests should not be of primary importance for forestry.

1. Introduction
The biggest part of the forest covered area of the Moscow region (23.3\%) is represented by dark coniferous spruce forests. After a 2010-year drought, vast territories of these forests have died. For further forest management of the Moscow region, it is very important to realize in what soil conditions the spruce stands turned to be the most sustainable [1].

Stand productivization has remained the dominant paradigm in Russian forestry over years. One of the ways of reaching this goal is to maximize the use of natural soil fertility by choosing the species that are the most productive in the given conditions. However, concerning protective forests, i.e. stands...
growing around large urban areas in densely populated regions of the country, the ecological, recreational and carbon sequestration functions of these stands come to the fore [2].

After the ratification of the Kyoto protocol and the further signing of the Paris agreement, the climate-regulating role of forests has become a more economical and political rather than a scientific issue. That is why protective forests have transformed from an unprofitable part of the forest complex into forested areas allowing carbon sequestration [3–5].

The aim of this research was to find out correlations between spruce stands and soil factors in the north-eastern part of the Moscow region. To reach this goal, according to the Earth remote sensing (ERS) data and the latest forest survey materials, territorial zoning for the spruce stands conservation was conducted. For zones still with spruce stands, soil survey was carried out, and the major inventory and silvicultural characteristics were specified. Based on these data, using expert and clustering methods, an applied classification of the studied soils was retrieved regarding their influence on the spruce stands sustainability. Moreover, quantitative correlation models of spruce productivity and soil factors are provided. As spruce stands occupy significant territories of the Moscow region forests, the amount of data collected, as well as laboratory research, is considered as a detailed characteristic of the soils and dark coniferous forests of this region.

In terms of recreational potential of protective forests in the Moscow region, when sustainability and ecological properties are being adversely affected by anthropogenic factor, as well as when fires, insect damage and other unfavorable conditions negatively influence forest growth, a certain quantitative and qualitative correlation between soils and forest plants is one of the main issues of silviculture and soil science.

Underlying a rationale for ecological but not productive approach to planning of the spruce stands location in protective forests, as well as identifying sustainable and potentially susceptible spruce stands according to inventory and soil indicators, is an important practical result of this work.

2. Methodology

Current research has been conducted on the territory of the Moscow study-experimental forest unit, located in the north-eastern Moscow region.

The work program considered the examination of spruce stands of different productivity and sustainability in various soil conditions.

The first step was conducted table-top in the geoinformation environment QGIS (Quantum GIS). The process included the creation of attribute inquiries in the vector stratum-based database of the Moscow study-experimental forest unit, on the basis of which the areas of pure or roughly pure (at least 50% spruce) spruce stands were identified.

Zones of spruce growth were combined with the recent high and ultra-high resolution space images from open sources (Google.com, Yandex.ru). On these images, damaged spruce stands are well-diagnosed via visual manual deciphering. Figure 1 shows the process of visual deciphering of dead spruce stands, where the space image is overlapped with the network of forest stratum (green solid line). Dead spruce stands are marked with a red dotted line.

![Figure 1. Visual deciphering of dead spruce stands.](image-url)
Thus, the initial set of forest plots with a high level of spruce stands damage was identified. For this purpose, a cross-analysis of forest management data with the ERS data was conducted for 7826 spruce strata. A group representing the diversity of growing conditions and productivity class variety of spruce stands in the north-eastern Moscow region was formed from the given plots. After on-site investigation of these forest plots, the final set of 20 sample plots was formed, their inventorial characteristics are given in table 1.

Table 1. Forest inventorial data of sample plots.

| No | Species composition | Site type | Productivity class acc. to M. Orlov | Age, yrs | Height, m | Diameter, cm | Stand density | Growing stock, m³/ha | Growing stock of spruce, m³/ha |
|----|---------------------|-----------|------------------------------------|----------|-----------|-------------|---------------|----------------------|-----------------------------|
| 1  | 60% spruce          | C2        | Ia                                 | 61       | 25        | 26          | 0.7           | 370                  | 222                         |
| 2  | 90% spruce          | C2        | Ia                                 | 65       | 25        | 24          | 0.7           | 350                  | 315                         |
| 3  | 60% spruce          | C2        | Ia                                 | 61       | 24        | 22          | 0.7           | 330                  | 198                         |
| 4  | 80% spruce          | C2        | Ia                                 | 75       | 27        | 26          | 0.7           | 390                  | 312                         |
| 5  | 80% spruce          | C2        | Ia                                 | 75       | 27        | 26          | 0.7           | 390                  | 312                         |
| 6  | 70% spruce          | C3        | I                                  | 90       | 27        | 30          | 0.6           | 340                  | 238                         |
| 7  | 70% spruce          | C2        | I                                  | 95       | 27        | 28          | 0.6           | 340                  | 238                         |
| 8  | 80% spruce          | C2        | I                                  | 75       | 25        | 26          | 0.7           | 350                  | 280                         |
| 9  | 90% spruce          | C2        | I                                  | 85       | 27        | 28          | 0.7           | 390                  | 351                         |
| 10 | 60% spruce          | C2        | I                                  | 90       | 27        | 28          | 0.6           | 340                  | 204                         |
| 11 | 50% spruce          | C2        | II                                 | 120      | 29        | 32          | 0.6           | 390                  | 195                         |
| 12 | 100% spruce         | C2        | II                                 | 110      | 28        | 30          | 0.6           | 360                  | 360                         |
| 13 | 80% spruce          | C2        | II                                 | 120      | 28        | 30          | 0.6           | 360                  | 288                         |
| 14 | 80% spruce          | C2        | II                                 | 120      | 29        | 30          | 0.6           | 360                  | 304                         |
| 15 | 90% spruce          | C2        | II                                 | 110      | 28        | 30          | 0.6           | 360                  | 324                         |
| 16 | 80% spruce          | C4        | III                                | 110      | 23        | 28          | 0.3           | 130                  | 104                         |
| 17 | 60% spruce          | C3        | III                                | 100      | 22        | 26          | 0.4           | 190                  | 114                         |
| 18 | 60% spruce          | C3        | III                                | 110      | 22        | 26          | 0.4           | 190                  | 114                         |
| 19 | 70% spruce          | C3        | III                                | 120      | 22        | 26          | 0.4           | 200                  | 140                         |
| 20 | 60% spruce          | C3        | III                                | 110      | 22        | 26          | 0.4           | 190                  | 114                         |

Field research was conducted from 2006 to 2013 in the middle of summer (July) within limited time in order to exclude or, if possible, reduce the impact on the soil properties dynamics during the vegetation period.

The object of the study was spruce stands of natural origin of different productivity classes (from Ia to III class), located on the territory of the Moscow study-experimental forest unit. A total of 20 sample plots were allocated.

At each sample plot, a soil survey was carried out, 5 sections were allocated, from which samples were taken for laboratory tests. The most important morphological, physical and chemical properties of soils were studied.

The research is based on the empirical data from 100 soil sections, 500 samples on chemical and physical-chemical properties of the soil (acidity, complex indicators of soil absorption, moving forms of nitrogen, phosphorus, potassium, soil organic matter). In total, more than 4,500 soil analyses were performed in the laboratory, which enabled to provide high accuracy of experiment execution within 5% at a significance level of 0.05.

In the mathematical and statistical processing of data in MS Excel, methods of variation statistics were used—the main descriptive statistics were calculated at a significance level of 0.05.

Cluster analysis was conducted by means of Statistica 10.
3. Results and discussion

As a result of field soil research, morphometric indicators were obtained that characterize the studied soil differences. According to the averaged data, the schematic structure of the profiles of soil series formed according to a number of studied productivity classes was shown (figure 2).

For more highly productive classes, zonal soddy podzolic soils with different podzolic horizon and weak (or absent) gleying in the bottom part of the profile are typical.

In the obtained soil series, the higher the level of the subsoil waters is, the lower the biological productivity of stands is. It is accompanied by the intensification of peat and gley formation processes, which leads to the formation of swamp podzolic and swamp soils. The capacities of organic horizons also increase due to the intensification of peat formation, as well as the capacity of gley horizons.

![Figure 2. Schematic soil profiles according to average morphometric data.](image)

It is typical for the received data on physical-chemical properties to have a high correlation between exchangeable acidity and active soil acidity \((r > 0.8)\). In general, the studied soils can be estimated as strongly acid, which is characterized by a high level of hydrolytic acidity of the soil. Taking into consideration the low level of S-value, it is easy to explain base unsaturation in the studied soils. Besides, in the studied soils series, together with the productivity decrease, there is a noticeable reduction of base saturation of soils and a slight decline of cation exchange capacity.

The content humus indicator in all studied soils expectedly goes down along the soil profile. Moreover, with the decrease in stands productivity, the amount of humus in the soil drops. There is a direct correlation between the humus content and the nitrogen forms available to plants. A slight reduction in the moving forms of phosphorus and potassium has been noticed.

Profile regularities in the change of parameters for the studied soils are typical and correspond to the zonal soils.

The final step of the work was the selection of the minimum set of soil indicators that have the maximum effect on spruce stands growing on the studied soils. The following methods were used for this purpose:

- Finding a pair correlation coefficient;
- Student t-test;
- Cluster analysis;
- Peer inspections.
Due to the large size of the weight matrices, they cannot be placed in the paper, so only the final result of using the above methods can be shown.

Thus, based on the approaches stated above, the following indicators showing the development of spruce stands on the studied soils were identified:

- Level of subsoil water, cm;
- Top line of gleying appearance, cm;
- Content of organic carbon in the 50 cm layer.

Using regression analysis constraint equations of phytomass, net primary production and stand productivity were formed.

As a dependent variable, the stand height at the age of 100 years, numerically equal to the productivity class according to V. V. Zagreev, was chosen.

Using linear regression analysis, the following constraint equation was obtained (1), which has the multiple coefficient of determination \( R^2 = 0.89 \) with a constant error of 1.12:

\[
y = 16.93 + 0.05 \cdot x_1 + 0.08 \cdot x_2 - 0.03 \cdot x_3,
\]

where:
- \( y \) – stand height at the age of 100 years, m;
- \( x_1 \) – level of subsoil water, cm (\( \beta = 46\% \));
- \( x_2 \) – top line of gleying appearance, cm (\( \beta = 41\% \));
- \( x_3 \) – content of organic carbon in the 50 cm layer, % (\( \beta = 13\% \)).

In the second equation, phytomass carbon was chosen as the dependable variable (2). Using linear regression analysis, the following constraint equation was obtained (2), which has the multiple coefficient of determination \( R^2 = 0.53 \) with a constant error of 1.12:

\[
y = 93.78 + 0.38 \cdot x_1 + 0.35 \cdot x_2 - 0.67 \cdot x_3,
\]

where:
- \( y \) – phytomass carbon, tC per ha;
- \( x_1 \) – level of subsoil water, cm (\( \beta = 52\% \));
- \( x_2 \) – top line of gleying appearance, cm, cm (\( \beta = 28\% \));
- \( x_3 \) – content of organic carbon in the 50 cm layer, % (\( \beta = 20\% \)).

The third dependable variable was the net primary production of the stand (3). Using linear regression analysis, the following constraint equation was obtained (3), which has the multiple coefficient of determination \( R^2 = 0.65 \) with a constant error of 1.12:

\[
y = 2.41 + 0.02 \cdot x_1 + 0.03 \cdot x_2,
\]

where:
- \( y \) – net primary production, t C per ha per year;
- \( x_1 \) – top line of gleying appearance, cm (\( \beta = 65\% \));
- \( x_3 \) – content of organic carbon in the 50 cm layer, % (\( \beta = 35\% \)).

The obtained values of the coefficient of determination indicate the high veracity of mathematical models using empirical data.

Partial determination coefficients (\( \beta \)-coefficients) are shown in brackets as a percentage of the total determination coefficient. Given \( \beta \)-coefficients are coefficients that would be obtained if all variables were standardized beforehand, i.e. that is made the average value equal to 0 while standard deviation equal to 1. One of the advantages of \( \beta \)-coefficientsis that \( \beta \)-coefficients allow to compare the relative contribution of each independent variable to the forecast of a dependent one.

4. Conclusion

As a result of the conducted research, a large amount of statistically reliable empirical data characterizing morphological, chemical and physical-chemical soil properties was obtained.
The following soil types were found under spruce stands of various productivity (from Ia to III productivity class): sod-highly podzolic, sod-highly podzolic gleyish, sod-podzolic surface-gleyed and peat-podzolic surface-gleyed.

The main soil factors defining biological productivity and the ecological properties of spruce stands are: the content of organic carbon at 50 cm soil layer, the level of subsoil water, the top line of gleying appearance that is indicative of the leading role of water regime and nutrient status of spruce stands in the north-eastern Moscow region.

For these soil indicators, constraint equations were formulated with phytomass carbon, net primary production and stand height at the age of 100 years. The values of the determination coefficients indicate the high statistical reliability of the obtained mathematical models.

The resistance to unfavourable environmental factors (drought) of averagely productive stands was higher than that of high-productive ones, so from the ecological point of view, increasing the productivity of stands should not be of primary importance for forestry in recreational forests. The richer and wetter the conditions are, the more sustainable the spruce stands are.

Taking into the consideration the current tendency in counting the run-offs and sources of greenhouse gases, as well as the peculiarities of forest management in the Moscow region, all spruce stands require an ecological evaluation of sustainability and further monitoring in this direction.

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