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# Pine Forests in Moscow Region: History and Perspectives of Preservation

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**Abstract**—Features of the structure and composition of forests with admixture of pine (*Pinus sylvestris*) were studied in central, northern, and western parts of Moscow region, a central part of the East European plain. Pine stands and mixed pine and spruce forests comprise around 16% of the total area of woodlands within the studied territory. This study addressed a possibility of conservation of indigenous pine communities in Moscow region and considered landscape conditions where it could most likely occur. In order to assess the prospects for pine regeneration in various types of communities, the dynamics of its coenopopulations was analyzed. It was found that various types of pine communities are associated with relief parameters (altitudes, slopes, varying curvatures, and lighting) and localization in physical–geographical provinces. The spatial structure of groups of pine forest associations was characterized using landscape and ecological metrics. These data improve the understanding of the phytocoenotic structure of pine communities. Their composition is indicative of succession stage (1), domain-specific features of vegetation cover of the region (2), and associations with landscape elements (3). Pathways of secondary successions on watershed surfaces involve active demutation of spruce forests and, in some cases, mixed woods. This will limit the occurrence of pine and pine–spruce communities in Moscow region after several decades. Only a small part of pine forests will remain on steep river banks.

*Keywords:* pine forests, Moscow region, digital mapping, habitat ecology, landscape and ecological metrics

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Scots pine (*Pinus sylvestris*) is one of the main forest-forming species in the European part of Russia. A significant area of pine forests belongs to the boreal zone; in the zone of mixed forests and to the south, in the forest–steppe and steppe zones, they are found in the form of isolated stands (Bohn, 2004; Rysin and Savel'eva, 2008; Kucherov, 2018). The ecological range of pine is wide; it grows on soils of various particle-size distribution and moisture regime. While having high resistance to certain stressful abiotic conditions (nutrient deficiency, drought, excessive moisture, pyrogenic factor), in the juvenile stage, the pine does not withstand competition from the moss cover and hardly overcomes the forest floor; pine undergrowth develops poorly under shading of the canopy of spruce, deciduous species, and the shrub layer (Rysin, 1964; Ryazapov and Kabanov, 2010).

The issue of the spruce replacing pine has an almost century-old history and has been widely debated among foresters and phytocenologists. The majority of authors recognized that, with the exception of habitats with an upland swamping type on peaty soils, as well as on thick sandy deposits, spruce will definitely replace pine. In the latter case, the continued existence of pine forests on dry and poor sandy soils is maintained by periodically occurring fires. This allowed some researchers (Morozov, 1924; Sambuk, 1932; etc.) to attribute this type of pine stand to indigenous ones, which later received partial confirmation in accordance with the theory of cyclic erosion–pyrogenic evolution (Sannikov, 1992).

People have populated the East European Plain since the end of glaciation (Bader, 1936; Korol', 1994–1997; Kharitonov, 2010); therefore, fires in coniferous forests from this period could have arisen not only from atmospheric electric discharges, but also as a result of human activity. In modern conditions of enhanced fire control in the forest fund, especially in forests of high conservation value, as well as due to silvicultural practices, natural cycles of autogenic successions are disrupted. Thus, in conditions of changing natural dynamics, the problem of preservation and reproduction of modern pine forests, taking into account zonal and regional aspects, as well as edaphic confinedness, becomes even more relevant. The purpose of this paper is to study the features of the structure and composition of forests formed with participation of pine in the main canopy in the central part of the East-European Plain (central, northern, and western sectors of Moscow region).

This paper assesses the possibility of preserving pine forests in Moscow region depending on landscape conditions. State-of-the-art technologies are employed, the need for the use of which in recent years was indicated in the works of Academician A.S. Isaev (Isaev and Chernen'kova, 2015).

## MATERIALS AND METHODS

Moscow region is located in the central part of the East European Plain. In accordance with the layout of geobotanical zoning, most of Moscow region is located within the coniferous–broad-leaved forest zone; in the south the region borders the broad-leaved zone (Petrov, 1968; Gribova et al., 1980). Forests in Moscow region are distinguished by several features: a significant recreational impact due to the high population density; limited functionality, as in accordance with the Forest Code of the Russian Federation these forests belong to the protected group; poor pathology conditions and unstable environmental conditions caused by restrictions on forest cutting; the presence of a large volume of mature and overmature small-leaved stands. According to official data (Forest plan..., 2018), the composition of the forests of Moscow region and the city of Moscow on the forest land and on the defence and security land is represented in half by small-leaved species (birch, 41%; aspen, 9%; grey alder, 3%; black alder, 2%), as well as spruce, 23%; pine, 20%; and broad-leaved species, 2%.

The studied territory occupies most of Moscow region (central, northern, and western sectors) and the so-called New Moscow; its area is 40532 km$^2$ (Fig. 1). The features of the genesis, geological, morphological, and structural characteristics within the studied territory made it possible to distinguish five large physical–geographical provinces (FGP): (1) Upper-Volga, (2) Moscow, (3) Smolensk, (4) Moskvoretsko-Okskaya, and (4) Meshcherskaya provinces (its western part) (Annenskaya et al., 1997) (Fig. 1).

Communities that include pine were considered as part of the general coenotic diversity of the forests of the territory. In classifying the communities, the ecological–phytocenotic approach was used (Chernen'kova and Morozova, 2017). The complete species composition of the shrub, herb–small shrub, and moss layers was revealed with an estimated projective cover in percentage[1]. Cultures were identified on the basis of forest plantation plans (scale 1 : 25000) with verification at the site. To study the organization of various types of pine stands and the cenopopulation dynamics of major forest-forming species (spruce, pine, oak, linden, and maple) with the identification of prospects for pine regeneration, a detailed analysis of the composition of all tiers of communities[2] was carried out according to the species activity index (A) (Malyshev, 1973)[3].

We analyzed 231 relevés in pure pine plantations and communities, where the pine canopy in the composition of the overstorey was at least 40%. For storage and analysis of materials of relevés, the created database FORDIV (in the DBMS Access) was used (State Registration Certificate no. 2014620979).

Statistical methods were used in three directions: (1) in the classification to identify the floristic composition of the distinguished syntaxa and their characteristics; (2) in assessing the relationship of the distinguished community groups with environmental factors (including spatial variables). The calculations were carried out in applied software packages (PC-ORD 5.0, STATISTICA 10, IBM SPSS Statistics); (3) in the analysis of the spatial structure of territorial units of forest cover in the Fragstats software.

To assess the accuracy of the distinguished units, stepwise discriminant analysis was applied. The indicator significance of the species was estimated according to the *IndVal* method (Dufrêne and Legendre, 1997); species with an IndVal value >30 were considered differentiating. To interpret the ecological content of the groups, we employed indirect ordination methods, nonmetric multidimensional scaling (NMS ordination) in the PC-ORD 5.0 package (McCune and Mefford, 2006) using transformed (square root) data. The Bray–Curtis distance (Legendre, P. and Legendre, L., 1998; McCune and Grace, 2002) was used as a measure of similarity. The values of the factors and the ecological characteristics of the communities were estimated according to the scales of Tsyganov (1983): moisture (*HD*), soil nitrogen supply (*NT*), soil reaction (*RC*), trophicity (*TR*), and lighting (*LC*). The analysis of differences in the samples of community groups by factors and by the position of centroids of the groups along the ordination axes was carried out using the nonparametric Mann–Whitney *U*-test. The correlation of ordination axes with environmental factors was estimated using Spearman's rank correlation coefficients. In ordination, the composition of subordinate herb–small shrub and moss–lichen layers was taken into account.

For spatial assessment of the current composition of the forest cover, we used an approach that integrates ground and remote sensing data. The data from Landsat satellites (TM, ETM+, OLI, and TIRS sensors)

[1] Names of species of vascular plants are given according to (Cherepanov, 1995) and bryophytes according to (Ignatov et al., 2006).

[2] In distinguishing tiers, the traditional designation is accepted: A, the tree layer; B, the shrub layer and undergrowth (1–10 m high); C, the herb–small shrub layer (below 1 m); D, the moss–lichen layer. Layer A is divided into two sub-layers depending on the structure of the tree stand; layer B is divided into B1, undergrowth of trees, and B2, undergrowth (shrubs).

[3] Activity $A = \sqrt{FD}$, where $F$ is the relative occurrence of the species at all sites in all descriptions, $D$ is the average value of the species abundance (%) for the sites where this species is observed.

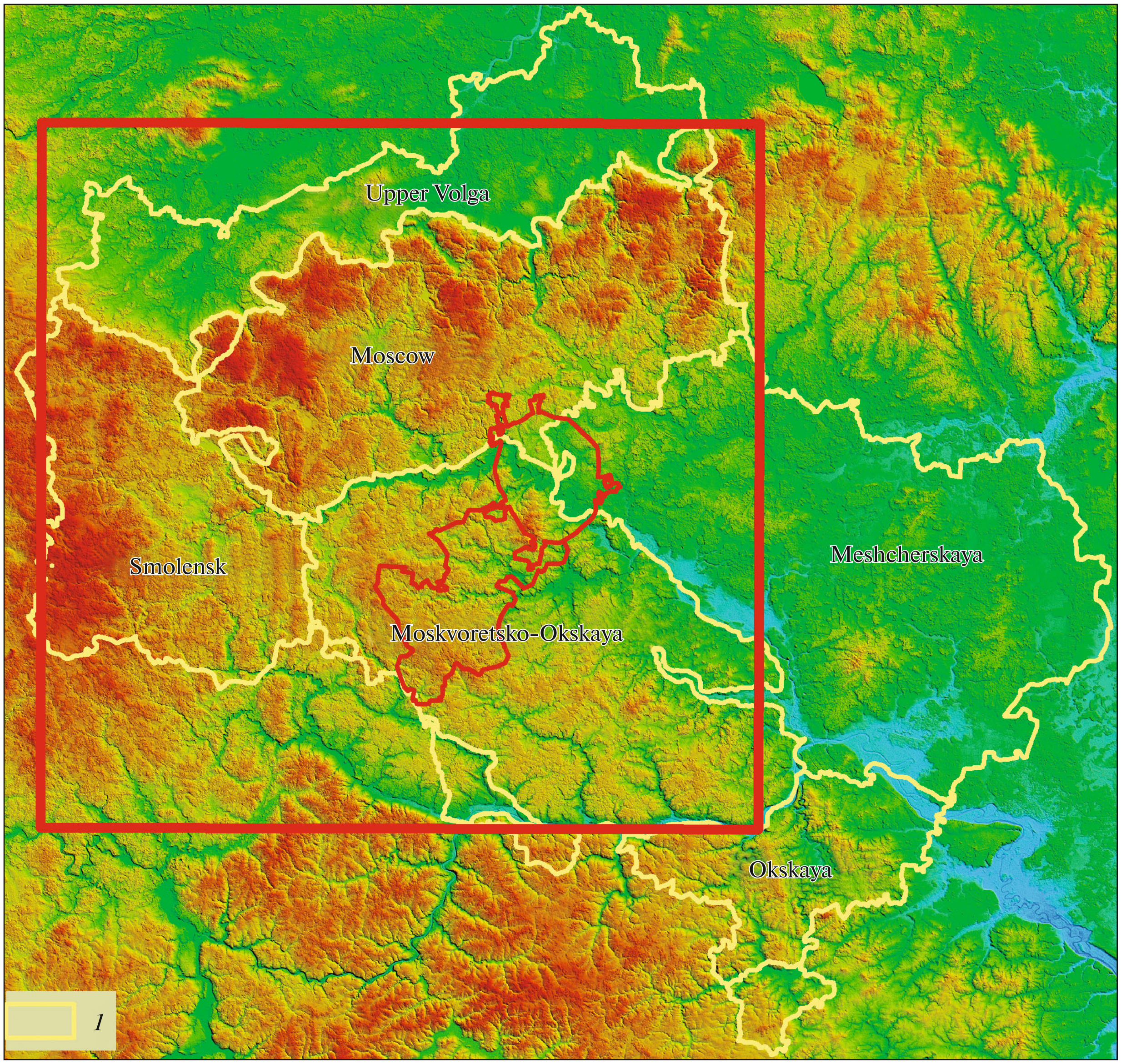


**Fig. 1.** Research area. *1*, Physical and geographical provinces; according to (Annenskaya et al., 1997).

from the last ten years were used as part of seven cloudless scenes from March to October. For a more complete use of remote sensing data, we calculated indices (NDVI, VI, NDWI, etc.) that are differences and normalized differences of the spectral reflectance of the survey (Jackson and Huete, 1991). The SRTM data were used as a digital elevation model (DEM). The DEM resolution corresponds to the resolution of Earth remote sensing data (ERSD). The morphometric characteristics of the relief (slopes, curvatures, lighting, convexity, etc.) were calculated on the basis of the DEM. The hierarchical levels of the terrain organization were determined using spectral analysis (Kotlov and Puzachenko, 2006).

The analysis of the spatial distribution patterns of the distinguished syntaxa and their spatial mapping consisted in interpolating the vegetation classes to the upper scale levels through their comparison with the ERSD and DEM based on the training sample (Puzachenko, 2004; Puzachenko et al., 2014). The group of associations was the basic cartographic unit and was used as a grouping variable or a training sample in multivariate analysis of multispectral images. Interpolation of individual vegetation cover characteristics obtained from relevés (distribution of individual dominant species in terms of their projective cover), in particular, the index of pine crown closeness, was also carried out. A more detailed description of this approach is given in earlier publications

(Chernen’kova et al., 2015; Puzachenko and Chernen’kova, 2016).

To assess geometric features of the contours and their relative positions, we used an approach based on the measurement of landscape-ecological metrics. The applicability of spatial metrics was previously shown for patch of soil (Fridland, 1972), landscape (Viktorov, 1986), and geobotanical patch (Kholod, 2017). The calculation was carried out in Fragstats (McGarigal et al., 2012). As a basic object of analysis, we employed the pine forest stands corresponding to the distinguished syntaxa in the rank of association groups.

Area metrics are quite simple, the area and the proportion of the area of a community group by province, as well as the average area of sections of each community group. The average area of a section is one of the indicators of fragmentation.

The shape index (*SI*) is an indicator of the complexity of contours of patch.

$$SI = \frac{0.25 p_{ij}}{\sqrt{a_{ij}}},$$

where $p_{ij}$ is the perimeter of the patch (m) and $a_{ij}$ is the area of the patch (m$^2$). The metric ranges from 1 (square) to infinity. In contrast to the simple ratio of the perimeter and the area, this indicator is insensitive to the size of the patches.

The ecological core area index (*CAI*) is based on the exposure of a particular patch to the effects of neighboring landscape types (for example, pollution of a forest site adjacent to a highway, or its hydromorphization near a water body). Based on the empirical assumption of the distance exposed to the impact, this index shows what proportion of the patch (core) is not affected by neighboring ecosystems. To calculate the metric, a matrix of pairwise distances of the impact of landscapes on each other is introduced in advance. Distances range from 0 for morphologically homogeneous ecosystems (various types of forests) to 200 m for heterogeneous combinations with anthropogenic territories.

$$CAI = \frac{a_{ij}^{c}}{10\,000},$$

where $a_{ij}^{c}$ is the patch area adjusted for the distance of the influence of neighboring sections.

The edge contrast index (*ECON*) is calculated according to a principle similar to the core area index. Instead of the area, the patch perimeter is taken as the basis. The values of contrast (heterogeneity) in the matrix vary from 0 to 1.

$$ECON = \frac{\sum_{k=1}^{m} (p_{ijk} d_{ik})}{p_{ij}} \times 100,$$

where $p_{ijk}$ is the length (m) of the edge of patch *ij* adjacent to the patch of class $k$, $d_{ik}$ is the heterogeneity (weight of the edge contrast) between the patches of classes $i$ and $k$, and $p_{ij}$ is the perimeter of patch *ij*.

The aggregation metric (*ENN*) is the Euclidean nearest neighbor distance for patches of the same group.

$$ENN = h_{ij},$$

where $h_{ij}$ is the distance (m) to the nearest patch of the same class, based on the distance between the edges and calculated from core to core.

## RESULTS AND DISCUSSION

In the composition of pine and pine–spruce communities, 11 groups of associations were distinguished, which differ in the composition of vegetation of the main layers (Table 1). According to the results of discriminant analysis, the classification accuracy was 84.5%. Groups of associations with a heterogeneous composition of woody layers (for example, the pine–spruce–small-herb group) or subordinate layers (for example, the pine small-herb–broad-herb group with linden, oak, and hazel), to a large extent represented by cultures (about 80%), were discriminated with less accuracy (<60%). According to the available data, the total proportion of forest cultures amounted to one third of all relevés.

Further analysis of the composition and structure of the distinguished groups was carried out after combining them into six groups of communities[4] according to the prevailing ecobiomorphe[5] of terrestrial vegetation tiers: small shrub–small-herb–green-moss (1), small-herb (2), small-herb–broad-herb (3), broad-herb (4), mixed-herb (5), and small shrub–sphagnum groups (6).

The small shrub–small-herb–green-moss group of pine communities is differentiated by the boreal species *Vaccinium myrtillus* and *Melampyrum pratense* and green mosses *Hylocomium splendens* and *Dicranum polysetum*, which have IndVal values > 50 (Table 2). The presence of young spruce in the field layer indicates active spruce demutation.

The small-herb and small-herb–broad-herb groups of communities[6] within the subordinate layers exhibit codomination of typical representatives of taiga short herbs *(Rubus saxatilis*, *Gymnocarpium*

[4] The group of communities is the name of a typological unit and is given by analogy with the representation of species-dominants of the herb layer that form series, cycles, and bioecogroups (Porfir’ev, 1960; Saburov, 1972; Savel’eva, 2000; Zaugol’nova and Morozova, 2006).

[5] An ecobiomorph is a set of plants existing in similar environmental conditions and having a certain type of adaptive structure and related physiological characteristics (Ecobiomorph, 1978; Bykov, 1983).

[6] In the literature, in accordance with the dominant classification, these types of communities are often referred to as acidic and acidic–broad-herb forests.

**Table 1.** The analyzed community groups with the assessment of the classification accuracy using the results of discriminant analysis

| Community group | Association group | Amount of descriptions | Proportion of correct classification, % | |
|---|---|---|---|---|
| | | | compared to species composition | compared to ERSD and DEM data |
| Small shrub—small-herb—green-moss | 1. Pine-spruce, small shrub—small-herb—green-mos | 16 | 81.3 | 43.8 |
| | 2. Pine with spruce and birch, small shrub—small-herb—green-moss | 16 | 81.3 | 68.8 |
| Small-herb | 3. Pine—spruce, small-herb | 11 | 54.6 | 63.6 |
| | 4. Pine with spruce and birch, small-herb | 17 | 94.1 | 52.9 |
| Small-herb—broad-herb | 5. Pine—spruce, small-herb—broad-herb | 37 | 83.8 | 30 |
| | 6. Pine with spruce and birch, small-herb—broad-herb | 12 | 91.7 | 57.1 |
| | 7. Pine with linden, oak, and hazel, small-herb—broad-herb | 14 | 57.1 | 54.5 |
| Broad-herb | 8. Pine—spruce, broad-herb | 55 | 78.2 | 46.5 |
| | 9. Pine with linden, oak, and hazel, broad-herb | 34 | 85.3 | 55.9 |
| Mixed-herb | 10. Pine with spruce and birch, mixed-herb | 12 | 100 | 75 |
| Small shrub—sphagnum | 11. Pine with spruce and birch, small shrub—sphagnum | 7 | 100 | 100 |

*dryopteris*, and *Oxalis acetosella*), green mosses *(Hylocomium splendens*, *Pleurozium schreberi*) and species of broad-leaved and broad-leaved—coniferous forests (*Circaea alpine*, *Paris quadrifolia*). The presence of hazel as an indicative species in the small-herb—broad-herb group of pine trees with participation of spruce, birch, linden, and oak is quite representative and distinguishes this group from the short-grass one, whose tree canopy has no broad-leaved species but only spruce and birch besides pine. Such a picture as a whole is, on the one hand, characteristic of a group of complex pine forests in Moscow region (Rysin, 1964), and on the other hand, indicates a "nemoralization" of middle-aged stands, including those of artificial origin, upon transition to the stage of more "mature communities" (Pesterova, 2013). In the composition of the small-herb—broad-herb group of communities as a whole, pine cultures made up the largest proportion (66%).

Broad-herb pine and pine—spruce forests are differentiated mainly by species of nemoral broad grasses, and broad-leaved tree species are observed in the upper tier (Table 2). The proportion of artificial plantations, mainly in the composition of pine—spruce broad-herb communities, is also high (65%).

Indicative species of the group of mixed-herb pine forests with spruce and birch in the canopy include meadow-fringe species (*Trifolium medium*, *Agrimonia eupatoria*, etc.), as well as *Calamagrostis arundinacea*. These communities grow on terraces and steep river slopes on light sandy soils with good drainage, including anthropogenically disturbed habitats. In the composition of the herb—small shrub layer, *Pinus sylvestris* is present as an indicative species (Table 2).

Small shrub—sphagnum pine forests with spruce and birch are noted in depressions of swampy lowlands; the indicative species include *Vaccinium vitisidaea*, *V. uliginosum*, *Ledum paluster*, *Eriophorum vaginatum*, and *Carex globularis* and *Sphagnum angustifolium* and *S. magellanicum* in the moss cover (Table 2).

The position of six groups of communities in the ordination axes (Fig. 2) shows their distribution in the space of environmental factors: (1) groups of small shrub—small-herb—green-moss, broad-herb, mixed-herb, and small shrub—sphagnum pine forests are well differentiated; (2) the small-herb—broad-herb and short-herb groups partially overlap, indicating a similar floristic composition of the communities of these two groups, which is represented by species that are ecologically close. The positions of centroids of the six groups along the ordination axes are statistically sig-

**Table 2.** Indicator value (IndVal) indices for species in groups of pine communities

| Community group | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| small shrub–small-herb–green-moss | | small-herb | | small-herb–broad-herb | | broad-herb | | mixed-herb | | small shrub–sphagnum | |
| species | IV | species | IV | species | IV | species | IV | species | IV | species | IV |
| *Pleurozium schreberi* | 76 | *Mycelis muralis* | 43.2 | *Corylus avellana* B | 37.5 | *Athyrium filix-femina* | 47.5 | *Trifolium medium* | 66.7 | *Eriophorum vaginatum* | 71.4 |
| *Vaccinium myrtillus* | 58.5 | *Oxalis acetosella* | 41.9 | *Dryopteris carthusiana* | 35.6 | *Ranunculus cassubicus* | 36.4 | *Calamagrostis arundinacea* | 60.5 | *Sphagnum magellanicum* | 71.4 |
| *Hylocomium splendens* | 51.8 | *Circaea alpina* | 30.9 | *Paris uadrifolia* | 32.2 | *Galeobdolon luteum* | 31.5 | *Agrimonia eupatoria* | 58.3 | *Ledum palustre* | 57.1 |
| *Dicranum polysetum* | 50.2 | *Sorbus aucuparia* B | 30 | *Viburnum opulus* C | 30.8 | | | *Knautia arvensis* | 58.3 | *Vaccinium uliginosum* | 57.1 |
| *Picea abies* C | 31.8 | | | | | | | *Leucanthemum vulgare* | 55 | *Sphagnum angustifolium* | 57.1 |
| *Melampyrum pratense* | 31.7 | | | | | | | *Veronica officinalis* | 51.4 | *Vaccinium vitis-idaea* | 54.9 |
| | | | | | | | | *Clinopodium vulgare* | 45.8 | *Carex globularis* | 53.8 |
| | | | | | | | | *Carex pallescens* | 44.1 | *Oxycoccus palustris* | 42.9 |
| | | | | | | | | *Vicia cracca* | 41.7 | *Polytrichum strictum* | 42.9 |
| | | | | | | | | *Campanula persicifolia* | 40.6 | *Aulacomnium palustre* | 40.7 |
| | | | | | | | | *Fragaria vesca* | 40.2 | *Betula pubescens* B | 37.9 |
| | | | | | | | | *Pinus sylvestris* C | 36.5 | | |
| | | | | | | | | *Lathyrus vernus* | 34.9 | | |
| | | | | | | | | *Melica nutans* | 33.7 | | |
| | | | | | | | | *Antennaria dioica* | 33.3 | | |
| | | | | | | | | *Astragalus glycyphyllos* | 33.3 | | |
| | | | | | | | | *Viola hirta* | 33.3 | | |
| | | | | | | | | *Chamaenerion angustifolium* | 32.4 | | |

IV, an index of the indicator value. In cases where a species may occur in several tiers, its particular tier is indicated. Only the leading indicator species are shown, in which the index of the indicator value (IV) is above 30 at the significance level <0.05.

nificantly different for all pairs of groups of communities along at least one axis (according to the results of the Mann–Whitney test, at $p < 0.05$). The exception was a pair of small shrub–small-herb–green-moss and small shrub–sphagnum groups, as the position of their centroids differs only in three-dimensional space. All vectors of environmental factors have a statistically significant relationship with both the ordination axes, with the exception of moisture (Table 3). However, the correlation coefficients are low and exceed 0.5 only in the case of trophicity and soil richness with nitrogen in relation to the first axis.

Moisture (*HD*) is the highest in the habitats of small shrub-sphagnum forests and the lowest in the habitats of mixed-herb forests (Fig. 3). The small-herb, small-herb–broad-herb, and broad-herb groups do not statistically significantly differ between each other in terms of this ecological regime. The remaining pairs show significant differences. The highest trophicity (*TR*) is characteristic of broad-herb and mixed-herb forests, and they do not statistically significantly differ between each other in terms of this ecological regime, while the lowest trophicity is typical of habitats of small shrub–sphagnum forests. All pairs, except for the first, are statistically significantly different in soil trophicity. The most nitrogen-rich soils (*NT*) are found in the habitats of the small-herb, small-herb–wide-herb, and broad-herb groups of forest communities. The most nitrogen-poor soils are characteristic of small shrub–sphagnum forest communities. For this ecological regime, all pairs are statistically significantly different, with the exception of the small-herb vs. small-herb–broad-herb and small-herb vs. broad-herb groups. The highest values of soil reaction (*RC*) (the lowest scores) were noted for small shrub–sphagnum forest communities and the lowest (the highest scores on the scale) for habitats of small-herb–broad-herb, broad-herb, and mixed-herb groups. In terms of soil reaction, all pairs statistically significantly differ from each other, with the exception of small-herb–broad-herb vs. mixed-herb and broad-herb vs. mixed-herb ones. The most illuminated (*LC*) (lowest scores) is of mixed-herb and small shrub–sphagnum forests, and they are not statistically different in terms of this regime. The subordinate layers of the small-herb, small-herb–broad-herb, and broad-herb forest groups are the most obscured, and these pairs also do not statistically significantly differ in light exposure.

To assess the sustainability of communities and the prospects for preserving pine plantations, the presence of pine and the ratio of the major tree species (spruce, pine, oak, linden, and maple) in different layers of the selected community groups are considered. As can be seen from Fig. 4, the presence of pine in subordinate layers (A2 and C) is not observed in all groups of communities: in layer A2, in small-herb and small shrub–sphagnum groups; in layer C, in small shrub–small-herb–green moss, mixed-herb, and small shrub–sphagnum groups; in layer B, the undergrowth pine is absent in all groups. In layer A2, spruce prevails in three groups of communities; the broad-herb group is predominated by broad-leaved species; in layer B, the situation is similar; in layer C, spruce is "active" only in small shrub–small-herb–green-moss communities, while the remaining groups are predominated by broad-leaved tree species or pine undergrowth.

To assess the spatial distribution of communities with pine, joint processing of ground-based field data and spatial information, ERSD and DEM, was carried out. The relative quality of discrimination of the distinguished syntaxa using the ERSD and DEM data is 64.6% (Table 1). The distribution of communities is characterized by various dependences on ERSD and DEM variables. The pine–spruce small-herb–broad-herb group of communities, characterized by a mixed composition of both overstorey and understorey, is classified with less accuracy from ERSD (30%); that is, there is no clear spectral response for this group, which may indicate the derivative nature of these communities, their artificial origin in landscape conditions uncharacteristic of natural pine plantations (lack of association with morphometric relief data). Groups associated with habitats characteristic of indigenous

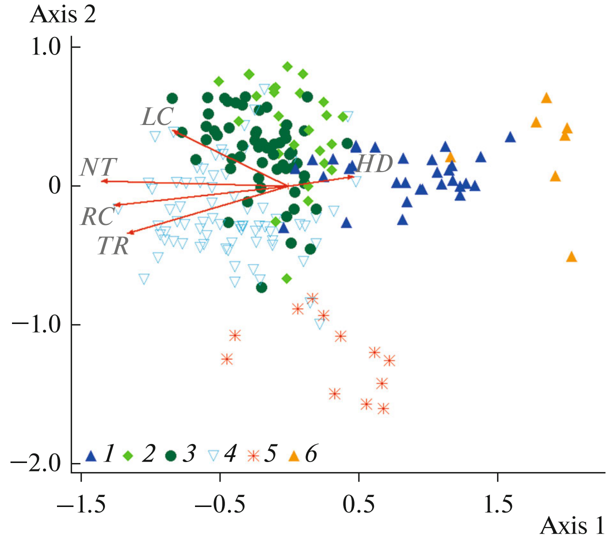


**Fig. 2.** Distribution of communities involving pine along NMDS ordination axes. For Figs. 2–4, designations of vectors of environmental factors: *HD*, soil moisture, *HD*, soil humidification; *NT*, soil nitrogen supply; *RC*, soil acidity; *TR*, soil trophicity; *LC*, light exposure. Community groups: *1*, small shrub–small-herb–green-moss; *2*, small-herb; *3*, small-herb–broad-herb; *4*, broad-herb; *5*, mixed-herb; *6*, small shrub–sphagnum.

pine forests (small shrub–sphagnum and mixed-herb) and groups that are more homogeneous in the tree stand composition are better discriminated.

The discriminant analysis makes it possible to assess individual characteristics of the vegetation cover obtained from relevés. The accuracy of the discriminatory distribution model of pine communities in terms of the canopy cover of trees of the upper layer (A1) was 69.6%. At the same time, a fairly high value of the discrimination quality is observed only in terms of relief indicators, 56.1%, which proves a certain dependence of the distribution of pine stands on landscape features.

The analysis of the spatial distribution of the distinguished community groups with the participation of pine for the studied area (Fig. 5) revealed that the greatest occurrence of pine massifs is observed in the northern part of the region along the northern spurs of the Klin-Dmitrov ridge and in the south along the steep banks of the Oka river. It is characteristic that in

**Table 3.** Spearman correlation between the values of NMS ordination axes and the values of environmental factors

| | *HD* | *TR* | *NT* | *RC* | *LC* |
|---|---|---|---|---|---|
| Axis 1 | **0.219000** | **0.532710** | **0.540015** | **0.443258** | **0.169022** |
| Axis 2 | 0.077736 | **0.433672** | **0.392263** | **0.287883** | **0.398358** |

Bold indicates values significant for $p < 0.05$. *HD*, soil humidification; *TR*, soil trophicity; *NT*, soil nitrogen supply; *RC*, soil acidity; *LC*, light exposure.

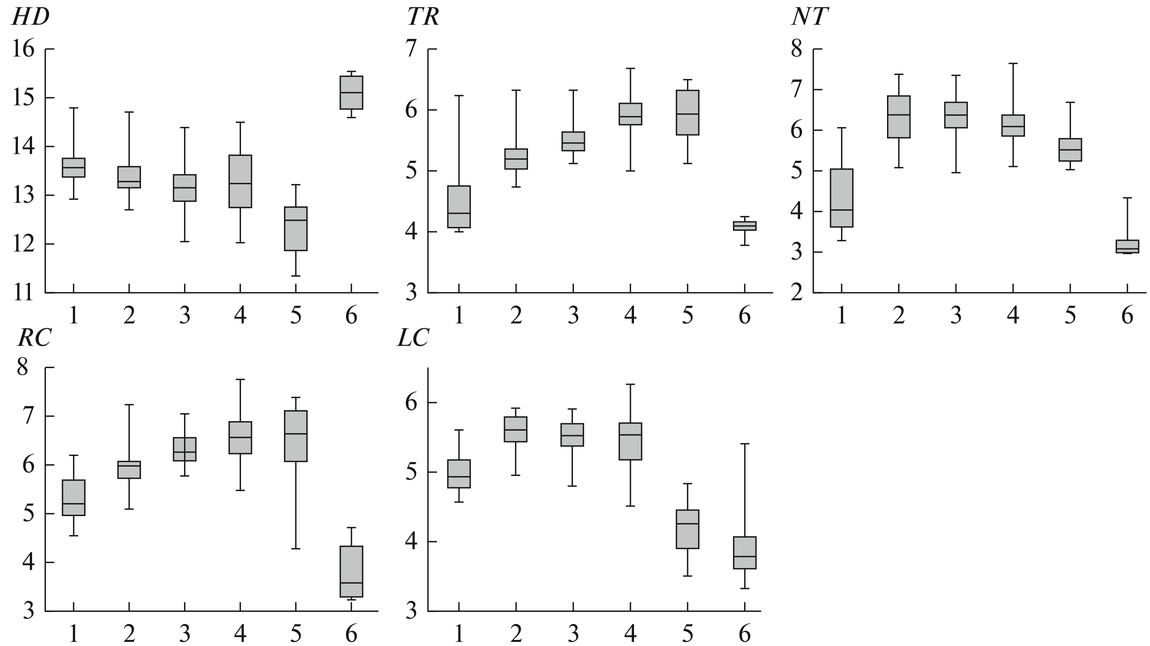


**Fig. 3.** Variation of ecological characteristics of habitats of forest communities. The median values, interquartile distances (25–75% variation), and the minimum and maximum values are reflected on the boxplots. For designations, see Fig. 2.

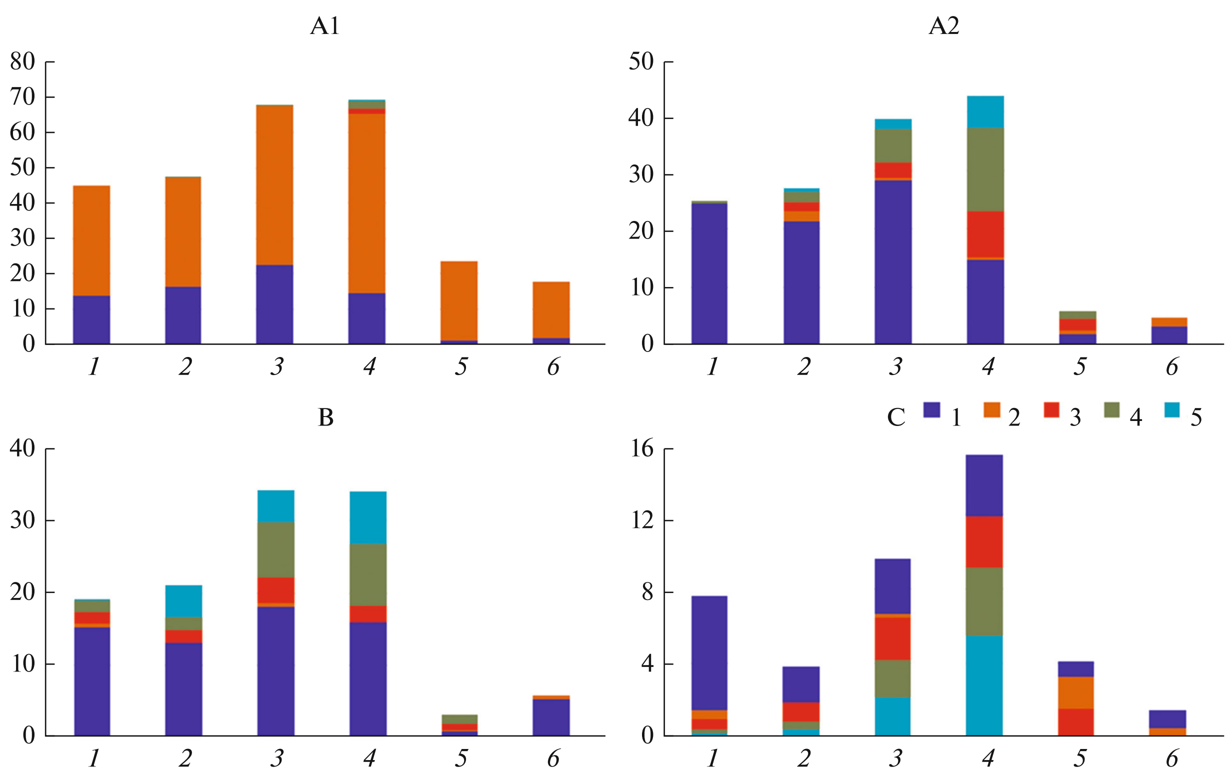


**Fig. 4.** Changes in the activity of tree species in different tiers of pine stands. A1, the first subtier of the stand; A2, the second subtier of the stand; B, the shrub layer; C, the herb–shrub layer. For designations of groups, see Fig. 2.

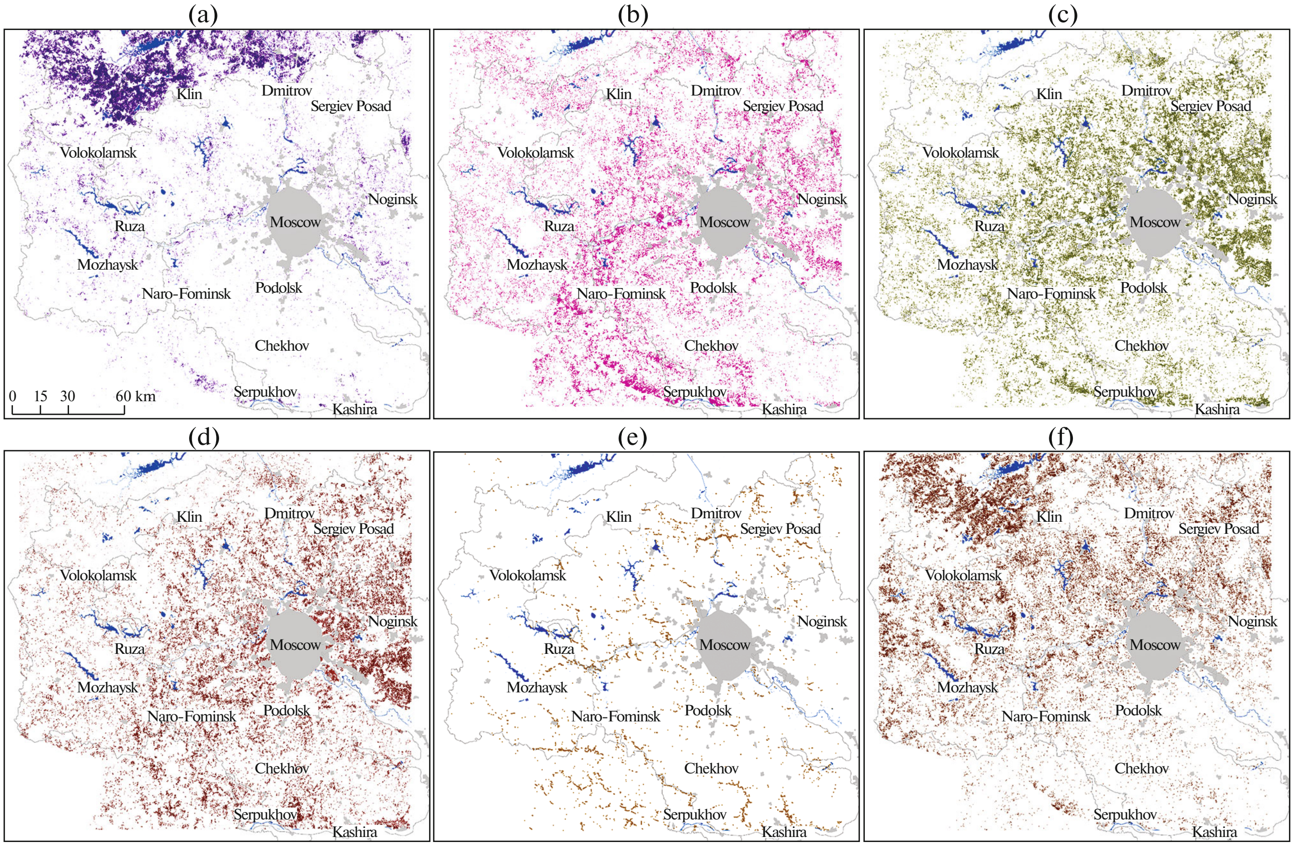


**Fig. 5.** Distribution of community groups with participation of pine for the studied territory of Moscow region. Community groups: (a) small shrub–small-herb–green-moss; (b) small-herb; (c) small-herb–broad-herb; (d) broad-herb; (e) mixed-herb; (f) small shrub–sphagnum.

a relatively small geographical area within the studied territory of Moscow region in the sublatitudinal direction one can trace zonal patterns of the distribution of pine plantations. Thus, forests of the small shrub–small-herb–green-herb group prevail in the northwestern sector (Fig. 5a), while forests of the broad-herb group of communities have a higher coverage area in the southeastern sector of the studied territory (Fig. 5d). The areas of distribution of pine communities of various types in terms of Physiographic provinces (PGP) (Table 4) confirm the visual assessment of their distribution according to cartographic schemes. The area of pine forests of the small shrub–small-herb–green-moss group in the Upper Volga PGP is an order of magnitude larger, and that of the broad-small-herb group, respectively, is an order of magnitude less than their representation in the remaining PGPs of the studied territory. Intrazonal groups of communities (pine mixed-small-herb and small shrub–sphagnum ones) are distributed more or less evenly in the studied region (Figs. 5e and 5f), which is confirmed by the uniform ratio of their areas in different PGPs (Table 4). Mixed-small-herb pine forests have a distinct ribbon-like configuration of polygons, indicating that they are confined to morphosculptural relief forms, river terraces.

For a more detailed study of the spatial patterns of the distribution of communities, a variance analysis of the association of pine plantations with different landscape conditions at different hierarchical levels of relief organization was carried out. It was found that the association groups are most significantly related to elevations for different hierarchical levels of relief, slopes, varying curvatures, and lighting for levels in the range of 300–1140 m. The most convex relief forms are characteristic of broad-leaved pine forests with linden, oak, and hazel and the most concave forms are typical of small shrub–sphagnum pine forests. The distribution of small shrub–small-herb–green-moss pine forests is associated with habitats characterized by very low indicators of the relief elevation and its forms for the hierarchical level of relief organization with a linear size of 19980 m, but, at the same time, the distribution of broad-herb and small shrub–small-herb–green-moss pine forests is associated with high altitudes for the level of 300 m and with medium altitudes for levels of 540 and 2220 m. Slopes of more than 6° are noted only for mixed-herb pine stands. Solar exposition at an azimuth of 90° and 180°, determining the

**Table 4.** Landscape-ecological metrics for various groups of pine communities within the physigraphic provinces of Moscow region

| PGP | Community group | Area, thousand ha | Proportion in the province, % | Average section area, ha | Shape index | Core index, % | Distance, m | Contrast index |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 60.5 | **13.20** | **5.64** | **1.20** | **90.08** | **184.27** | **13.03** |
| | 2 | 1.9 | 0.41 | 0.54 | 1.03 | **95.35** | 390.39 | 4.99 |
| | 3 | 1.8 | 0.40 | 0.68 | 1.06 | **94.73** | 364.60 | 4.30 |
| | 4 | 2.7 | 0.59 | 0.64 | 1.05 | **97.94** | 322.56 | 5.91 |
| | 5 | 0.1 | **0.02** | **2.32** | 1.11 | **93.50** | 2187.43 | **12.90** |
| | 6 | 8.5 | 1.85 | 1.17 | 1.09 | **96.14** | 253.28 | **13.33** |
| 2 | 1 | 3.2 | 0.51 | 0.79 | 1.07 | **90.84** | 344.92 | 7.01 |
| | 2 | 4.5 | 0.70 | 0.73 | 1.04 | **91.90** | 369.86 | 7.09 |
| | 3 | 6.6 | **1.04** | 0.86 | 1.07 | **89.89** | **289.54** | 5.67 |
| | 4 | 6.1 | **0.95** | 0.78 | 1.07 | **96.15** | **298.23** | 5.64 |
| | 5 | 1.3 | 0.20 | **3.03** | **1.16** | **86.14** | 858.51 | **18.42** |
| | 6 | 6.0 | 0.93 | 0.76 | 1.06 | **94.88** | **287.80** | **12.61** |
| 3 | 1 | 5.0 | 0.53 | 0.69 | 1.05 | 70.50 | 349.53 | **20.59** |
| | 2 | 7.8 | 0.83 | 0.67 | 1.05 | **86.61** | 321.41 | 8.71 |
| | 3 | 30.1 | **3.19** | **1.34** | **1.12** | **90.14** | **208.11** | 5.59 |
| | 4 | 16.7 | **1.77** | 0.98 | 1.09 | **94.61** | **244.38** | 5.45 |
| | 5 | 3.4 | 0.36 | **3.16** | **1.15** | **86.36** | 621.20 | **17.56** |
| | 6 | 14.2 | 1.51 | 0.83 | 1.07 | 86.88 | **258.44** | **24.66** |
| 4 | 1 | 2.3 | 0.25 | 0.63 | 1.04 | 55.59 | 462.63 | **31.42** |
| | 2 | 8.6 | 0.91 | 0.77 | 1.06 | **81.96** | 309.04 | **12.77** |
| | 3 | 16.7 | **1.77** | **1.20** | 1.10 | **91.46** | **251.95** | 6.71 |
| | 4 | 26.3 | **2.78** | **1.48** | 1.11 | **93.67** | **232.85** | 7.29 |
| | 5 | 2.6 | 0.28 | **2.68** | **1.15** | **86.14** | 607.42 | **19.68** |
| | 6 | 3.2 | 0.34 | 0.61 | 1.04 | 77.63 | 427.72 | **27.47** |
| 5 | 1 | 3.3 | 0.94 | 0.59 | 1.05 | 61.11 | 272.91 | **25.18** |
| | 2 | 3.6 | 1.04 | 0.63 | 1.05 | **82.38** | 285.69 | 11.62 |
| | 3 | 14.6 | **4.16** | **1.38** | **1.14** | **89.60** | **184.58** | 5.88 |
| | 4 | 22.6 | **6.47** | **1.82** | **1.16** | **91.24** | **176.67** | 6.88 |
| | 5 | 0.1 | 0.04 | **1.27** | **1.12** | **84.78** | 2056.33 | **19.57** |
| | 6 | 2.2 | 0.62 | 0.58 | 1.04 | 77.43 | 335.27 | **26.73** |

Names of PGPs: 1, Upper Volga; 2, Moscow; 3, Smolensk; 4, Moskvoretsko-Okskaya; 5, Meshcherskaya. Community groups: 1, small shrub–small-herb–green-moss; 2, small-herb; 3, small-herb–broad-herb; 4, broad-herb; 5, mixed-herb; 6, small shrub–sphagnum. Bold indicates high values, underscore indicates low values.

exposure, is most pronounced for mixed-herb pine forests, which have the greatest slopes of the relief and the prevalence of south-western aspect of the slopes. The least exposition from the east and south is noted for pine–spruce small-herb and broad-herb forests occupying the slopes of the north-western aspect.

The assessment of the heterogeneity of the spatial structure of contours of the community groups is based on the calculation and analysis of spatial landscape-ecological metrics; the area, shape, the ecological core area, the aggregation, and contrast (Table 4). For groups of pine forest communities, metrics were calculated in terms of PGPs. Within the studied territory, the area of pine forests is the largest in the Upper Volga and Meshcherskaya provinces (16.45 and 13.27%, respectively), the smallest in the Smolensk province (4.33%), and in Moscow and Moskvoretsko-Okskaya provinces it amounts to 8.19 and 6.32%. Two areal characteristics were analyzed, the proportion of a group of communities in the total area of the province and the average area of the patch. In all the five provinces, pine forests are characterized by a small average patch area (1.31 ha). Mixed-herb forests are distinguished from other groups, having medium areas above the average of 1.27–3.16 ha, however, the proportion of this group in the total province is minimal

(0.02–0.36%) (Table 4). This indicates a focal (island) nature of their distribution associated with confinedness to river terraces.

The Upper Volga province is predominated by the small shrub–small-herb–green-moss group, 13.2%, where the largest average size of the section is 5.64 ha. Dominant groups in the Smolensk province are not identified. In the Moscow, Moskvoretsko-Okskaya, and Meshcherskaya provinces, broad-herb and broad-herb–small-herb groups dominate with small differences (Table 4).

The groups dominating in their province usually have a higher shape metric (and, accordingly, a more complex form, which indirectly indicates a lesser degree of impact of anthropogenic processes, often "straightening" the borders). The exception is the mixed-herb pine stands, which retain the natural complex shape of the contours when having large sizes of the patches.

The core area index for all groups of pine forests of the Upper Volga and Smolensk provinces is high (93.13% on average), which indicates the proximity of pine forests to forests of other types, and, consequently, a low degree of anthropogenic disturbance. In the Moscow, Moskvoretsko-Okskaya, and Meshcherskaya provinces, the groups with largest areas have a high core area index (small-herb, broad-herb–small-herb and broad-herb ones have 83.65, 90.4, and 93.18%, respectively), as well as mixed-herb pine forests (85.76%) (Table 4). For the other two groups, a significant decrease in the area of the ecological core is observed due to the proximity to heterogeneous types of vegetation and land cover. Together with the small average areas of sections, this indicates the "risky" status of these groups.

The aggregation (distance) varies for pine forests as a whole from 176 to 2187 m (458 m on average). For the above-mentioned mixed-herb pine forests regarding isolation, it averages 1266 m for all the provinces. The dominant groups of the Moscow, Moskvoretsko-Okskaya, and Meshcherskaya provinces are characterized by shorter distances between patches (264 m) than the subdominant small shrub–small-herb–green-moss and small shrub–sphagnum (317 m) groups in general (Table 4).

The edge contrast metric is generally low for sections of the dominant groups (6.9 on average), which correlates with the conclusion that pine forests are adjacent to other types of forests. For mixed-herb pine grasses, it is 17.63; for subdominant groups, 11.46 within the Upper Volga and Smolensk provinces and 26.0 within the Moscow, Moskvoretsko-Okskaya, and Meshcherskaya provinces (Table 4).

## CONCLUSIONS

It is believed that pine–spruce forests with the participation of broad-leaved species are a native type of vegetation in certain landscape conditions of the geomorphological region of the Klin-Dmitrov ridge (Ogureeva et al., 1996). The obtained data and the developed classification clarify the existing understanding about the typological diversity of communities with the participation of pine in Moscow region. The absence of pine regeneration in the communities of automorphic habitats indicates a derivative origin of pine stands after fires and at the site of felling, as well as in the composition of artificial plantations. Our conclusion about the derivative nature of all pine stands of Moscow region, with the exception of pine stands of the upper bogs, is consistent with opinions of other researchers (Maslov, 2000, 2002; Rysin and Savel'eva, 2002).

In total, in the rank of association groups, 11 syntaxa were distinguished, which were grouped according to the prevailing ecobiomorph of vegetation of understorey into six groups of communities: small shrub–small-herb–green-moss, small-herb, small-herb–broad-herb, broad-herb, mixed-herb, and small shrub–sphagnum ones. The analysis of the composition of the distinguished community groups reflects, on the one hand, the ecological specificity of their set of species, on the other hand, the transitional succession status towards a more "mature" stage, in particular, for communities of artificial origin. In the so-called "complex" small-herb–broad-herb pine stands with the participation of linden and oak, the proportion of cultures (based on relevés) is about 80%. On watershed surfaces, recovery successions proceed in two directions: in one case, recovery is accompanied by active demutation of spruce; in another case, with increased soil richness, recovery is accompanied by active demutation of broad-leaved species, which will prevent the existence of pine and pine–spruce communities after several decades. A small proportion of pine plantations will remain on the steep slopes of the rivers due to favorable environmental conditions for the pine (light sandy soils with good drainage) with constantly maintained recreational impact, as well as in hydromorphic conditions.

The distribution of pine forests in Moscow region vary significantly across five physical–geographical provinces due to zonal differences, as well as due to varying degrees of anthropogenic transformation. The landscape-ecological metrics are reliable indicators of both zonal differences in groups of communities and the degree of fragmentation, which is more pronounced in the central and southeastern parts of the studied territory. Communities classified as small shrub–small-herb–green-moss and small shrub–sphagnum groups within the Moscow, Moskvoretsko-Okskaya, and Meshcherskaya provinces are most susceptible to fragmentation. The patch areas are minimal and the distances between the sections are large compared to other groups. The patches, as a rule, are surrounded by landscape types heterogeneous with respect to the pine forest. The penetration depth of edge effects reduces the area of the ecological core by up to 70%. Most vulnerable in all the provinces are mixed-herb pine stands. Despite the fact that some massifs retain an area above the average, 2.49 ha, the isolation of the patches reaches almost 2200 m. Under such conditions, the patches lose the ability to gene flow and so approach the state of "islands."

The obtained data supplement the current understanding of the phytocenotic structure and spatial distribution of communities with participation of pine, the composition of which reflects the succession stage (1), zonal features of the vegetation of the studied region (2), and confinedness to certain landscape elements (3). In the sublatitudinal direction, different ratios of communities with a predominance of plant species of the boreal, subnemoral, and nemoral spectrum in the understorey are observed.

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## COMPLIANCE WITH ETHICAL STANDARDS

*Conflict of interests.* The authors declare that they have no conflicts of interest.

*Statement on the welfare of animals.* This article does not contain any studies involving animals performed by any of the authors.

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