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Article

Landscape features of the spatial distribution of mixed pine and spruce stands in the Leningrad region

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Article. Mixed stands with the dominance of pine and spruce occupy up to a quarter of the area of the forest fund in the conditions of the North-West of Russia. Modern forest management and the current regulatory framework are aimed at the formation and cultivation of pure softwood stands, but in certain climatic, soil and hydrological conditions mixed softwood stands grow more successfully and productively. Modern silvicultural activities and the current regulatory framework are aimed at the formation and cultivation of pure coniferous stands; however, under certain climatic, soil, and hydrological conditions, mixed coniferous stands grow more successfully and productively. This study examines the spatial distribution patterns of mixed pine and spruce stands in the Valdai-Tikhvin and Luga-Volkhov landscape districts of the Leningrad region. To identify the predominant types of mixed stands in each landscape, the Shannon, Simpson, and Pielou biodiversity indices were calculated. To assess the influence of landscape conditions on the distribution of mixed stands, the Spearman rank correlation coefficient was calculated. It has been established that different types of mixed stands are formed depending on landscape conditions, with soil-hydrological conditions having a decisive influence on their distribution. In the Valdai-Tikhvin landscape district, spruce-deciduous and spruce-pine stands predominate among mixed stands by area. In the Luga-Volkhov landscape district, spruce-deciduous stands occupy the largest area among mixed stands, which is associated with significant anthropogenic impact on this landscape district. Under predictive modeling through the felling rotation cycle (100 years), spruce-deciduous stands will predominate in the studied territories.

Keywords: geographic landscape, biodiversity, stand composition, geographic distribution, forest dynamics and condition, landscape conditions, landscape approach, stand modeling, Markov chain

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Научная статья

Ландшафтные особенности пространственного размещения смешанных древостоев сосны и ели Ленинградской области

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Аннотация. Смешанные древостои с преобладанием сосны и ели занимают до четверти площади лесного фонда в условиях северо-запада России. Современные лесохозяйственные мероприятия и действующая нормативная база направлены на формирование и выращивание чистых хвойных древостоев, однако в определенных климатических, почвенных и гидрологических условиях смешанные хвойные древостои растут более успешно и продуктивно. Данное исследование рассматривает особенности пространственного распределения смешанных древостоев сосны и ели в Валдайско-Тихвинском и Лужско-Волховском ландшафтных районах Ленинградской области. Для выявления преобладающих типов смешанных древостоев в каждом ландшафте были рассчитаны индексы биологического разнообразия Шеннона, Симпсона и Пиелу. Для оценки влияния ландшафтных условий на распространение смешанных древостоев рассчитывался корреляционный показатель Спирмена. Установлено, что в зависимости от ландшафтных условий формируются различные типы смешанных древостоев, причем решающее влияние на их распределение оказывают почвенно-гидрологические условия. В Валдайско-Тихвинском ландшафтном округе среди смешанных древостоев по площади преобладают елово-лиственные и елово-сосновые древостои. В Лужско-Волховском ландшафтном округе наибольшую площадь среди смешанных древостоев занимать елово-лиственные, что связано с сильным антропогенным воздействием на данный ландшафтный округ. При прогнозном моделировании через оборот рубки (100 лет) на исследованных территориях будут преобладать елово-лиственные древостои.

Ключевые слова: географический ландшафт, биоразнообразие, состав древостоя, географическое распределение, динамика и состояние лесных массивов, ландшафтные условия, ландшафтный подход, моделирование древостоя, Марковские последовательности

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Introduction

In the first quarter of the last century, G.F. Morozov expressed the idea of conducting silvicultural studies within the limits of landscapes, which are "like focal points or nodes, where the mutual influences of the general and local climate, from one side, topographical relief and geological conditions, from the other, flora and fauna - from the third, are meeting each other..." (Morozov, 1913, as cited in Yakovlev, 2024). Planning of forest management on a landscape basis should take into account the effect of social changes on natural systems (Estreguil and Mouton, 2009; Qiu et al., 2018; Uuttera et al., 2004). For example, with an increase in anthropogenic impact on the forest landscape, the area of stands with a predominance of deciduous species increases.

For planning silvicultural activities, the most important characteristics of the landscape is its resilience. Initially, resilience in ecology was defined as the capacity of a system to absorb external stress factors or perturbation without changing its fundamental structure and function or without moving to a qualitatively different state (Holling, 1973). Over the past three decades, the concept of resilience has expanded from its original focus to socio-ecological systems and stability, where it takes into account the capacity of the system for self-organization, adaptation to changes, and transformation (Folke, 2006). This idea was later integrated into landscape ecology, leading to the development of landscape resilience concept (Cumming, 2011). Landscape resilience emphasizes the critical importance of spatial heterogeneity and spatial interactions between complex adaptive systems for the overall stability of systems against external factors of disturbance or perturbation.

Biodiversity is the main criterion for the ecological resilience of landscapes. Habitats with spatially heterogeneous abiotic conditions are known to provide a wide variety of potentially suitable niches for plant species. The scientific background of landscape ecology suggests that, at a higher spatial level, the composition and structure of landscape mosaics also affects biotic processes and, thereupon, species richness (Honnay, et al., 2003). There are several studies on the relationship between the landscape structure (assessed through landscape indices) and plant diversity (Burton and Samuelson, 2008; Hernández-Stefanoni and Dupuy, 2008; Moser et al., 2002).

Mixed coniferous stands largely affect overall biodiversity (Angeistam and Kuuluvainen, 2004; Felton et al., 2020). And the spatial distribution of mixed stands is, in its turn, greatly influenced by landscape features and specific soil and hydrological conditions (Etheridge et al., 2006). Each landscape has its own characteristic type of mixed stands, which will have higher mensuration characteristics compared to pure stands (Yakovlev and Danilov, 2019; Mina et al., 2018; Popov, 2017). Age distribution of dominant stands is clearly related to the intensity of forest use (Tikhonova et al., 2017).

A number of studies employing the landscape approach have been carried out for the forests of the boreal zone of the European part of Russia (Angeistam and Kuuluvainen, 2004; Chertov, 1981; Danilov et al., 2018; Fedorchuk et al., 2005; Gromtsev, 2002, 2015; Isachenko, 1994; Isachenko et al.,

2010; Tikhonova et al., 2017). Nevertheless, the comprehensive studies on the influence of landscape conditions on the distribution of mixed stands are few. Most studies emphasize only one predominant species. The question regarding the duration of succession stages in the development of mixed stands has not been fully defined and different researchers provide various conflicting terms (Danilov et al., 2018; Gromtsev, 1988, 1990, 2000, 2002; Isachenko, 1994; Rautiainen et al., 2016; Yaroshenko et al., 2001).

Our work is dedicated to the landscape ecology of the Leningrad region and the forecasted distribution dynamics of mixed stands. By landscape ecology we understand the science that studies the interconnections between the spatial structure and ecological processes. Here, the causes and consequences of spatial heterogeneity and vegetation, including landscape composition (type and quantity) and landscape configuration (shape, connectivity, and spatial location), are examined at different scales (Farina, 1998; Lindenmayer, 2002; Turner, 2005).

The study of the spatial structure and fragmentation of stands is necessary for landscape planning at the regional level for sustainable forest management. Furthermore, it is necessary to forecast changes under the influence of felling and restoration of forest cover in the context of climate changes. Previous studies demonstrate that in the boreal zone of the European part of Russia mixed pine and spruce stands have higher productivity comparing to single-dominant coniferous stands (Danilov et al., 2018; Tretiakov, 2007; Yakovlev and Danilov, 2019). Therefore, the aim of our study was to assess the landscape relations of the regional distribution of stands with different pine and spruce ratios in the Leningrad region.

Material and methods

Research object

The Leningrad region is located in the north-west of the Russian Federation. In the north, the region borders the Republic of Karelia, in the east – the Vologda region, in the south – the Novgorod and Pskov regions, and in the west – Finland and Estonia (Administrativno-territorial'noe..., 1997).

The entire territory of the region belongs to the boreal (taiga) zone of Eurasia. According to forest vegetation zoning, it belongs to the Baltic-Belozersky taiga district[1]. The Leningrad region is part of two physiographic countries: Fennoscandia (the Baltic Shield country) and the Russian (East European) Platform Plain (Sostoyanie okruzhayuschei..., 2018).

The climate of the region is continental. Maritime air masses cause relatively mild winters with frequent thaws and moderately warm, sometimes cool summers. The average annual air temperature decreases from west to north-east of the region from +4.5 °C to +2.0 °C. The duration of the period with an average daily air temperature above 5 °C is about 160 days in the east of the region and 170 days in the south-west. The sum of average daily temperatures on days with temperatures above +10 °C is 1600–1800 °C. The entire territory of the Leningrad region is in a zone of excessive moisture. Relative air humidity is always high (from 60% in summer to 85% in winter). Annual precipitation is 600–700 mm.

The forest-covered area of the Leningrad region is 4805.5 thousand ha, or about 60% of the total area of the region[2]. The dominant coniferous species – Scots pine *Pinus sylvestris* L. (32%) and Norway spruce *Picea abies* (L.) H. Karst. (28%) – occupy up to 60% of the forest fund territory. Among deciduous species, a significant share of the area belongs to silver birch Betula pendula L. (31%) and aspen Populus tremula L. (7%). About 75% of the forest fund area belongs to four forest types: Lingonberry, Bilberry, Wood Sorrel, and Sphagnum, as well as their transitional subtypes (Fedorchuk et al., 2005). In the region, as a result of anthropogenic activity over the past 300 years, large tracts of old-growth and indigenous spruce and pine forests have practically not survived. Mature coniferous forests of spruce and pine occupy 812 thousand ha, mature deciduous forests of birch, aspen, and alder – 833 thousand ha of the forest-covered area of the region[2]. The area of wetlands included in the forest fund is 714 thousand ha.

This study examines two landscape districts located on the Russian Plain and having a high percentage of forest cover: the Luga-Volkhov district (forest-covered area is about 60%) and the Valdai-

[1] Order No. 367 of August 18, 2014 "On Approval of the List of Forest Vegetation Zones of the Russian Federation and the List of Forest Districts of the Russian Federation" (as amended on October 18, 2018).

[2] Forest Plan of the Leningrad Region. Web page. URL: https://kpr.lenobl.ru/ru/deiatelnost/lesopolzovanie/lesnoj-plan-leningradskoj-oblasti/ (accessed: 27.12.2018).



Fig. 1. Location of the study sites: 1 - Valdai-Tikhvin landscape district; 2 - Luzhsko-Volkhovsky landscape district.

Tikhvin district (80%) (Danilov and Yakovlev, 2020; Sostoyanie okruzhayuschei..., 2018) (Fig. 1). In total, these districts occupy more than 70% of the area of the Leningrad region.

The Luga-Volkhov district is a vast, highly wetlands lowland plain. Its foundation is mainly composed of the Lower Paleozoic rocks: the Ordovician and Devonian glaciolacustrine sands overlain by boulder loams, varved clays. The foundation of the Izhora Plateau stands out, as it is uplifted and composed of limestones and dolomites covered by moraine (Isachenko, 1994). The climate is continental. The average temperature in January is −8.5 °C, in July – +16.7 °C. The frost-free period lasts 120 days a year. The predominant terrain type is abrasion and accumulatively terraced glaciolacustrine plains. The area of the district is 31.1 thousand km² (Mashovets, 1967). The 13 landscapes distinguished within the Luga-Volkhov district can be grouped as follows (Danilov and Yakovlev, 2021; Isachenko et al., 1965) (Fig. 2):

1) elevated plateau on carbonate rocks (Izhora landscape);
2) flat moraine landscapes (Luga-Oredezh, Pashsk-Syas, Putilovsk, Samro-Plyussa, Vishersk);
3) glacio-lacustrine clay landscape (Tosno-Volkhov);
4) glacio-lacustrine sandy landscapes (Luga, Narva-Luga, Tikhvin);
5) kame landscapes (Luga, Mginsky);
6) lowland plain on carbonate rocks (Upper Luga landscape).

Valdai-Tikhvin district is mainly situated on a raised bedrock of carbonate limestones and dolomites. The position of the district in the region, combined with a higher hypsometric level compared to other landscape districts, determines the continentality and severity of the climate (Isachenko, 1994). The average temperature in January is −10.7 °C, in July – 16.2 °C. The frost-free period lasts 107 days a year. The annual precipitation is 800 mm.

The following relief types prevail: hilly-basin and hilly moraine; somewhere are found abrasion and accumulatively terraced glaciolacustrine plains, swamp plains are common in depressions. The area of the district is 22.6 thousand km² (Mashovets et al., 1967). Within the Valdai-Tikhvin district, three groups of landscapes are represented (Isachenko et al., 1965) (Fig. 3):

1)hilly moraine landscapes (Tikhvin ridge, Veps, Svir-Oyat, Olonets, Middle Oyat, Kapshinsky);
2) flat moraine landscapes (Svir-Olonets, Upper Svir, Shoksha);
3) glacio-lacustrine sandy landscapes (Lower Svir, Suda-Chagoda).

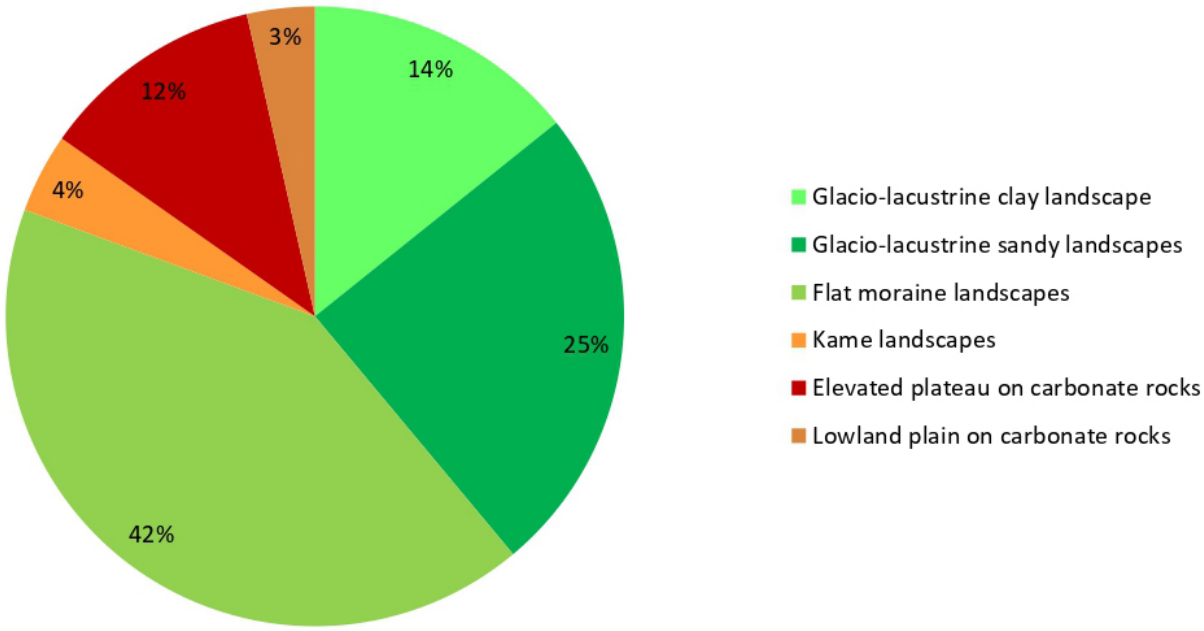


Fig. 2. Percentage distribution of area by groups landscape types of the Luzhsko-Volkhovsky District.

A typical feature of hilly moraine landscapes are frequent cenotes (sinkholes) and lakes. The landscape is dominated by the following soils: medium to heavy podzolized medium loamy soils, swamp, and peat soils. The main parent rocks are sandy loams, sands, boulder loams, and peat. The main soil types are: podzolic sandy loam soils with a contact-podzolic loamy soil horizon, medium and heavy podzolic sandy loam soils on boulder, peaty-podzolic-gley sandy loam soils, cryptopodzolic sandy soils. In the landscape, there is an active soil erosion. Soils are dry on the slopes, whereas in the hollows and basins between the hills swampy soils are common. Swamps are upland and small lowland by origin. The landscape is characterized by a developed river network with pronounced drainage, gradually weakening from the slopes to the hollows. It should also be noted that lake basins are present in the hilly moraine relief. Humidity changes from insufficient (atmospheric) at the peaks to permanently excessive (groundwater and groundwater-pressure). On hilltops and in lowlands, pine dendrocenoses predominate, while on slopes – spruce forests, due to the optimal humidity in these areas (Blagovidov, 1946; Chertov, 1981; Isachenko, 1994; Pestryakov, 1973; Yakovlev, 2024).

Flat moraine landscapes typically have a flat undulated surface made of moraine with different contents of boulders. Dual-layer sediments are found in some places, the diffused moraine is covered in the upper part of the soil horizon with a thin (up to 50 cm) layer of sandy loam or sand. The following soils prevail in the landscapes: medium and heavily podzolic sandy loam and loamy soils, peaty-swamp soils are also common. The main parent rocks are: sandy loam, sands, loams, boulder loams, and peat. The region is characterized by high swampiness (up to 60% of the territory) with a poorly developed drainage system. Only sections along rivers and on hilltops are well drained. Watersheds are largely occupied by swamps in the study area. Due to the predominance of loamy soils and the spread of dual-layer sediments, spruce stands are most common in flat moraine landscapes (Blagovidov, 1946; Chertov, 1981; Isachenko, 1994; Pestryakov, 1973).

Glaciolacustrine sandy landscapes have a typically undulated hilly relief. The widespread swampiness is caused by the close bedding of the water-resistant horizon of moraine or varved clays. Closed hollows and basins are often filled with peatbogs and lakes. The following soils prevail in the landscapes: slightly and medium podzolic sandy and loamy soils, swamp soils in the lowlands. The main parent rocks are: sands and sandy loam, boulder loam, peat. Good drainage is observed exclusively near riverine areas. Large upland moors are mostly located in river watersheds. On sandy and sandy loam soils, pine dendrocenoses predominate, while on loamy soils – spruce dendrocenoses (Blagovidov, 1946; Chertov, 1981; Isachenko, 1994; Pestryakov, 1973; Yakovlev and Danilov, 2018).

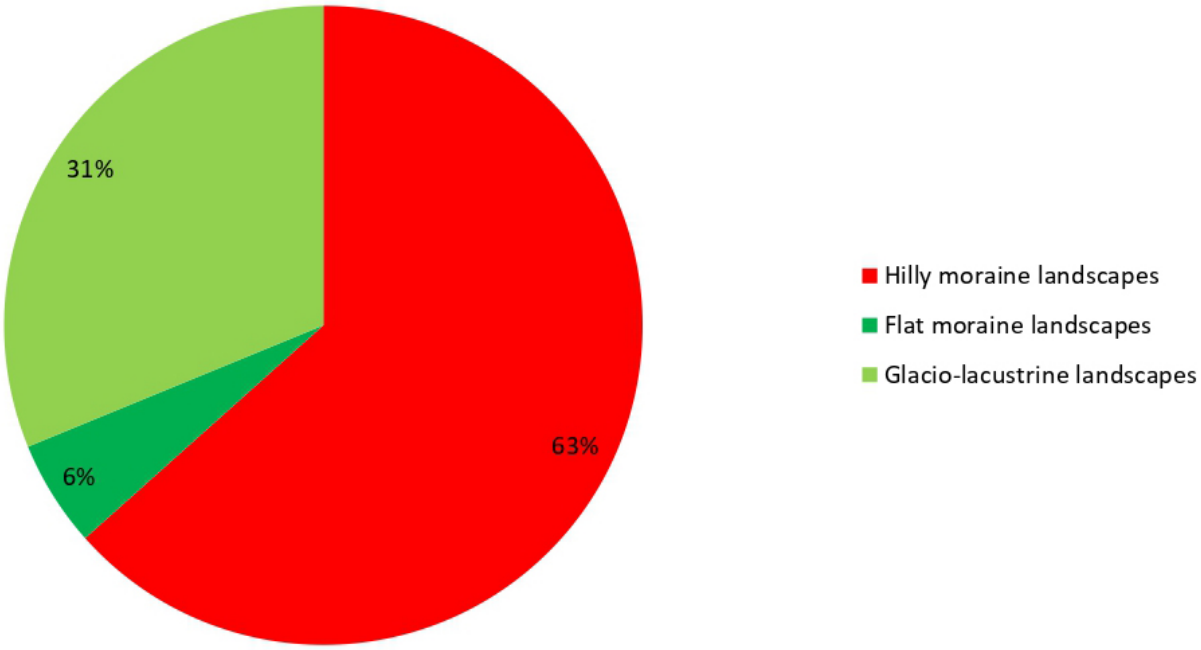


Fig. 3. Percentage distribution of area by groups landscape types of the Valdai-Tikhvin District.

Glaciolacustrine clay landscapes have a typical plain, flat relief. Weak surface flow and poor permeability of clay rocks leads to a large spread of swamps (predominantly upland) and swampy podzolic soils. Up to 60% of the territory in these landscapes are excessively humid. The following soil types are dominant: podzolic-gley and podzolic-gleylike heavily loam soils and clay soils, swamp soils. The main parent rocks are: varved clays, moraine and boulder loam and clay. In the drained areas, spruce forests grow, often with an admixture of broad-leaf species. In heavily moist and swampy areas, pine forests prevail (Blagovidov, 1946; Chertov, 1981; Isachenko, 1994; Pestryakov, 1973).

Kame landscapes combine groups of sand hills (kames) and flat marshy glaciolacustrine plains. There are relatively few swamps (mostly with small basins, around lakes). Upland moors are dominating, lowland and transitional-type moors are rare. The following soils prevail: slightly and medium podzolic sandy, sandy loam and loamy soils, peaty-podzolic sandy and swamp soils. Due to the release of Devonian carbonate rocks, the parent rocks are also carbonate. The main parent rocks are: dual-layer sediments (fine-grained dusty sands, sands, moraine loams bedding under the reddish loam). The prevalence of sandy and sandy loam soils determines the spread of pine stands (Blagovidov, 1946; Chertov, 1981; Isachenko, 1994; Pestryakov, 1973).

The elevated plateau on the carbonate rocks of the Izhora landscape is characterized by a slightly undulated relief, scattered karst sinkholes, depressions, and moraine hill groups. This area is well drained due to the fracturing of the forming limestone. Its swampiness is low, the swamps are relatively small in size. The following soils prevail: humus-carbonate, slightly podzolic loamy, sandy loam soils underlain by carbonate clay. The main parent rocks are: highly carbonate moraine loams and clays. In this landscape, spruce forests with an admixture of broad-leaf species prevail. Due to the strong economic exploitation, small-leaved stands - birch forests and aspen forests are widespread (Blagovidov, 1946; Chertov, 1981; Isachenko, 1994; Pestryakov, 1973).

The lowland plain on the carbonate rocks of the Upper Luga landscape has a characteristic plain undulated relief, which is dissected by wide river valleys. Its swampiness is moderate (20%). Its distinctive feature is the close bedding of Devonian limestones, covered with carbonate loam. The following soils prevail: slightly podzolic loamy, humus-carbonate soils are found in some locations. The main parent rock is morain medium, sandy, and light loam. Soil richness dictates spruce forest dominance with the presence of broad-leaf species, mainly mixed with spruce-birch stands (Blagovidov, 1946; Chertov, 1981; Isachenko, 1994; Pestryakov, 1973).

Experimental design and data analysis

Our study of mixed coniferous stands combined the ecosystem, succession, and landscape approaches. The object of the study was forests defined within administrative and landscape boundaries. We used a quantitative assessment of the composition of the stands, reflecting the dynamics and condition of the forests. During the analysis of natural objects of various sizes and complexity, the hierarchy of spatial levels is taken into account.

The study of the landscape distribution of mixed pine and spruce stands used the following sources: a landscape map of the region (Mashovets et al., 1967), the state forest inventory materials on the Leningrad Oblast[3], and other cartographic data on the Leningrad Oblast and district forestries within the Region's landscapes[4].

Dendrocenoses with the dominant species share up to 90% in the composition were classified as pure forest stands. Mixed coniferous stands are understood as tree communities in which the share of coniferous species is at least 40% of the total composition (Danilov and Yakovlev, 2020). Forest types were determined using the edafic cenotic scale of V.N. Sukachev (Sukachev et al., 1957).

According to the methods used in the state forest inventory[5], four age categories of trees were distinguished:

– young-growth aged up to 20 years;
– mid-aged from 21 to 40 years;
– maturing aged between 41 and 60 years;
– mature and over-mature older than 81 years.

The analysis of the spread of stands was done by summing the area of each multidominant tree community.

To qualitatively assess distribution of mixed stands on the objects of study, three biodiversity indices were calculated: the indices of Shannon, Simpson, and Pielou. The indices are calculated to interpret the results and to make a conclusion about the existing landscape diversity features in the considered area. For assessing landscape diversity, administrative and landscape territorial units can be used (Viktorov, 1986; Liebhold and Gurevitch, 2002; Perry et al., 2002).

The Shannon index was calculated as:

$$H = -\sum p_i \log 2p_i,$$

where H is the diversity in bits, and p_i is the specific abundance of the community.

This index has no upper limit. The Shannon index compares two components: occurrence and evenness. An increase in the index indicates an increase in the number of contours and their distribution. To determine biodiversity in landscapes, the index was calculated as follows:

$$H = -\sum_{i=1}^{n} \frac{S_i}{S} \log \frac{S_i}{S},$$

where S_i is the area of the ith landscape type, S is the total area of the territory, n is the number of landscape types in the given territory.

The Simpson diversity index was also calculated using the following formula:

$$C = \sum \left({}^{n_i}/_{N}\right),$$

rwhere n_i is the significance rating of each species, N is the sum of the significance ratings.

The Simpson index shows the dominance of certain types of community. Index values range from 0 to 1. Index value of 0.1 already indicates a high level of dominance. This index increases with the increase of one or more species dominance (Danilov et al., 2020).

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[3] Forest Plan of the Leningrad Region. Web page. URL: https://kpr.lenobl.ru/ru/deiatelnost/lesopolzovanie/lesnoj-plan-leningradskoj-oblasti/ (accessed: 27.12.2018).

[4] Forest Management Regulations of the Leningrad Region. Web page. URL: https://kpr.lenobl.ru/ru/deiatelnost/lesopolzovanie/informaciya-o-lesah-glavnaja/proekty-lesohozyajstvennyh-reglamentov/ (accessed: 27.12.2018).

[5] Forest Plan of the Leningrad Region. Web page. URL: https://kpr.lenobl.ru/ru/deiatelnost/lesopolzovanie/lesnoj-plan-leningradskoj-oblasti/ (accessed: 27.12.2018).

The Pielou index as a measure of the uniformity of the species spectrum was calculated as follows:

$$E_H = {}^{H}/_{H_{max}},$$

where H is the actual value of the Shannon index; H_{max} is the maximum value of the Shannon index for a given number of senior taxa:

$$H_{max} = \log N,$$

where N is the number of species in biota.

The Pielou index is a modification of the Shannon index, obtained by excluding the species richness parameter. The Pielou index value ranges from 0 to 1. A dominance can be considered high when the index value is at least 0.9 (Megarran ,1992).

Spearman's rank correlation coefficient is the most suitable for assessing the influence of specific landscape conditions on the spatial distribution of stands. The Spearman's rank correlation coefficient is calculated as follows (Agresti, 2007; Danilov et. al., 2020; Gardener, 2017):

$$\mathrm{p} = 1 - \frac{\sum 6\mathrm{d}^2 + \mathrm{A} + \mathrm{B}}{\mathrm{n}^3 - 3},$$

$$\text{где } \mathrm{A} = \frac{1}{12}\sum(A_j^3 - A_j)$$

$$B = \frac{1}{12}\sum(B_k^3 - B_k)$$

jj – sequential numbers of correlated variables for the attribute x; A_j is the number of identical ranks in the jth correlated variables for x; *k* – sequential numbers of correlated variables for the attribute y; B_k is the number of identical ranks in the kth correlated variables for y.

The changing process of mixed stands area can be considered to be Markov process. The dependence of the diversity dynamics of the vegetation in boreal landscapes on the frequency of felling and fires was studied using an unsteady Markov model with variable probabilities using generalized data. The following formula was used for model calculation (Viktorov, 1986; Neshatayev, 2002):

$$S_{i,j+20} = S_{i,j} \times (1 - \sum P_{i,m} - \sum K_f \times P_{i,n}) + \sum S_k \times P_{k,i} \ ,$$

rwhere $S_{i,j+20}, S_{i,j}$ is the fraction of the area covered by the i-th state at steps j and j+10, K_f is the felling frequency coefficient; $P_{i,m}$ is the probability of tree stand destruction, as a result of which the i-th state is replaced by the m-th state at K_f = 1, $P_{i,n}$ is the probability of the i-th state to be replaced by the n-th state during succession, S_k is the area of the k-th state , $P_{k,i}$ is the probability of the kth state to be replaced by the i-th state.

Results and discussion

According to forest inventory data[6], mixed coniferous stands with a predominance of pine and spruce cover up to a quarter of the forest fund of the North-West and about one half of the forested area of the Leningrad Oblast. It should be noted that distinguishing forest dendrocenoses solely by the dominant species is incorrect due to the different development patterns of mixed stands of different composition and leads to the wrong assignment of silvicultural measures. The growth pattern of mixed stands strongly depends on the composition and species ratio; however, in different landscape districts and landscape types, these features manifest differently. It is important to consider that the concept of "geographic landscape" is not limited to relief, but also includes soil-hydrological and climatic conditions. Thus, the Luga-Volkhov district is characterized by a longer growing season and a less continental climate. Accordingly, the Valdai-Tikhvin district shows lower variability of coniferous stands by composition and

[6] Forest Plan of the Leningrad Region. Web page. URL: https://kpr.lenobl.ru/ru/deiatelnost/lesopolzovanie/lesnoj-plan-leningradskoj-oblasti/ (accessed: 27.12.2018).

lower average mensuration characteristics of stands in mixed dendrocenoses (Figs. 4, 5). The formation of stands of different composition is largely determined by abiotic environmental factors; however, it can also critically depend on past economic activities in these territories (Danilov and Yakovlev, 2020).

An analysis of mensuration indices of coniferous stands in the green-moss forest type group revealed significant differences depending on the share of species in the composition. In the Valdai-Tikhvin landscape district, dendrocenoses with a predominance of pine have lower stocks and average heights than stands where spruce predominates; however, the average diameter is larger in pine stands. In spruce-pine dendrocenoses, there is a tendency for average diameters and tree heights to increase with an increase in the share of spruce in the stand composition.

In the Luga-Volkhov landscape district, the stand stock increases with an increase in the share of pine in the composition. It is important to note that in mixed stands with pine participation, stand productivity increases when the share of pine in the composition is from 6 units. In mixed spruce-pine stands, with spruce present in the composition at 5 and 8 units, the highest stock of stemwood is observed. In dendrocenoses with a predominance of spruce, average diameters and heights are lower than in dendrocenoses with a predominance of pine. In spruce and pine stands, with an increase in the share of coniferous species in the composition, their mensuration characteristics also increase.

Differences in the formation of the stand stock depending on the share of spruce and pine in the considered landscape districts demonstrate the role of these geographical units in the formation of coniferous tree communities in the analyzed region.

Valdai-Tikhvin district is characterized by larger forest cover and a high number of intact forest lands. Due to strong anthropogenic exploitation, the Luga-Volkhov district has virtually no intact forests, and its forest cover is significantly lower. Here, mixed dendrocenoses with a predominance of coniferous species are more widespread (Fig. 6). In the Luga-Volkhov district, due to strong anthropogenic development, intact forests are practically absent, and forest cover is significantly lower. Here, small-leaved species dominate (Fig. 7).

The main difference between the districts lies in the area occupied by pure pine stands. Due to the presence of kame landscapes in the Luga-Volkhov landscape district, a larger area of conditionally pure pine stands is observed here than in the Valdai-Tikhvin landscape district. Due to strong anthropogenic impact, a decrease in spruce-pine and pine-spruce dendrocenoses is observed in this district.

Stands with a predominance of coniferous species are most common in the bilberry forest type (Figs. 8, 9). Since this forest type is the most common in the territory of the considered landscape districts and the Leningrad Oblast as a whole, its conditions are optimal for the growth of mixed coniferous forests; however, in the considered landscape districts, a different structure of forest types is observed (Fedorchuk et al., 2005).

Waterlogged forest types (long-moss, carex-sphagnum, grass-sphagnum, and sphagnum) are more widespread in the Valdai-Tikhvin district than in the Luga-Volkhov district. This is associated with large areas of clay parent rocks, the predominance of hilly moraine landforms, in which swamps occupy depressions between the hills, and with hydrological characteristics (Danilov and Yakovlev, 2020).

Rank analysis using the Spearman criterion was used to characterize the influence of specific landscape features on the distribution of stands by area. This approach has previously proven itself in the studies of pine and spruce distribution in various landscapes of the region (Shutov, 1994). The obtained values show that landscape features have the greatest influence on the distribution of pure coniferous and pine-broad-leaf stands (Fig. 10). Landscape characteristics also significantly influence the distribution of pure pine stands, since they grow in extreme conditions (on very dry and poor or swampy soils). The influence of landscape on the distribution of pure spruce, pine-spruce, and broad-leaf stands is insignificant. The spread of pure spruce and broad-leaf stands is primarily associated with human economic activity. Pine-spruce stands, as a rule, are confined to light sandy loam soils at the boundaries between different landscape locations (Belyaeva et al., 2020).

The minimal influence of landscape conditions is observed in spruce-pine stands. This is one of the most common types of stands in the region, capable of growing in all habitats with moderate moisture and relatively rich sandy loam soils (Danilov and Yakovlev, 2021).

The negative index value for mixed coniferous and spruce-broad-leaf stands is associated with a strong decrease in their area resulting from felling and substitution with pure spruce species or recurrence of small-leaved tree species.

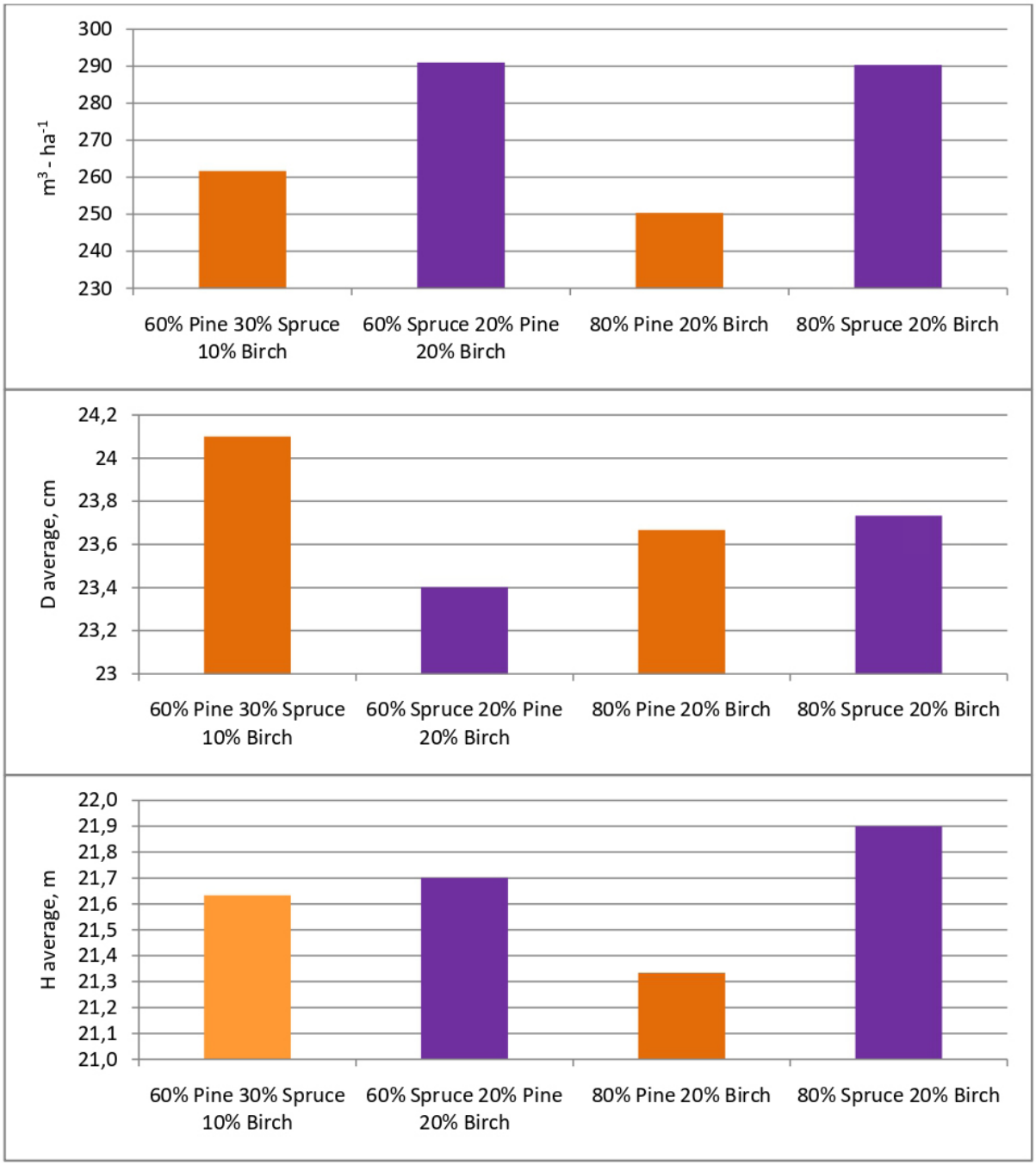


Fig. 4. Average taxation indices of mixed stands of pine and spruce in Valdai-Tikhvin District.

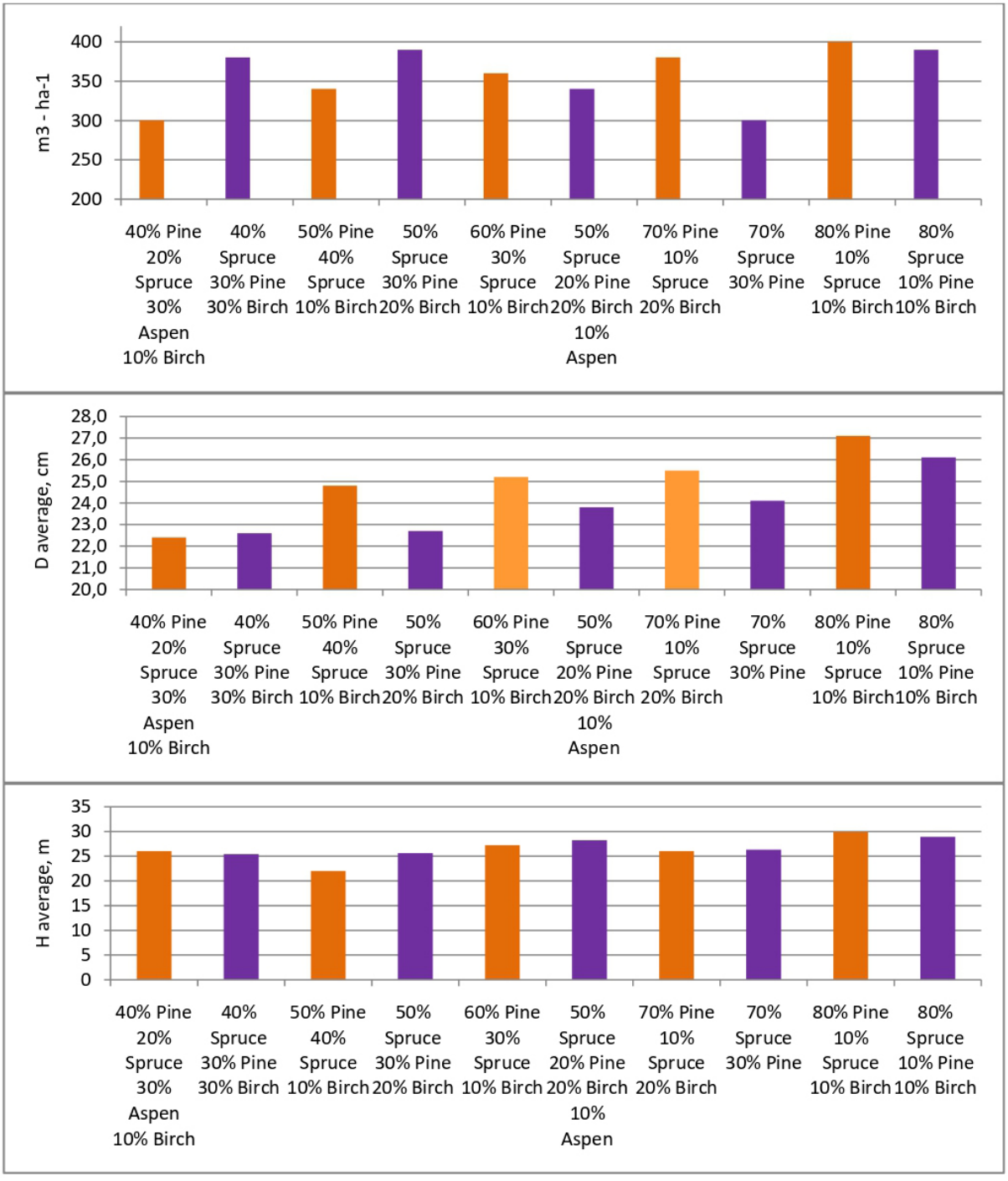


Fig. 5. Average taxation indices of mixed stands of pine and spruce in the Luzhsko-Volkhovsky District.

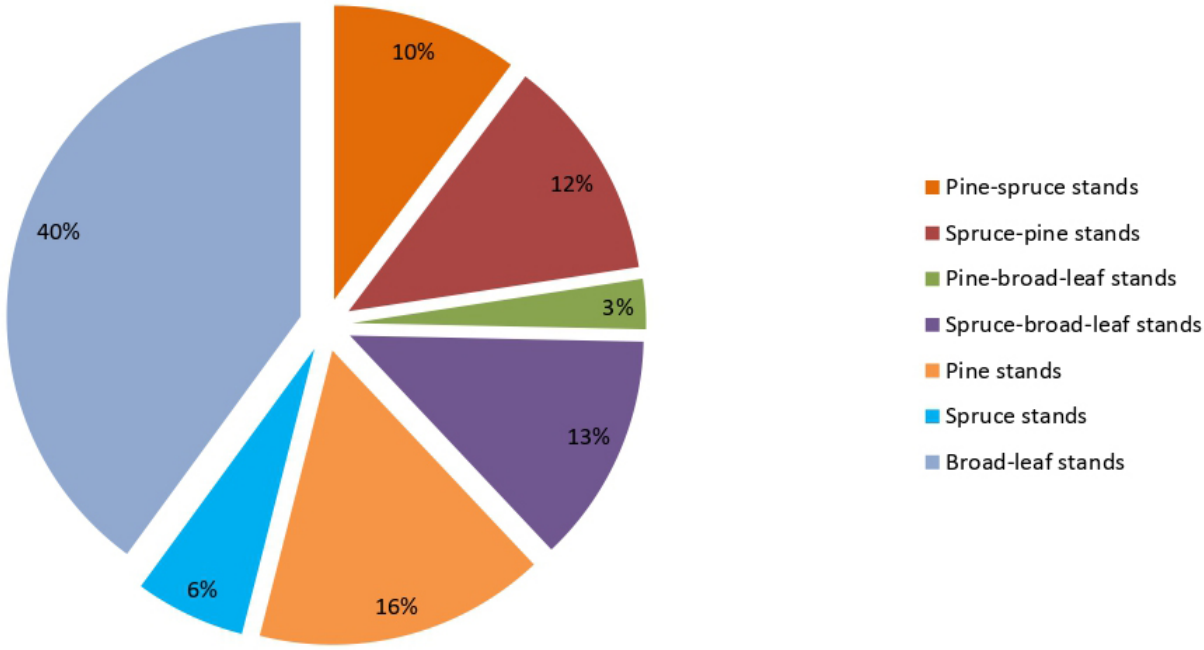


Fig. 6. Percentage distribution of area by stand types in Valdai-Tikhvin District.

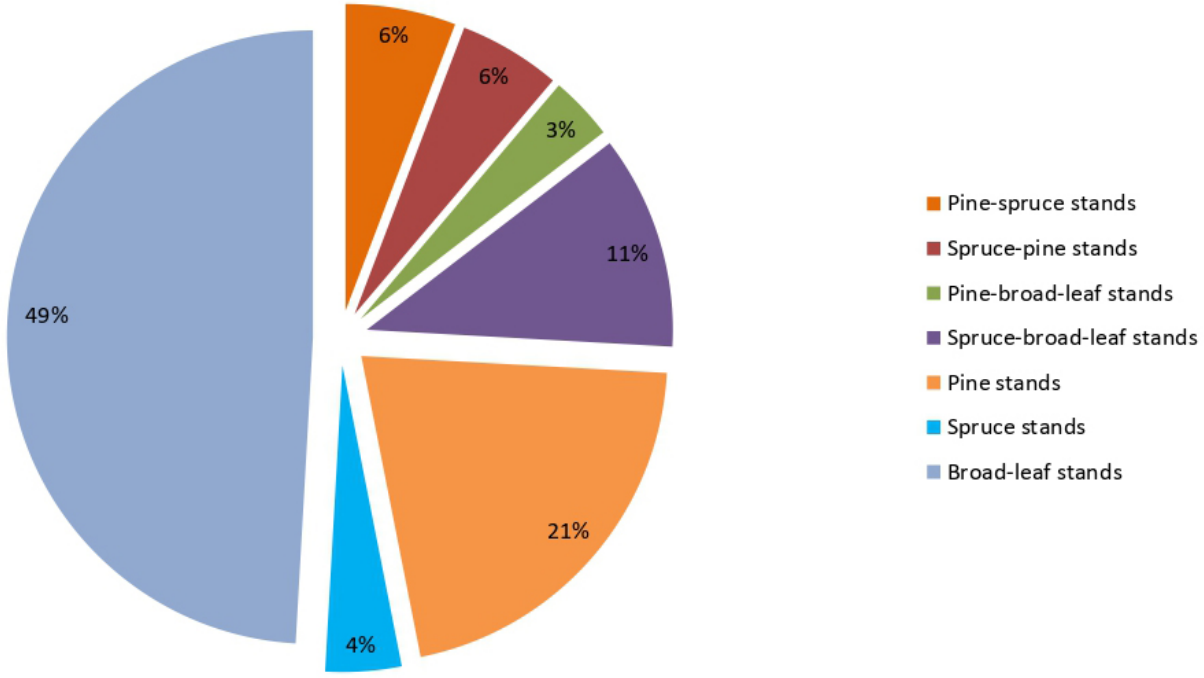


Fig. 7. Percentage distribution of area by stand types in Luzhsko-Volkhovsky District.

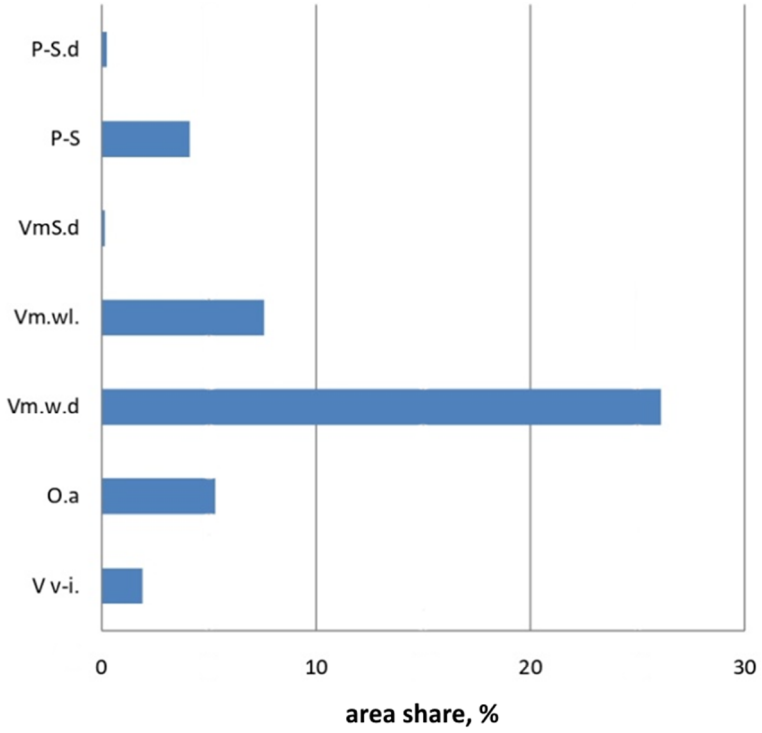


Fig. 8. Distribution of mixed coniferous stands by forest type in Val-Dai-Tikhvin District. P-S.d – Polytrichoso-Sphagnosa waterlogged and drained forest type, P-S – Polytrichoso-Sphagnosa forest type, VmS.d – Vacciniummyrtillus waterlogged and drained forest type, Vm.wl. – Vacciniummyrtillus waterlogged forest type, Vm.w.d – Vacciniummyrtillus well-drained forest type, O.a – Filipendulo-Herbosum forest type, V v-i – Vacciniumvitis-idaea forest type.

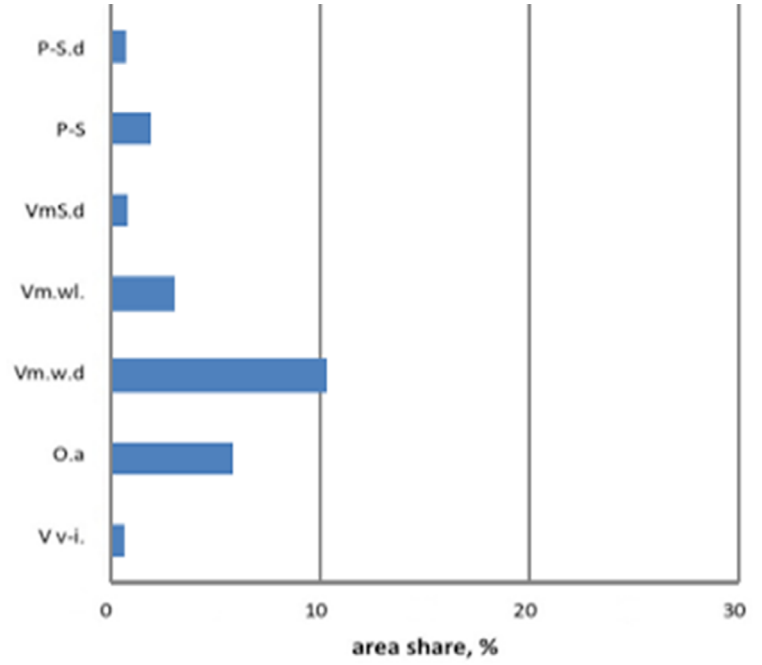


Fig. 9. Distribution of mixed coniferous stands by forest type in the Luzhsko-Volkhovsky District. Notations as in Fig. 8.

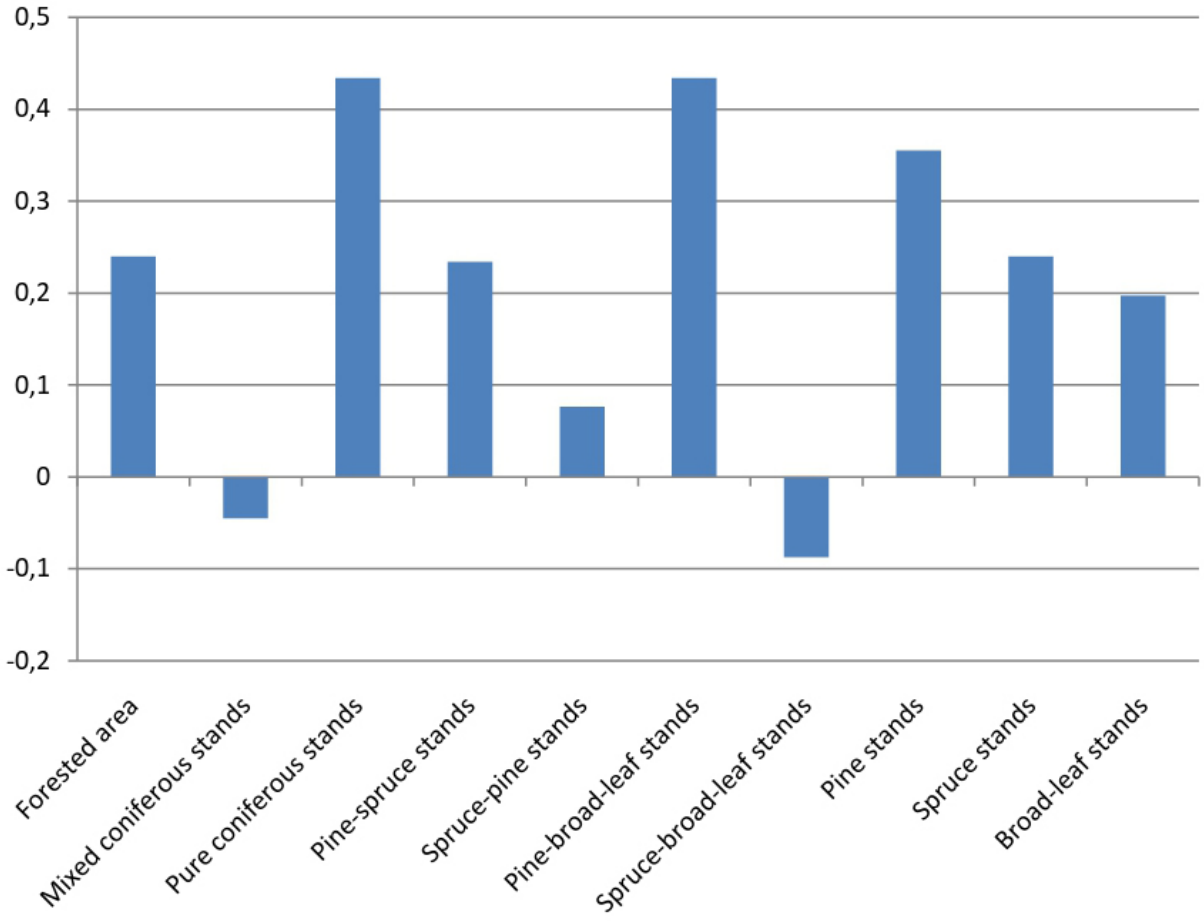


Fig. 10. Calculated values of Spearman's coefficient.

The total forested area of the region only weakly depends on landscape characteristics. Its size is more affected by anthropogenic impact in the form of felling and fires, while among natural factors, the greatest influence is exerted by soil and hydrological conditions.

To study the nature of the distribution of stands by area of landscape districts and to assess dominance, we used several biodiversity indices. The calculated values of the Shannon index showed that in both landscape districts the most evenly distributed stands are dominated by broad-leaf species (Fig. 11). However, the index value is lower in the Luga-Volkhov landscape district, which is the result of its high economic exploitation.

Mixed stands are most evenly distributed in the Valdai-Tikhvin landscape district; the same tendency is observed also in each individual type of stands, except for pine-broad-leaf. Apparently, this is explained by the lower exploitation of this district. Pure coniferous stands are most evenly distributed in the Luga-Volkhov district due to the wider spread of pure pine stands.

The Simpson Index shows the dominance of one type of stands over others. Its values are significantly higher for the Valdai-Tikhvin landscape district (Fig. 12), which is associated with its higher forest cover and lower anthropogenic impact. In all landscape districts, dominance of broad-leaf stands is observed as a result of human activity. A high index value is also observed for mixed stands in the Valdai-Tikhvin district. Among mixed stands, the maximum index value was obtained for spruce-pine stands, which indicates their wide distribution and greater plasticity to growing conditions.

The Pielou index, characterizing the evenness of stand groups over space, showed patterns similar to the distribution of the Shannon index (Fig. 13). It can be concluded that the most informative in this work are the Shannon and Simpson indices; therefore, below we analyze the data only using these two indices. Next, indicators are examined for each of the landscapes of the Luga-Volkhov and Valdai-Tikhvin districts separately.

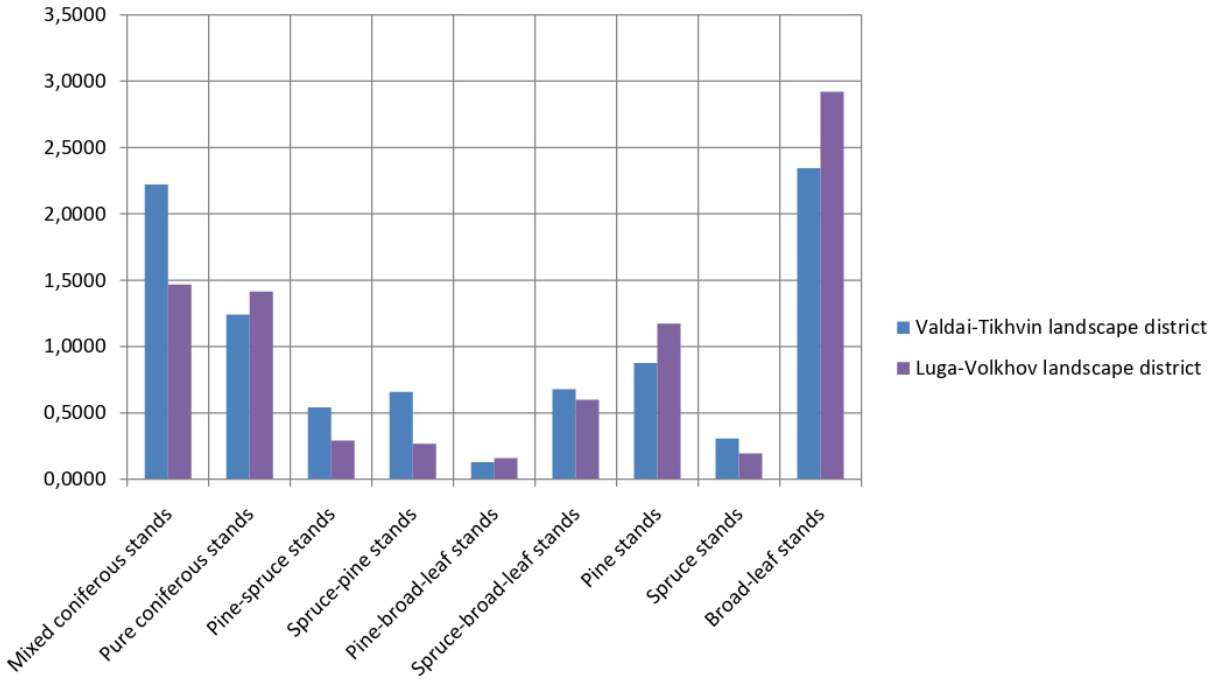


Fig. 11. Comparison of Shannon Index values for the two counties.

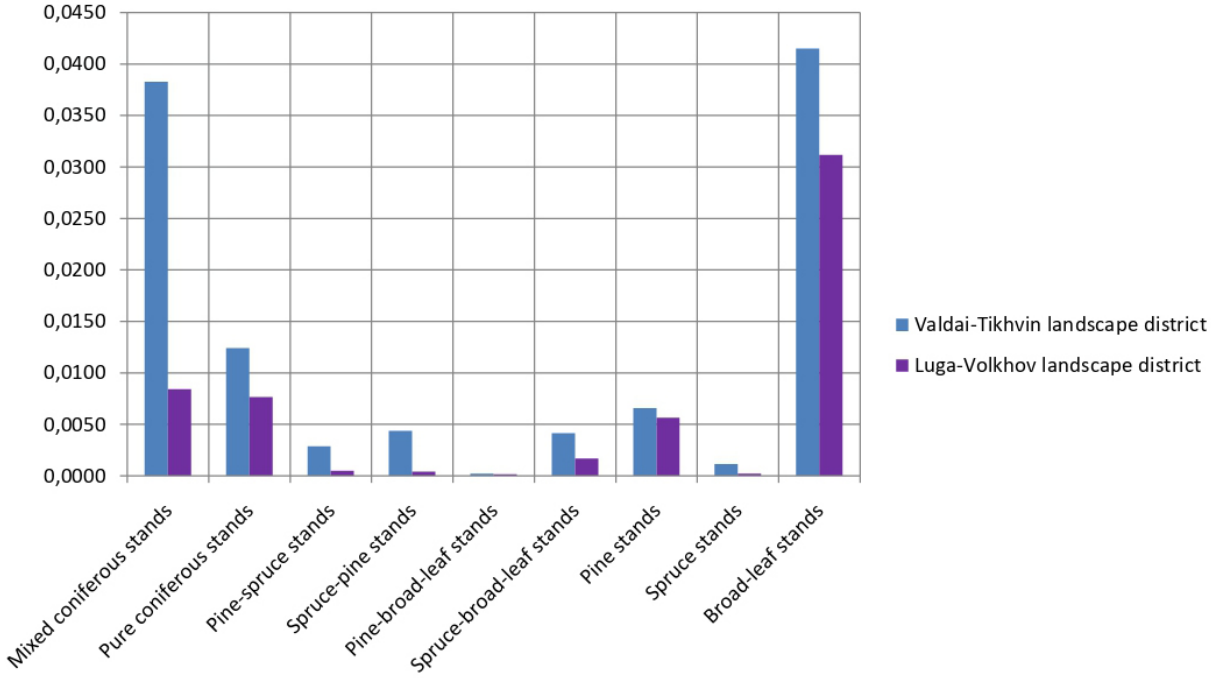


Fig. 12. Comparison of Simpson index values for the two counties.

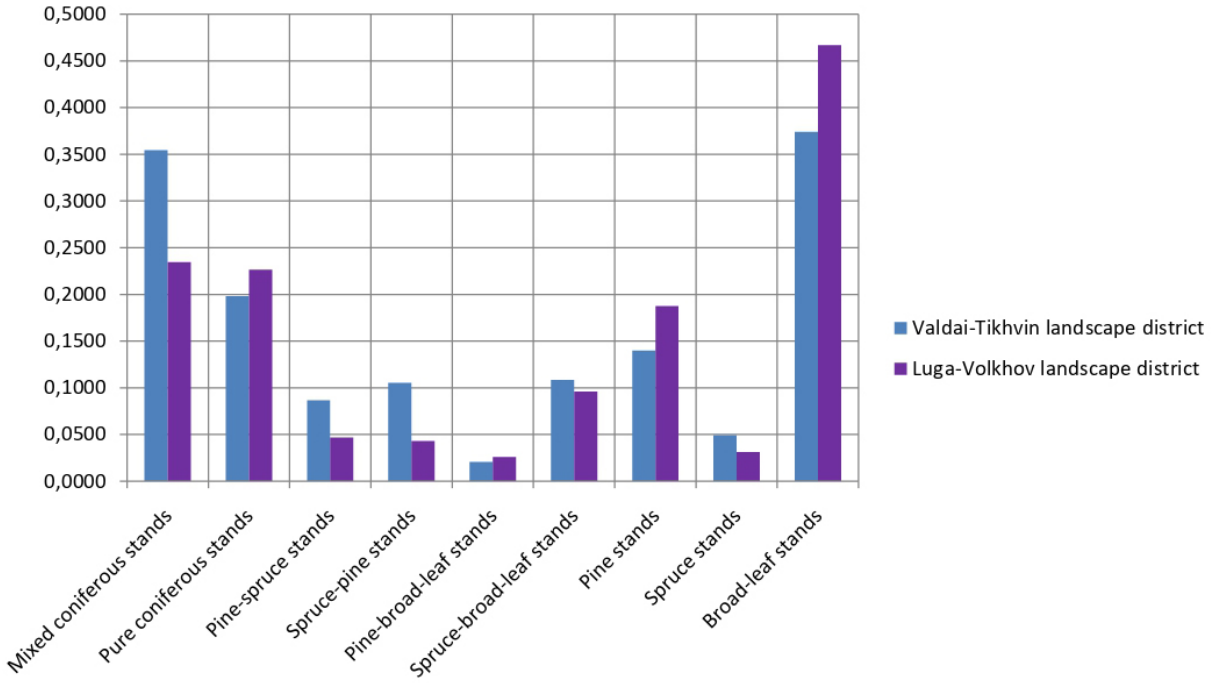


Fig. 13. Comparison of Pilu index values for the two counties.

In the Valdai-Tikhvin landscape district, the highest Shannon index value for broad-leaf stands is in the Suda-Chagoda landscape (Fig. 14). This indicates the most even distribution of these stands on the territory of the forestry and the high exploitation degree of its forests. Among coniferous stands, the highest index value is observed for pure pine stands in glaciolacustrine sandy landscapes. In the territory of the Svir-Oyat hilly moraine landscape, the most evenly distributed are spruce-broad-leaf, spruce-pine, and spruce-broad-leaf stands.

The distribution of Simpson indices for the landscapes of the Valdai-Tikhvin district showed strong dominance of broad-leaf stands (Fig. 15). Among coniferous stands, in glaciolacustrine sandy landscapes, pure pine stands dominate. In the territory of the Svir-Oyat hilly moraine landscape, spruce-pine stands dominate. The index value for the remaining types of stands is insignificant and does not allow us to speak of any dominance.

The observed distribution of stand types over the territory of the Valdai-Tikhvin landscape district is closely related to its landscape structure. Thus, among glaciolacustrine landscapes, landscapes of the sandy group prevail, which determines the widespread distribution in this territory of stands with a predominance of pine. In the territory of the Svir-Oyat hilly moraine landscape, dominance of stands with a predominance of spruce is observed.

In the Luga-Volkhov district, the Shannon index is maximum for broad-leaf dendrocenoses in all landscapes except the Mginsky kame landscape (Fig. 16), where the highest index value is observed in pure pine stands. Among coniferous stands, the maximum Shannon index is observed in all landscapes except the Izhora landscape. The latter is confined to the outcrop of carbonate rocks; in this regard, the highest index value here is observed for spruce-broad-leaf dendrocenoses.

The predominance of broad-leaf stands in all landscapes of the district, except the Mginsky landscape, is also confirmed by the high value of the Simpson index (Fig. 17). As in the case with the Shannon index, among coniferous stands, conditionally pure pine stands predominate in all landscapes except the Izhora landscape, while in the Izhora landscape – spruce-broad-leaf dendrocenoses. For the remaining dendrocenoses, the value of the Simpson index does not allow us to distinguish the dominance of stand types over one another.

The prevalence of sandy loam soils in glaciolacustrine sandy and kame landscapes, combined with the high swampiness of flat moraine and hilly moraine landscapes in both districts, determines the extensive occurrence of conditionally pure pine dendrocenoses. In turn, the large share of landscapes with loamy soils and high anthropogenic development causes the dominance of soft-leaved stands.

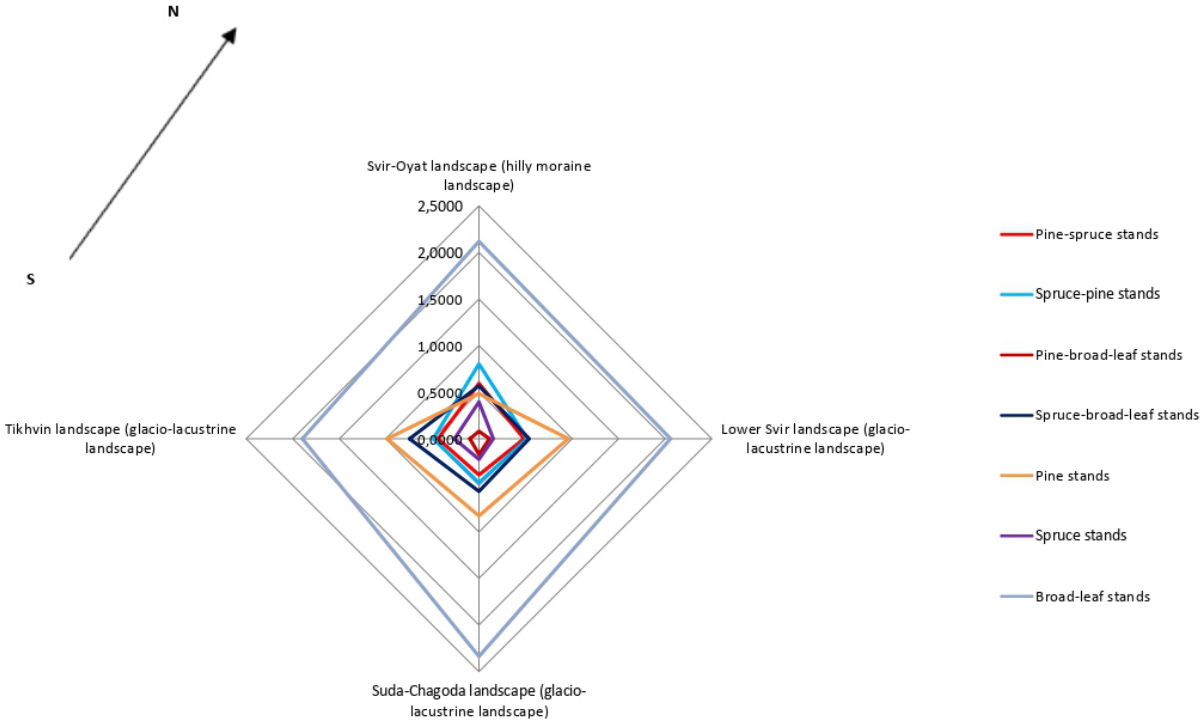


Fig. 14. Shannon index values for the Valdai-Tikhvin District forestries.

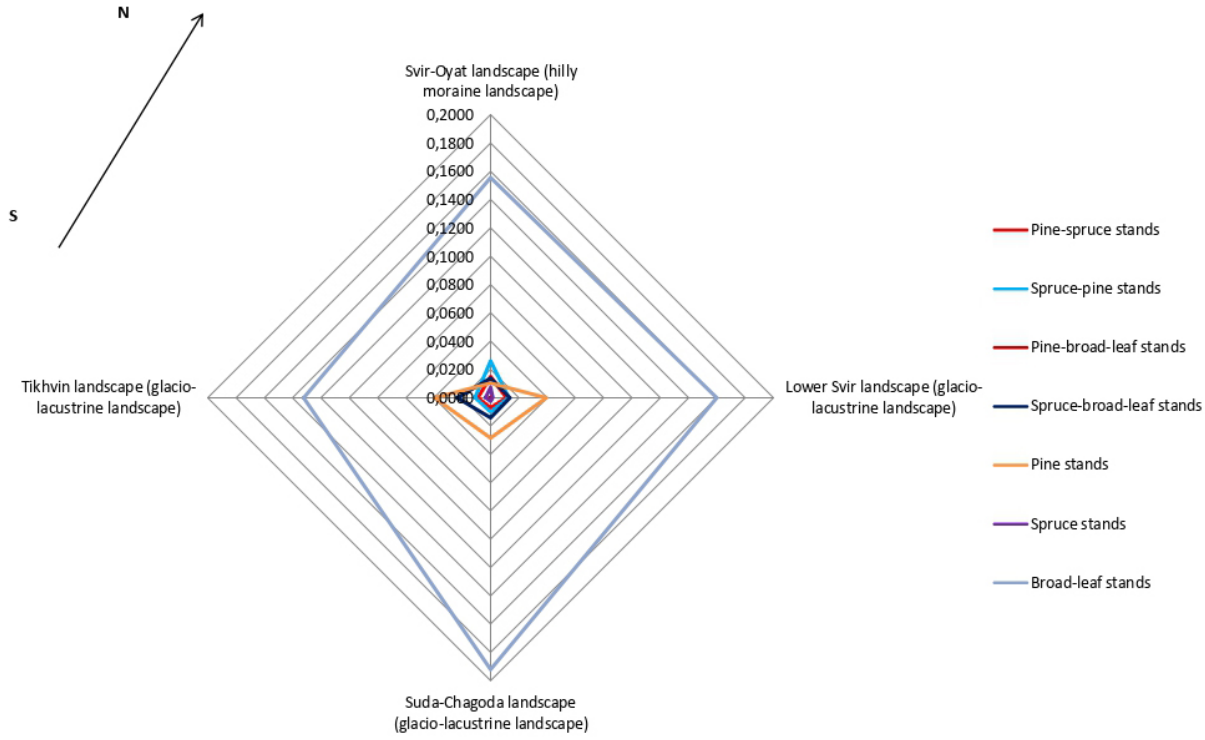


Fig. 15. Simpson index values for the Valdai-Tikhvin District forestries.

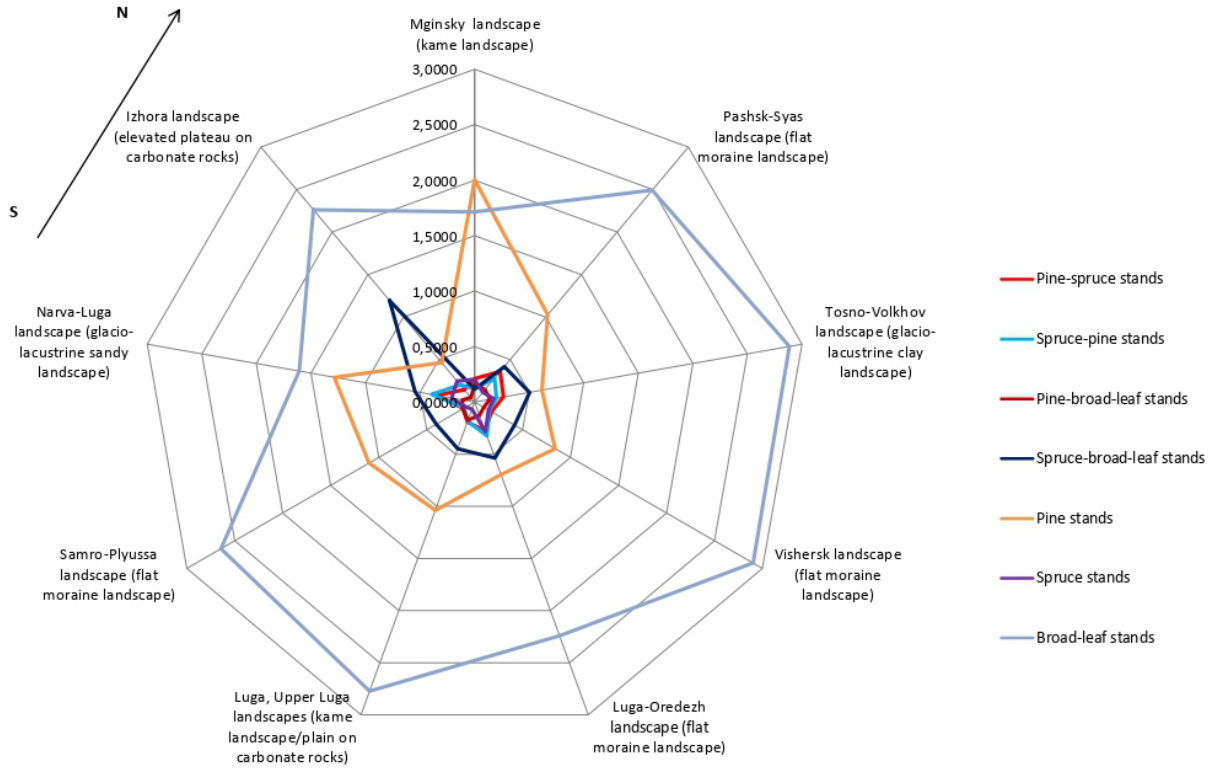


Fig. 16. Shannon index values for the forestries of the Luzhsko-Volkhovsky District.

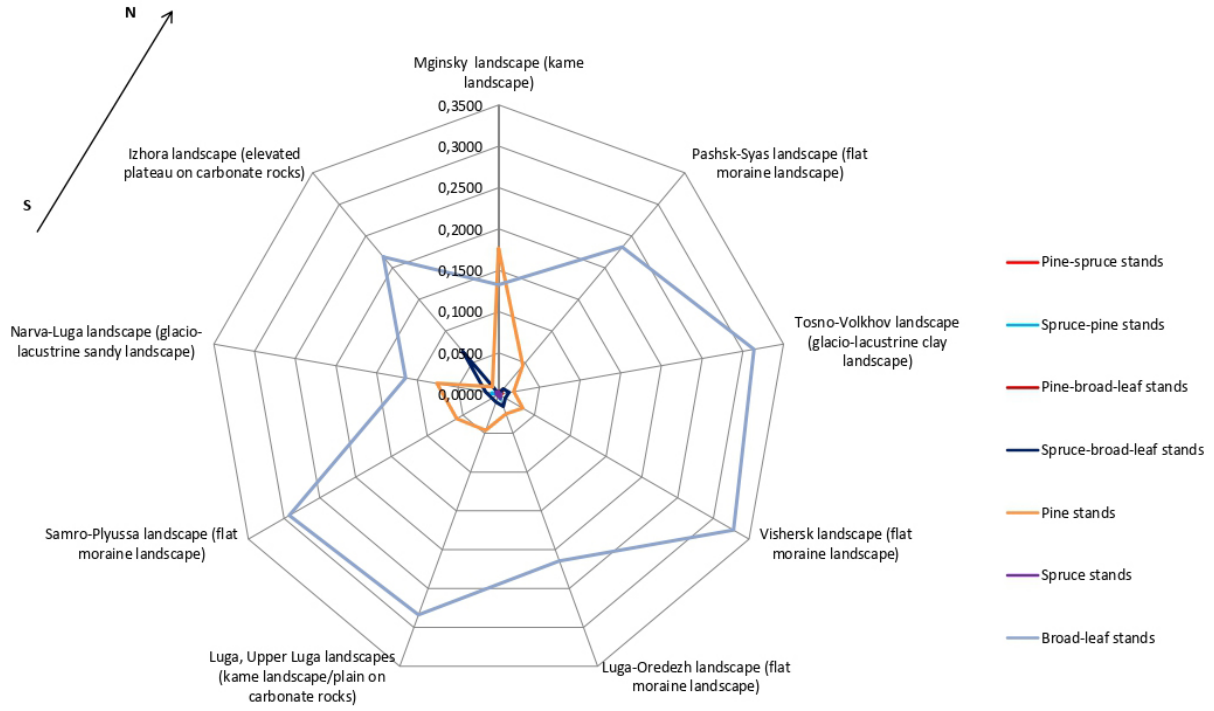


Fig. 17. Simpson index values for the forestries of the Luzhsko-Volkhovsky District.

Indigenous spruce stands, after clear-cutting, due to the lack of care for the composition of undergrowth and plantations, are replaced by deciduous stands (Danilov and Yakovlev, 2020).

Modeling of the dynamics of species composition changes in the Valdai-Tikhvin and Luga-Volkhov landscape districts using the Markov chains method (Figs. 18, 19), showed the probabilistic direction of succession processes in mixed coniferous stands. However, it should be noted that the following assumptions were made when constructing the forecast model:

– The total area of mixed pine and spruce stands was considered unchangeable;

– The transitions from mixed stands to pure or broad-leaf stands and vice versa were not taken into account;

– Markov chains were built for the stands of the green-moss forest type, since transitions between forest types are extremely rare.

In the Valdai-Tikhvin landscape district, at the present time, among mixed stands, the largest area is occupied by spruce-broad-leaf stands, and a slightly smaller area by spruce-pine stands. Spruce-broad-leaf stands prevail in up to 20 years old stands, while spruce-pine stands in mature and over-mature stands (Fig. 18). According to the forecast model, over time, the area of spruce-broad-leaf and spruce-pine stands will increase. There is also a tendency for the area of mature and over-mature stands to increase. In one hundred years, the maximum area will remain with spruce-broad-leaf stands, while the minimum area will be occupied by pine-broad-leaf stands.

In the Luga-Volkhov landscape district, the largest area among mixed stands also belongs to spruce-broad-leaf stands, while all others occupy significantly smaller areas. In forest stands up to 20 years old, spruce-broad-leaf stands prevail, whereas in all other age groups pine-spruce stands dominate (Fig. 19). In this landscape district, there is also a tendency for the area of mature and over-mature stands to increase over time, which in one hundred years will lead to their complete domination. In contrast to the Valdai-Tikhvin district, in the Luga-Volkhov district, the area of stands with the presence of pine in the composition will also increase. Thus, in one hundred years, the second place in terms of occupied area will belong to pine-spruce stands.

Conclusions

The conducted study showed that, depending on landscape conditions, mixed stands of spruce and pine of various composition are formed. The spatial distribution of mixed stands over landscape groups is most influenced by soil and hydrological conditions. In landscapes of a hilly and flat moraine group with richer loamy soils, the area of mixed stands is noticeably higher than in kame and glaciolacustrine sandy landscapes with sandy soils, where pure pine forests predominate.

In landscapes with the richest carbonate soils, broad-leaf stands dominate. Their general predominance is a response to intense anthropogenic impact, since after clear-cutting in areas rich in soil fertility, natural regeneration occurs mainly through small-leaved species.

Mixed stands with a predominance of pine and spruce are found in all landscape districts and areas. However, the ratio of pine-spruce, spruce-pine, pine and spruce stands with broad-leaf species, as well as conditionally pure spruce and pine stands, varies and is confined to the landscape conditions of the area and, as a consequence, of the district. The predominance of one or another mixed tree formation in landscape areas allows us to determine the most productive stands by composition. Multi-species coniferous stands are more productive compared to compositionally pure stands; thanks to this, it is possible to direct forest management towards the formation and exploitation of mixed stands in certain landscape groups.

The planning of forest usage on a landscape basis that takes into account the optimal felling method and regime in mature and over-mature stands will allow to use the forest plot constantly and inexhaustively and to create a stand with high mensuration indexes, which allows obtaining the maximum amount of harvested wood with a good commodity structure. Furthermore, it becomes possible to regulate the growth pattern of dendrocenoses in the direction desirable for forestry. In turn, modeling of succession transformations on a landscape basis will allow timely planning and prevention of undesirable species change on a regional scale.

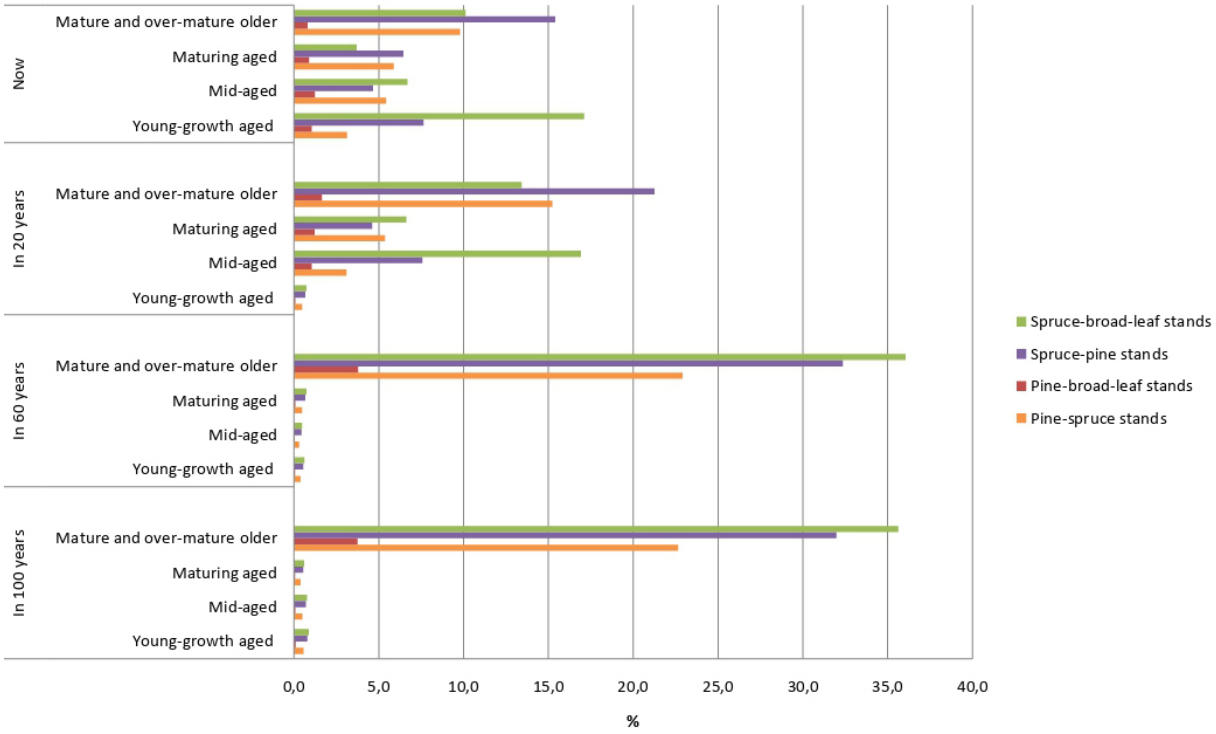


Fig. 18. Changes in the areas of mixed stands over one hundred years in the Valdai-Tikhvin District.

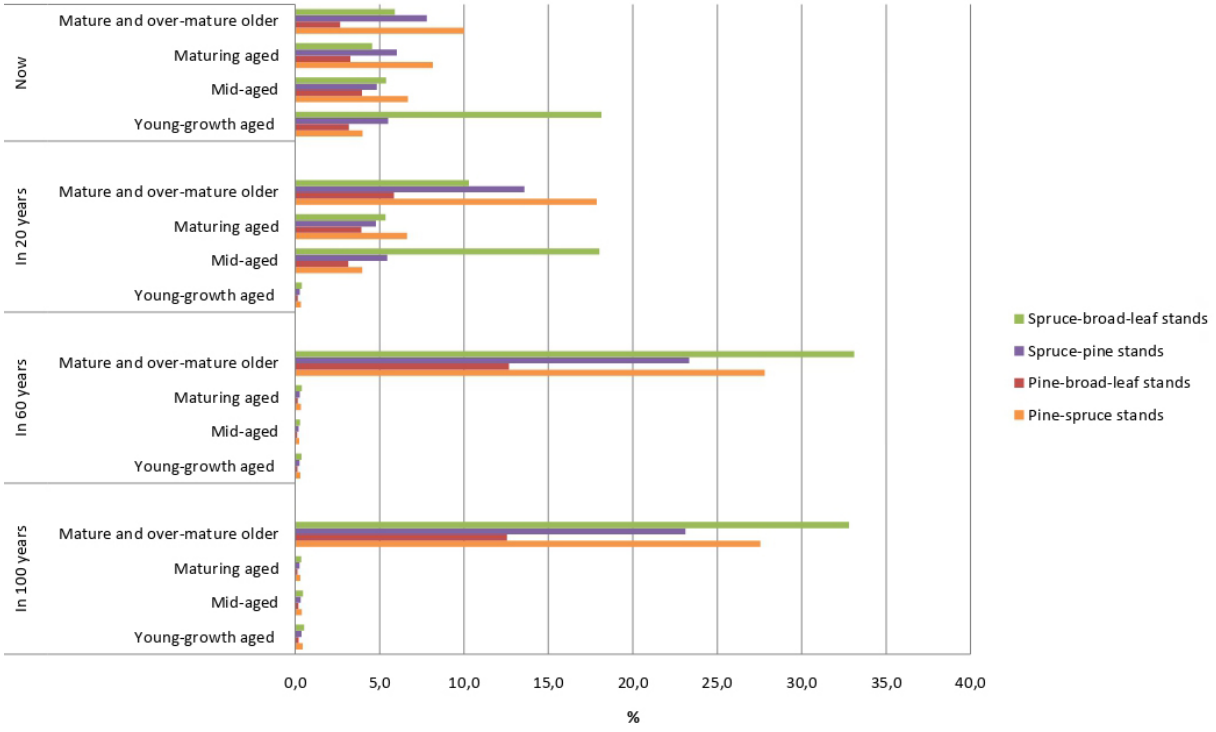


Fig. 19. Changes in the areas of mixed stands over one hundred years in the Luzhsko-Volkhovsky District.

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