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СВОЕОБРАЗИЕ РАСТИТЕЛЬНОГО ПОКРОВА ПОДТАЙГИ И ЛЕСОСТЕПЕЙ ЮГО-ВОСТОКА ЗАПАДНО-СИБИРСКОЙ РАВНИНЫ И СЕВЕРО-МИНУСИНСКИХ ВПАДИН

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В статье рассматривается своеобразие растительного покрова подтайги и лесостепей юго-востока западно-сибирской равнины и северо-минусинских впадин. Даётся общая характеристика растительного покрова и его разновидностей: южно-таежные елово-кедрово-пихтовые леса с березняками, осинниками и болотами; березовые и осиновые леса в сочетании с хвойными лесами, лугами и болотами; березовые и осиновые леса с включением хвойных растений – преимущественно ели и пихты, с луговыми и травяными болотами; луговые степи, остепененные луга с участием березовых и осиновых лесов; травяно-кустарничковое и травяные сосновые и осиново-березово-осиновые леса; горная темнохвойная тайга; пойменные луга в сочетании с болотами, кустарниками и лесами. Наличие ряда реликтовых признаков указывает, что формирования почв, изменение границы растительных зон и состав растительного покрова, связано с изменением климатических условий в послеледниковую эпоху. Следы засушливого времени имеются как в подтайге, так и в лесостепи. Отмечено, что вблизи населенных пунктов лесные массивы расположены на сенокосных и пастбищных угодьях и среди пашен в виде колков и перелесков, представлены мелколиственными березовыми и осиновыми насаждениями. Лес имеет водорегулирующее значение, но формирует сложную конфигурацию полей и сенокосных площадей, что снижает эффективность использования сельскохозяйственных машин. Показана актуальность проблемы вырубки лесных массивов и возможные риски деструктивных изменений окружающей среды при недостаточном внимании к данному негативному процессу. Поднимаются проблемы лесовозобновления.

Ключевые слова: *подтайга, лесостепь, Причулымье, травостой, лесовозобновление.*

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PECULIARITIES OF THE VEGETATION COVER OF SUBTAIGA AND FOREST-STEPPES IN THE SOUTH-EAST OF THE WEST SIBERIAN PLAIN AND THE NORTH MINUSINSK BASIN

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The article deals with the peculiarity of vegetation cover of subtaiga and forest-steppe in the southeast of the West Siberian Plain and North-Minusinsk Basin. We give a general description of the vegetation and its varieties: South taiga spruce-pine-fir forests with birch, aspen and swamps; birch and aspen forests in combination with coniferous forests, meadows and swamps; birch and aspen forests with the inclusion of conifers – mainly spruce and fir, with meadow grass and swamps; meadow steppes, meadows with birch and aspen forests; herb-shrub and grassy pine and aspen-birch and aspen forests; mountain dark coniferous taiga; meadows combined with marshes, bushes and forests. The presence of a number of relict signs indicates that the formation of soil, changing the boundaries of vegetation zones and structure of the vegetation cover, is connected with the changing of climatic conditions in the post-glacial era. Traces of dry time are available in subtaiga and in the forest-steppe. It is noted that the forested areas near settlements are located on the hayfields, pastures and plowed fields among groves and woods, are presented by small-leaved birch and aspen stands. Forest has water-regulating value, but forms a complex configuration of fields and *meadows, thus reducing the efficiency for the use of agricultural machinery. The article shows the relevance of the problem of deforestation and the possible risks of environmental changes if insufficient attention is paid to this negative process. Problems of reforestation are being raised.*

Keywords: *subtaiga, forest-steppe, Prichulymye, herbage, reforestation.*

The south-eastern part of the West Siberian Plain within Krasnoyarsk Krai and the North-Minusinsk Basin is located in the basin of the Chulym River and is a part of the Prichulym region. Latitudinal and altitudinal zonation are clearly defined in Prichulymye. The northern part of the territory of the West Siberian Plain is located in the subzone of subtaiga (herbaceous forests), which is replaced by a zone of the northern island forest-steppes and represented by Achinsk-Bogotol forest-steppe. The southern forest-steppe of the Nazarovo and the North-Minusinsk Basin is located to the south of the Arga Ridge. The Arga Ridge and the Solgon Ridge are covered with lowland landscapes of mixed and coniferous forests. In Siberia, the transition zone between the southern taiga and the northern forest-steppe is called “subtaiga”. Some authors consider that this term is not appropriate for this type of forest. In their opinion, such forests have nothing in common with the taiga in terms of species composition, structure, ecology and provenance. They term this type of forest a zone of small-leaved herbaceous forests and insular forest-steppe (Britsina, Galakhov etc.).

The subzone of small-leaved herbaceous forests is characterised by soddy-podzolic and alfisol forest soils, which are part of the Northern Prichulymye soil province. The northern forest-steppe is characterised by dark-grey forest, leached and podzolised chernozems, which are part of the forest-steppe zone of the southern Prichulymye soil vegetation. The subzone of small-leaved herbaceous and coniferous forests is composed of birch and pine-birch forests, with an admixture of larch with vigorous grass cover. Pine and larch are confined to more drained interfluve slopes. Aspen forests are common on watersheds and in micro-slopes, while equal parts of the area are occupied by birch-aspen plantations with large meadow-forest herbs. The vegetation groups in the Prichulymye region include: southern taiga spruce-cedar-fir forests with birch forests, aspen forests and swamps; birch and aspen forests in combination with coniferous forests, meadows and swamps; birch and aspen forests with patches of conifers (mainly spruce and fir), with meadow and herbaceous swamps; meadow steppes, settled meadows with birch and aspen forests; grass-bush and herbaceous pine and aspen-birch-aspen forests; mountain dark-coniferous taiga; flood meadows with marshes, shrubs and forests.

Subtaiga is characterised by the first, second and third groupings. The fourth grouping is predominating in the forest-steppe. The fifth and sixth groupings are predominating in mountain forests. Flood meadows mixed with marshes, shrubs and forests are found in all zones. There are significant changes in the composition of each grouping due to changes in moisture, relief and soil cover. Spruce-cedar-fir forests in the area are rare; there is usually a mixture of birch and aspen. The major massifs of these forests are located in the Tyukhtetsky and Birilyussky Districts, as well as in the eastern part of the Bolsheuluysky District, in the north-western part of the Bogotolsky and the eastern part of the Achinsky Districts.

It is also known about the wider spread of coniferous forests in the recent past. Even now, in places where the coniferous forest is completely removed, coniferous reforestation takes place if the land is not used for a long period of time. Before the settlement of these regions, fires were the main reason for the destruction of coniferous forests; later humans began to deforest and prevent them from regeneration. Cedar, fir and spruce were replaced by pine and larch, and then by birch and aspen. Areas of regeneration of dark-coniferous southern taiga forests are always found at the site of fires and logging. At the same time, the frequency of forest regeneration depends on many factors, but above all on the soil cover. Thus, fir develops faster on soddy-podzolic plots rich in nutrients, spruce – on excessively wet podzolic-gleyey plots, cedar and pine – on light and well-drained plots. Now, spruce-fir forests are more often found on floodplain terraces. Forests consist of spruce, fir with greater or lesser admixture of birch (silver and downy), aspen and cedar. The undergrowth is represented by spirea, rowanberry, currant, bird cherry, dwarf alder, honeysuckle and other species. The herbaceous cover is formed by marsh and meadow-marsh vegetation, and forest and meadow-forest herbs.

The first terrace above the floodplain and high floodplain are covered with waterlogged spruce-fir forests with dense undergrowth and sedge grass cover. On light sod-podzolic soils, grassy spruce-fir forests are common, in which there are usually no shrubs, while the grass cover is diverse (cacalia, ostrich fern, sorrel, blueberry, alpina circaea, herb Paris, lungwort, etc.). Birch and aspen forests are represented in combination with coniferous forests, meadows, and marshes. This area is a passage from taiga to forest-steppe and occupies most of the subtaiga. Haircap-moss birch forests with abundant cuckoo-flax cover and occasional shrubs and grasses are spread on flat watersheds, waterlogged and greatly podzolized soils. Conifers grow here, but they are considerably fewer in number and are met on humid places along river valleys. On flat wetland watersheds, as well as on greatly podzolized and excessively moist soils, sphagnum birch stands with a small number of grass representatives can be found. Shrubs are well grown in well-drained areas under birch and aspen.

The watersheds in the northern forest-steppe are covered by leached or podzolized chernozems, which, in turn, are occupied by arable land and birch forest outliers. The following herbaceous plants prevail in the forest outliers: bird vetch, bastard lupine, greater burnet, sow thistle, meadowsweet, yarrow, etc. and also the shrubs: rose hips, spirea and currants. The chernozems further down the slope are replaced by meadow-chernozem soils under meadow grass vegetation. This meadow part of the slope is replaced by birches with grass cover. A narrow strip of birch stand turns into a very complex strip of birch, spruce, fir and cedar with an abundant cover of forest horsetail. The width of this strip in some places is only 15–20 meters. Even closer to the riverbed, there are noticeably more fir and cedar trees with green mosses, herbs and shrubs, cross-leaved heath and marsh tea. The lower valley areas are covered with green and sphagnum moss. The frozen seasonal layer in the peat is located at the depth of 58 to 69 cm, and below that, the wet peat is replaced with a gley horizon at a depth of 89 cm. The sedge-hummocky bogs and moss-lichen bogs are covered with river birch, willow, pine, spruce, cedar, and larch. These tree and shrub species are suppressed and poorly grown.

Birch and aspen forests with meadows characterize a further stage in the replacement of conifers by deciduous species, as well as deciduous meadows by meadow grasses. Here, as in the previous complex, there are conifers, but they are much fewer and accustomed to humid places among the birch forest and to river valleys. The predominant forest species are silver birch, which is replaced by downy birch and aspen in heavily moistened places. Tatarian dogwood, spirea, currant are found among the shrubs, and willow is found in wetlands. The meadow-steppe herbaceous cover, replacing the meadow-forest cover, becomes increasingly important in the most developed areas under the forest. Wetlands of meadows and hypno-grass bogs are widespread among the birch-aspen forests. Few grasses, dominated by sedges and horsetail, grow through the solid moss cover. There are birch and birch-aspen forest outliers with various grass cover among the massifs opened and developed for agriculture: motley grass, sedge, cereal, cereal-legume, reedgrass. In all cases, the grass cover is well developed, and the available shrubs consist of willows, spirea, and rose hips (Parmuzin, Kirillov et al. 1964.). Clusters of birch and aspen forests are widespread in the north-western and north-eastern parts of Bogotolsky District, the north-western and south-western parts of Achinsky District and in Bolsheuluysky District. These are replaced by grassland steppes and settled meadows. Birch and aspen forests form a transition zone to meadow steppes and steppe grasslands.

The Achinsk-Bogotolsky forest-steppe is meadow steppes and steppe grasslands with forest outliers. Currently, it has the appearance of man-made forest-steppe with many elements that are characteristic of other landscapes. For example, the river valleys have preserved the features of subtaiga. Despite the great changes in the shape of the forest-steppe, the natural conditions here are quite favorable not only for the growing of deciduous forests, but also for coniferous forests. In this regard, a small grove of coniferous forest which was planted about 60 years ago near the village of V-Kateyul is indicative. At the present time it consists mainly of thriving trees up to 25 m high - fir, spruce, pine, larch and birch with a large trunk. The second layer consists of elderberry, mountain ash, dog rose, spirea. The grass cover of forest motley grass is also well developed: celandine, geranium, fern, sorrel, sedge. And all this grow on podzolized chernozem.

There are two main zones in the vast area of meadow steppes and steppe grasslands with forest outliers and aspen forests of Achinsk-Bogotolsky forest steppe. South is the smaller part, bounded by the railway on the north, and by the Chulym River valley on the south. The near-valley side is heavily divided by ravines and gullies, and there is the forest steppe on the plain along the railway. According to the topography and land cover, there are several vegetation areas: pine forests on Chulym terrace: green moss forest, blueberry forest, lingonberry forest, grass forest, forest with undergrowth, pine-birch forest, birch and pine-birch forests of gullies, birch and aspen-birch clumps with meadow-forest vegetation, meadow steppes and steppe grasslands with forest, most of which are currently plowed.

Pine forests are located on soft soils of terrasses spreading mainly along the left bank of the Chulym river. Birch and pine-birch forests of gullies cover the left bank of the Chulym River. The bottoms of the gullies are partially swampy, while tall forest grasslands can be found on the hillsides. On the high watersheds, there are birch and aspen forests, often swampy along the micro-lowlands. The area usually has the silver birch, but we also find the downy birch in extremely humid areas. Among meadows, there are cereal and cereal-forbs meadows of medium moisture in floodplains of large rivers, wet meadows in floodplains of small rivers, settled meadows with forest on slopes and high floodplain terraces (Lyubimova, 1962.).

Cereal and cereal-forbs meadows occupy the near-river and central river valley. The vegetation cover includes Kentucky bluegrass, meadow foxtail, Timothy, couch grass, awnless brome and other valuable fodder plants. Yield of herbs is 12 - 16 c/ha. Meadows of small rivers are predominantly covered with reed grass and meadowsweet, steeplebushes and false spiraea. The steppe grasslands of the slopes are comprised of meadow-steppe and meadow species with a predominance of legumes and motley grass. On the open places, meadow steppes and steppe grasslands with forest are dominated by grasses and legumes. These are the most suitable areas for pasture and haymaking, and have been developed for agriculture for a long time. There are small isolated places of saline land among the meadow steppes. Thus, there is a vast tract of “Solontsy” located 2 km to the north of the village of Bely Yar near the railway line, which is a gully covered with grass, bulrush and reeds. There are shrubs (predominantly willow) at the junction of terraces 1 and 2 only. In wet year 1997, the tract was mostly wet until 30 July. During dry years, almost the entire area of the tract is used for haying. Solonchak barley, solonchak sow thistle, saltbush, foxtail, couch grass, fescue, horsetail, plantain and tufted vetch are widespread here. The soil is meadow solonchak (Kirillov & Yerokhina, 1962.).

The second location with solonchak associations is found on the boundary of a swampy land to the south-east of the Kritovo station. The surface is matted, in some places covered with cane, while the majority of the area consists of bentgrass, tufted hairgrass, and bekmania. Areas without vegetation are covered by cracked crust with white salt scurf. Among the grass cover, consisting predominantly of sedges in the swampy land, there are scattered sporadic and small bushes of willows and willow clumps.

In the Nazarovskaya and Balakhtinskaya forest steppe, forests occupy small areas along the northern hillsides and ravines, along saucer-shaped gullies among the arable land. They usually consist of small-stemmed birches with a variety of herbs in the gullies and ravines, and along the northern hillsides with the eagle fern. Park-type pine and birch forests are present on terraces of the Chulym River. In the Nazarovskaya and Balakhtinskaya forest steppe, forests occupy small areas along the northern hillsides and ravines, along saucer-shaped gullies among the arable land. They usually consist of small-stemmed birches with a variety of herbs in the gullies and ravines, and along the northern hillsides with the eagle fern. Park-type pine and birch forests are present on terraces of the Chulym River.

The northern forest-steppe (Achinsk-Bogotolskaya) is separated from the southern (Nazarovskaya) by the Arga Ridge. In the recent past, this ridge was clearly marked by altitudinal zonation. Now, forest is almost completely destroyed in the western part of the ridge, and the areas are used for arable land. The forest in the eastern part of the Arga is also largely cut down, but it is still preserved in some places (coniferous and mixed). The forest in the middle part is being destroyed more and more. If this process of forest extermination continues, the low mountains will turn into forest-steppe with active erosion processes.

Several types of phytocenosis are distinguished on the Arga Ridge according to the relief and soil cover. The western part is occupied by meadow steppes and steppe grasslands with forests areas of birch, aspen and wooden small forest stands, scattered among the vast areas of arable land. The smallest of forest stands consist almost exclusively of willows, and the largest - with an admixture of birch and aspen. Forest tall grasses predominate among the grasses and the sedge hummocky marsh are predominant in some small forest stands. The birch forest is preserved in small stands in the most elevated northwestern and south-eastern parts of this area (Bezrukikh, 2010; Sergeev, 1971). Most of the Arga Ridge is covered by grass-bush, pine and pine-birch-aspen forests. Narrow and deeply embedded in river valleys are occupied by controlled taiga, and steep convex slopes of southern exposures are often covered with grasses, among which xerophytes occupy a prominent place. Pure pine forests are rare, as they are constantly exposed to fires and logging. This largely explains both the young age of the stand and the diversity of composition.

Blueberry, lingonberry, fern (eagle fern) and herbaceous forests are widespread on the Arga. In herbaceous forests you can find stone bramble, thorow wax, crepis, eagle fern, reedgrass. The main background is mixed forests of pine, birch and aspen, to which larch is interspersed in some places. Depending on soils and exposition, the grass cover under the forest is also imputed. On the southern slopes, there is a wide distribution of red clover, burnet, common vetch, forest vetch, fescue, phleum, and clover. On the northern slopes, there is a large herb variety: meadowsweet, spurges, meadow-rues, cat grass, horsetail, and forest fern. This composition of forest tall grass is characteristic of areas dominated by aspen. Flat watersheds are often used for haying. The composition of such meadows is dominated by forest grasses: cat grass, reedgrass, clover, sedge, geranium, horsetail, phelum vetch, and burnet.

Steep convex slopes of southern exposures are usually covered with grasses such as wood-sorrel, white mugworts, white-headed veronicas, fescue, phelum, wild onion and others. Self-regenerating of pine is widespread and forest plantations are well developed. The pine plantings made in 1914 on the second terrace of the Chulym near the village of Bogotolsky Zavod are of interest. At present, it is a forest area under the canopy of which stone bramble, avens, horsetail, strawberry, currant, meadowsweets, and basilica are growing. Birch and aspen are becoming increasingly important in the eastern part of the Arga Ridge.

On the Kemchug uplands, heavily sparse mountain dark-coniferous taiga is spread on mountain-podzol soils with weakly leveled signs of destruction of clay particles from acid soils and good structure. Soils are sparse and rubbly. Forest composition is represented by spruce, fir and cedar. Forest regeneration is slow after fires and logging, hampered by a thick grass cover, so aspen and birch species are spread in many places where coniferous forests were destroyed. The vegetation cover in the subtaiga part of the Solgon Ridge and Kuznetsk Alatau is strongly changed. Here, in contrast to the Arga Ridge, there are more mountain taiga groups: there are dark coniferous forests in the Solgon Ridge, and larch forests are in the Kuznetsk Alatau.

The combination of floodplain meadows, swamps, shrubs and forests occur in different zones, however there are changes in the structure and combination of the ground vegetation cover. The growth of mesophytic plant, shrub and tree vegetation characterizes floodplain meadows. Meadows not used for haying are overgrown with shrubs and tree species. Thus, use of meadow impacts the frequency of occurrence of areas covered with scrubs and tree species. There are some areas mainly consisting of willow and forested lands. Pines or aspen-birchen and black alder grow on sand deposits and there are black alder woodlands on loamy soils. Typical floodplain meadows are composed of various meadow formations and their combinations. Bent-grass, timothy, foxtail and couch grass commonly grow on heavy-textured muddy soils, while couch grass and brome-grass characterize lighter soils. Miscellaneous herbs and legumes typically grow in grass stands. Meadow bogs are very common and consist of gramineous plants (canary-grass, bead-ruby, wood-reed, sedges and mesophilic herbs). There are canary-grass meadows on the lowest levels of floodplains in the southern part of the forest zone. Reed-grass and tussock-grass meadows occupy large territories.

In the forest-steppe and steppe zones, the sod-plants grow in the conditions of stagnant overwatering on peaty meadows of floodplains. Sedge-grass characterizes callows of the central parts of floodplains due to the conditions of excessive waterlogging. However, pure sedge associations are often replaced by gramineous plants and other mixed-sedge associations. Upon that, turfy hair grass, brown-bent and bod miscellaneous herbs mix in on sod-grass areas, while wood reed, bent and miscellaneous herbs grow together on sedge-grass areas.

Herbaceous and hypno-grass lowland bogs commonly appear on floodplains. They often occur in combination with transitional and upland bogs. Small areas of herbaceous and hypno-grass lowland bogs are usual for meadows and forested lands. High-grass lowland bogs appear along the lakes. They are replaced by coarse sediment marshes and sedge hummocks near lakes. Hypno-sedge bogs with continuous hypno-moss cover are widespread in the forest-steppe zones and in hemiboreal forests. Hypno-sedge bogs that are situated on increased relief elements in subtaiga are gradually replaced by transitional sedge-sphagnum and upland bogs that cover swampy watersheds. Herbaceous and hypno-grass bogs are used for haying in some areas. Relevant meliorating measures allow cultivating grain and vegetable crops in the forest-steppe zones.

Modern ecosystem and its components, including vegetation, preserve the recent geological past, when zonal boundaries and structure of the vegetation cover were changing. Many relict features mark the changes in climate, soil, and vegetation during the post-glacial era. This is proved by areas of spruce and spruce-fir forests that are distant from aspen woodlands with grass covering typical for dark coniferous forests. Apparently, such areas in the subtaiga zone are residual; they have been preserved since the Quaternary times. The traces of drought, such as some coniferous and coniferous-deciduous plantations, presence of hemiboreal and forest steppe species, are found both in subtaiga and in the forest-steppes (Lyubimova, 1962). Steppes and forest-steppes were more widespread during the arid post-glacial period. Evidently, the formation of vegetation and mountain areas is connected with changing climatic conditions and melting of mountain glaciers.

Vegetation cover of Prichulymye is highly diverse and is characterized by a predominance of pine, fir, spruce and a smaller percentage of cedar and larch, along with birch and aspen among the small-leaved trees. The distribution of forests and marshlands is also widespread in grasslands and pastures, as well as separated forest stands and copses are spread throughout arable lands. It is important to emphasize the fact that woodlands, particularly located close to populated areas, are shallow and demonstrate an irrational clearcutting process. Therefore, nowadays there is no construction of forest around settlements. Small-leaved birch and aspen forests are spotty scattered across meadows and fields, causing numerous inconveniences to the efficient use of big agricultural machines. It is not always easy to uproot the forest in the fields and grasslands. Woodland plays a certain water-regulating role; however, it creates a complex spacing of fields and grasslands affecting land littering.

Rational use of land is one of the most significant issues in the long-term development of the agricultural districts. This involves the proper placement of the land, as well as its constituent elements, hence it is necessary to conduct the range of measures. It is important to change the separated forest stands location within the crop rotation fields and across the grassland areas. The forest strips must satisfy the requirements that are set for the use of this or that piece of land. This requires clear-cutting in certain areas and afforestation in others.

It is necessary to aim at bringing the building forest closer to populated areas during afforestation as well as during the use of existing forests. Due to modern soil and climatic conditions, valuable forest species such as larch, fir, and spruce can be grown in various parts of the areas, where they used to occur and are now destroyed.

It is necessary to implement and maintain enhanced measures to improve the grass stand and expand the area of grasslands and pastures. It is important to pay attention to some inconsistency of soil cover and plant facies: there is a widespread distribution of forests and chernozem soils in the recent past. The surveyed area evidently experienced a post-glacial era with a drier, warmer climate and steppe vegetation. That dry and warm era was replaced by a colder and more humid one, an era that continues to the present day. Taiga of the West Siberian plain in the south was linked to the taiga of the Arga Ridge, and in the east to the forests of the Kemchug uplands. Archaeological evidence suggests that primitive man hunted forest animals there (Lyubimova, 1964.).

Deforestation has been particularly rapid since the colonization of the areas. The woodland was clear-cut for building villages. Primarily larch forests, which had a park type on the southern slopes, were logged for building purposes. Larch stumps aged 200 to 300 years can be found throughout the southern part of the described area. Thus, the villages Volynka, V-Kateyul and others villages of Bogotol District, as well as Yastrebovka, Barabanovka and other areas of Achinsk District were build in the larch forest. Reforestation and rational use of forests will have a positive impact on local climatic (mesoclimatic) conditions, provide forests for currently non-forested settlements and districts, enrich Prichulymye with fur peltries and so on.

Reforestation measures are extremely important in the Nazarovskaya forest-steppe, where conditions for human life and economic activity have become worse as a result of forest destruction. Ground water and reservoir water should be used rationally for artificial irrigation of grasslands, arable lands and field shelter belts. It is necessary to use overburden rocks for afforestation in coal mining areas. Wind and water erosion that exist in the forest-steppe can be suppressed and their consequences overcome only by a system of measures involving obligatory afforestation, as well as the field-protective and wind breaks.

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МОДЕЛИРОВАНИЕ ДЕФЕКТОВ В ГОРИЗОНТАЛЬНОЙ СТРУКТУРЕ ЛЕСНЫХ НАСАЖДЕНИЙ

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Реальный лес «заполнен» разными пустотами – полянами, прогалинами, квартальными просеками и лесными дорогами. Рассматриваются модели динамических процессов в лесу, связанных с появлением и исчезновением дефектов в горизонтальной структуре леса. Рассмотрены модели двух типов, описывающие процессы появления и исчезновения вакансий в горизонтальной структуре насаждения, и обсуждаются условия, при выполнении которых возможно существование устойчивых состояний насаждений с малым числом вакансий.

В кинетической модели рассматриваются процессы появления и исчезновения вакансий как стационарные во времени и характеризуемые постоянными значениями величин вероятности появления вакансий и вероятности их исчезновения. Показано, что в кинетической модели с независимыми стационарными интенсивностями переходов нет ограничений на число вакансий в лесу, что не согласуется с натурными данными.

В оптимизационной модели слабонеидеального ваканс-газа предполагается, что состояние отдельного дерева зависит как от его взаимодействия с другими деревьями, так и от взаимодействия с вакансиями. Вакансии же между собой не взаимодействуют в силу их редкости и большого расстояния между ними. В модели введена оптимизационная функция как характеристика риска гибели насаждения и предполагается, что в ходе эволюционных процессов ведется отбор на экосистемы с такой плотностью вакансий, при которой риск гибели системы минимален. Показано, что риск гибели деревьев в насаждении будет минимальным в ситуации, когда в насаждении имеется небольшое число вакансий, существенно меньшее общего числа деревьев в лесу.

Ключевые слова: лесные насаждения, появление вакансий, исчезновение вакансий, моделирование.

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SIMULATING DEFECTS IN THE HORIZONTAL STRUCTURE OF FOREST STANDS

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A wild forest is 'filled' with defects (or gaps) of various kinds, such as glades, clearings, cuttings, forest roads. The models of dynamic processes in the forest, which are connected with the appearance and disappearance of vacancies in the horizontal forest structure are considered. Two types of the models that describe the processes of appearance and disappearance of such vacancies are presented. The conditions under which the existence of stable states with small number of vacancies is possible are discussed.

The kinetic model considers processes of appearance and disappearance of vacancies as stationary with constant values of the probabilities of the appearance and disappearance. It is shown that the kinetic model with independent intensities of transitions has no restrictions on the number of vacancies in the forest, which is not consistent with the field data.

The optimizing model of the weakly imperfect gas of vacancies assumes that the condition of an individual tree depends on its interaction with other trees and with vacancies. Vacancies themselves do not interact because they are *rare and separated by vast distances. The model introduces an optimization function as the characteristic of the dieback risk of a stand, and it is assumed that the existing evolutionary processes select ecosystems with the density of vacancies at which the system has minimal loss risk. It is shown that the dieback risk of the trees in a stand is minimal if the number of vacancies in the stand is much less than the number of trees.*

Keywords: forest stand, appearance of vacancies, disappearance of vacancies, simulation.

When the term 'forest' is used (it is preferable to use the term 'thick forest'), it is usually represented as a the whole of trees densely placed in some area, so that it is almost impossible for a person or a big animal to pass through this forest. Nevertheless, in effect (it can be clearly seen on the aerial and satellite images), the forest is 'filled' with gaps of various types – clearings, glades, 'openings' formed after deforestation (dieback and fall of individual trees), compartment lines and forest roads.

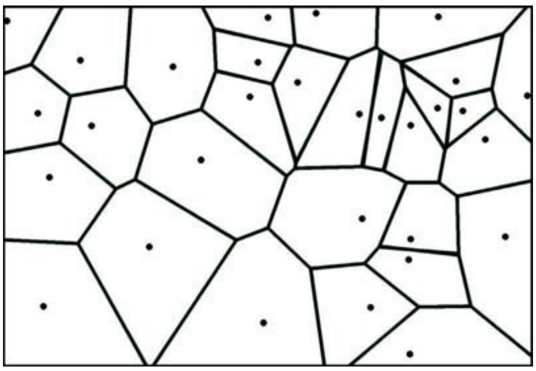
The modern concepts of forest dynamics take into account the existence of such gaps-defects, and a special term 'gap' has been proposed to describe these ecological objects (Botkin et al., 1972; Shugart, 1984). The concept of gap-dynamics is currently a constitutive theory that describes natural development and formation of the structure of undisturbed forests (Bugmann, 2001; Botkin et al., 1972; Ishikawa et al., 1999; McCarthy, 2001; Prentice, Leemans, 1990; Shugart, 1984; Yamamoto, 1992, 1995; Karev, 1999; Kislov et al. 2015; Omel'ko, Ukhvatkina, 2012). Nevertheless, it appears that the processes of forest dynamics associated with the existence of defects in a forest stand cannot be reduced to the fact that a defect is described as a place where a tree can grow. In the situation when using unmanned vehicle systems it becomes possible to obtain super-large-scale images of forest stands and count the number, density, and type of defects in these stands, the existence of a dynamic theory of defects in the forest and understanding the patterns of formation and disappearance of defects can make it possible to effectively decipher the resulting images and use the characteristics of the current structure of defects as indicators of the state and stability of forest stands.

Let us start with classifying the analysis of dynamic processes in the forest associated with the appearance and disappearance of defects in the horizontal structure of the forest. Defects in the horizontal structure of a stand can be divided into point and linear. A horizontal point defect (vacancy) is an 'opening' in the forest with an area slightly larger than the crown projection area of an average tree in a stand. Linear horizontal defects (dislocations) include glades, clearings or meadows with an area that is significantly larger than the crown projection area of an average tree in a stand. Obviously, such intuitive definitions cannot be used in a quantitative analysis, thus we will give more precise definitions of vacancies and dislocations.

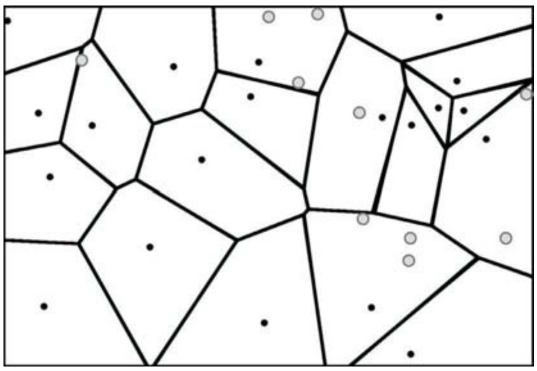
To determine defects in a forest stand, we construct Voronoi polygons for it (Vasilevich, 1969; Greig-Smith, 1976) and calculate the density function of test range area distribution. As an example, let us consider the simplest case where trees in the forest are placed randomly. Figures 1A and 1B show the construction of Voronoi polygons for the forest area without vacancies and with vacancies distributed over a distance; Figure 2 shows the density functions of distributing test range areas for the tracts without vacancies and with vacancies.

As we can see from Figure 2, in the absence of vacancies in the horizontal structure of the forest, the distribution density function is unimodal. If there are some defects in the model stand, the function of the Voronoi polygon area distribution density will be bimodal, and we can talk about the existence of defects in the horizontal structure of the forest.

The appearance of defects in the horizontal structure of the forest can be explained fairly straightforward: individual trees in the forest can die under the influence of wind, insects, viral and fungal diseases, lightning strikes, etc. In the simplest case, such defects should be randomly distributed over the forest. But cooperative effects are also possible. These effects are associated with the increase in the probability of falling out of trees adjacent to an already existing defect. In this case, the size of the defect can increase with time and the vacancy will turn into a dislocation.



A



B

Figure 1. Voronoi Polygons for the random arrangement of trees:
A – forest stand without defects; B – forest stand with defects.
1 – tree; 2 – vacancy; • – 1; ○ – 2

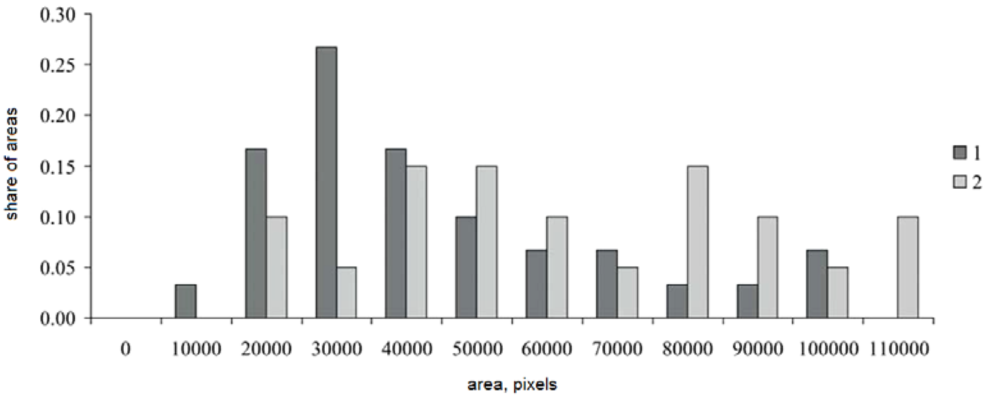


Figure 2. Histograms of distributing the areas of Voronoi polygons:
1 – forest stand without defects; 2 – forest stand with defects

It seems that the reasons for the disappearance of a vacancy cannot be reduced to the fact that the seeds of trees fall into the soil within the limits of the formed vacancy and germinate. Many field observations suggest that the renewal of trees in a defect may not occur, and the lifetime of a defect may be quite long (Buzykin et al., 1985).

The horizontal structure of the forest stand can be characterized both by the number of vacancies n_0 in the stand and by the density (relative area of vacancies) q in the forest:

$$q = \frac{\sum_{i=1}^{n_0} s(i)}{S_0} = \frac{S_d}{S_0}, \qquad (1)$$

where $s(i)$ – area of the i^{th} vacancy; S_0 – area of the forest stand; S_d – total area of vacancies in the forest.

It is obvious that $0 \le q \le 1$. The total area of S_d defects is usually much less than the total stand area S_0 and the density of defects is $q << 1$. If $S_d \sim S$, then $q \to 1$ and we do not deal with the forest but with the open stand or the grassland with individual trees on it. The thickened forest is characterized by the state $q \cong 0$.

When describing the spatial structure of defects and analyzing their ecological role in the forest, the following questions arise:

– is the distribution of defects in the stand uniform or is there a gradient in the number of defects?

– are there any stable spatial configurations of defects in the stand, or can the number of defects in the stand be arbitrary?

– is the appearance and disappearance of defects a process associated with the current state of forest stands, or do defects appear and disappear regardless of the current number and current spatial distribution of defects in the stand?

– do the defects affect the state and dynamics of the stand and can the changes in forest characteristics caused by the presence of defects affect the state and stability of the stand as a whole, the reproduction and species composition of the stand, the impact of insects on the stand;

– can the dislocations, being extended defects in the structure of a stand, distort the interactions of trees in a forest much more strongly than point defects.

In this paper, we consider two types of models that describe the processes associated with the appearance and disappearance of vacancies in the horizontal structure of a stand. The conditions under which the existence of stable states of stands with a small number of vacancies is possible are also discussed.

I. KINETIC MODEL OF VACANCIES

For simplicity, we will assume that the area S_0 of the crown projection of each tree in a mature stand is the same. If the total stand area is equal to S, then there will be $N = \frac{S}{S_0}$ areas in it, of which n areas ($n \le N$) can be occupied by trees. In the case of a tree fall, a vacancy appears on the site. This vacancy may be occupied by a tree of the next generation some time after its occurrence.

In the general case, these intensities of the appearance and disappearance of a vacancy depend on the nature of the interactions between the trees in the stand and on the impact of external critical factors (wind, fire, insect attacks, etc.). At an arbitrary point of time t there may be $n(t)$ trees and $k(t) = N - n(t)$ vacancies in the stand, provided that the following condition will be fulfilled: $n(t) + k(t) = N = \text{const}$. Thus, the dynamics of succession processes, expressed in the appearance and disappearance of vacancies, can be described using just one variable, for example, using the variable $k(t)$.

We will consider the processes of appearance and disappearance of vacancies as stationary in time and characterized by constant values of the probability of the appearance of vacancies λ and the probability of their disappearance μ – in fact, this is the standard model of reproduction and dieback (Tikhonov, Mironov, 1977; Kleinrok, 1979). The graph of transitions from state to state in such a system is shown in fig. 3.

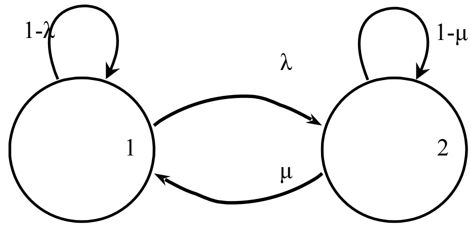


Figure 3. The graph of transitions from state to state in the model of appearance and disappearance of vacancies:
1 – territory occupied by a tree; 2 – vacancy

Using the graph in Figure 3, we can write a kinetic equation odescribing the dynamics of the number of vacancies in a forest:

$$\frac{dk}{dt} = \lambda(1-k) - \mu k = \lambda - (\lambda+\mu)k. \quad (2)$$

The phase image of the model(2) is shown in Figure 4.

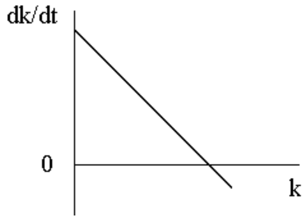


Figure 4. Phase image of the model (2)

As we can see in Figure 4, the model (2) has only one steady-state condition of a stand, when $\frac{dk}{dt} = 0$, with $k = \frac{\lambda}{\lambda+\mu}$. If $\lambda \to 0$ (vacancies in a stand do not appear) or $\mu > \lambda$ (the intensity of the disappearance of vacancies is much greater than the intensity of their appearance), then $k \to 0$ and there are practically no vacancies in the forest area. If $\mu \to 0$ or $\mu < \lambda$, then $k \to 1$ and in vacancies that appear in the forest area with the intensity λ new trees do not appear and the forest area loses its forest cover.

Since the model (2) does not impose any restrictions on the parameters, then if the model (2) is correct, stable stands with a very different number of vacancies should occur in the forest. However, under natural conditions, the number k of vacancies in a stand is usually quite small. Thus, in the kinetic model with independent stationary transition rates, there are no restrictions on the number of vacancies in the forest, which is inconsistent with field data.

II. MODIFIED KINETIC MODELS OF VACANCIES IN THE FOREST

Let us consider a more complex model, in which the magnitude of the intensity λ of the appearance of vacancies is still constant, but the intensity μ of the disappearance of vacancies depends on the number k of vacancies already existing in the stand.

$$\frac{dk}{dt} = \lambda(1-k) - \mu(k)k. \quad (3)$$

We specify the form of the function $\mu(k)$. Let us consider two options: a monotone function $\mu(k) = \mu_0 k + ak$ and a nonmonotone function with a maximum at $k = 1/\varepsilon$ $\mu(k) = \mu_0 k\exp(-\varepsilon k)$. Then for the first option we obtain:

$$\frac{dk}{dt} = \lambda(1-k) + (\mu_0 + \mathrm{a}k)k. \quad (4)$$

The stationary state of the stand will be achieved at the values of k corresponding to the solutions of the equation $\frac{dk}{dt} = 0$:

$$k_{1.2} = \frac{\lambda-\mu_0}{2a} \pm \sqrt{\frac{(\lambda-\mu_0)^2}{4a^2} - \frac{\lambda}{a}}. \quad (5)$$

If the intensity λ of the appearance of vacancies is sufficiently large and greater than the value μ0, the stable positive value of the number of vacancies in the forest will be close to $\frac{\lambda}{a}$. Nevertheless, this solution does not satisfy the condition $k \le 1$.

For the kinetic equation with another version of the function μ*(k)*, we obtain:

$$\frac{dk}{dt} = \lambda(1-k) + \mu_0 k exp(-ak). \quad (6)$$

In this case, provided that $\lambda > \mu_0$, there is one positive solution (6):

$$k = \frac{(\lambda-\mu_0)}{\mu_0\varepsilon} \pm \sqrt{\frac{(\lambda-\mu_0)^2}{(\mu_0\varepsilon)^2} - \frac{\lambda}{\mu_0\varepsilon}}. \quad (7)$$

Thus, in the kinetic model, where the intensity of the disappearance of vacancies depends on their current number, the appearance and disappearance model gives the only positive solution characterizing the stable number of vacancies in the stand.

It should be noted that the reciprocals of the intensities of transitions from state to state in kinetic models provide indicators that are very important from the point of view of understanding ecological processes in the forest – the characteristic times of changes in the state of the stand.

III. OPTIMIZATION MODEL OF A WEAKLY IMPERFECT VACANCY GAS IN THE FOREST

Optimization models differ from kinetic ones in that a certain function is introduced to describe the model system, and it is assumed that in the steady state of the system, the value of this function reaches a minimum. In this situation, when constructing an optimization model, an optimization function is first introduced, and then the values of the system parameters are found, at which the optimization function reaches a minimum.

In the optimization model describing the dynamics of vacancies in the forest, it is supposed that part of the forest area is occupied by trees, and part is free (these are vacancies). We also believe that the state of an individual tree depends both on its interaction with other trees and on its interaction with vacancies. Vacancies do not interact with each other due to their rarity and the large distance between them. This condition allows us to consider vacancies in the forest as analogs of particles of an ideal gas, and we call it the model of a weakly imperfect vacancy gas. As $N = n + k$, then dividing both sides of the equation by N, we obtain $\frac{n}{N} = 1 - \frac{k}{N} = 1 - x$ (where $x = \frac{k}{N}$). Thus, the state of the stand can be characterized by one variable x.

Let us introduce some optimization function $Q(x)$ as a characteristic of the risk of stand dieback and assume that in the course of evolutionary processes, selection is made for ecosystems with such a value of x at which the risk of system dieback is minimal, that is, in a steady state $Q(x) \to \min$.

The risk of dieback of trees in a stand with vacancies may depend on the following reasons:

– competitive interactions between trees;

– loss of trees near an existing vacancy;

– dieback of a tree due to external influences (insect damage, lightning strikes a tree, etc.) that do not depend on the features of the horizontal structure of a stand.

It is also necessary to take into account the reduction in the risk of falling trees near the vacancy due to the replacement of the vacancy by a tree.

Considering all these risks as additive, we write the risk function:

$$Q(x) = g(1-x)^2 + \frac{mx}{A+x} - wx + M, \qquad (6)$$

where A, g, w, m are some constants.

The first term on the right side of (6) describes the competitive interactions between trees, the second term describes the effect of the appearance of a new vacancy in a stand with an already existing share of vacancies x, the third term describes the disappearance of a vacancy and the appearance of a new tree in its place, and, finally, the last term characterizes the risk of a vacancy arising under the influence of modifying factors, the intensity of which does not depend on the current state of the stand.

To determine the value of x, at which the risk $Q(x)$ function will take a minimum value, we calculate the derivative and equate it to zero. Then we obtain:

$$-2g(1-x) + \frac{mA}{(A+x)^2} - w = 0. \qquad (7)$$

After simple transformations, taking into consideration that $x << 1$ (there are few vacancies in the real forest) the cubic term x^3 is rejected in (7) due to its smallness, and we obtain the following quadratic equation:

$$\alpha x^2 + \beta x - D = 0, \qquad (8)$$

where

$$B = \frac{w}{2g}; C = \frac{mAB}{w}; D = A^2 + A^2B - C,$$

$$\alpha = (2A - 1 - B);\ \beta = A(A - 2 - 2B).$$

Let us write the solution (8):

$$x(opt) = \frac{-\beta \pm \sqrt{\beta^2 + 4\alpha D}}{2\alpha}. \qquad (9)$$

Provided that the discriminant $(\beta^2 + 4\alpha D)$ of the equation (9) is positive, it has two positive solutions: one – in the case when $\alpha > 0$ and the other – in the case when $\alpha < 0$. Thus, in a situation where there are a small number of vacancies in a stand, the risk of dieback of trees in the stand will be minimal.

In the considered models, it is assumed that their parameters are known, and it is necessary to find the optimal value of x. Nevertheless, in a real situation, by analyzing large-scale aerial and space images, it is possible to estimate the value of x – proportion of the forest area occupied by vacancies, while the model parameters, on the contrary, are unknown. If we assume that the successional processes in a climax forest are stationary, then we can consider the inverse problem of estimating the parameters of models describing the dynamics of vacancies by the value of x. It is obvious that different values of model parameters can correspond to the same value of x, however, it is possible to estimate at least the ratio of the values of these parameters from one image and, based on this, to evaluate the intensity of ecological processes in a stand. Thus, for the model of the appearance and disappearance of vacancies, it is possible to estimate the ratio of the intensities λ and μ from the x value analyzing one image.

CONCLUSION

The comparison of the simplest kinetic and optimization models of vacancies in the forest show that both in some types of the kinetic model and in the optimization model there is one stable state of the stand, when a small part of the forest area is occupied by vacancies, and if this condition is met, the stand is stable.

It is obvious that the proposed form of the optimization function is not the only possible one, and other forms of this function can be considered based on the concept of the risk function as an analogue of free energy in defect models in partially ordered physical media (Kleman, Lavrentovich, 2007).

For the detailed analysis of the spatial structure of vacancies, we can consider the spatial correlation functions $R(r)$, which characterize the probability that other defects will occur at a distance r from an arbitrary defect in the stand. If the correlation function does not depend on r, then the distribution of defects is stationary in space. Other forms of the spatial correlation function will describe the short-range or long-range order in the spatial distribution of defects.

In the development of the defect model, it is possible to consider a replacement model in which a vacancy is not an area free from trees, but an area where trees of a species that is not dominant in the stand grow. The concept of a substituted defect can be defined in exactly the same way as the concept of an ordinary defect – through the construction of Voronoi polygons. The spatial structures of heterogeneous stands are considered in labeled models of spatial random fields (Grabarnik, 2010; Ripley, 2004). The difference between these models and the optimization models of vacancies is in using the ideas about the risk function of the stand dieback in the optimization replacement model and using a risk function minimum principle, which determines which trees will replace the vacancy in the stand structure.

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ФИЗИЧЕСКИЕ ПАРАМЕТРЫ СТРУКТУР КОРЕННЫХ ЕЛЬНИКОВ ТАЙГИ ЕВРОПЕЙСКОЙ ЧАСТИ РОССИИ

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Обсуждаются смысловые содержания понятий «устойчивость» и «неистощительное лесопользование» при разных вариантах их применения.

Цель работы заключается в определении физических (числовых, объёмных) параметров возрастных структур древостоев, динамики изменения количества естественного возобновления, объёмов валежа по стадиям разложения, поражённости грибами биотрофного комплекса деревьев в возрастных поколениях, состояния деревьев лесов, обладающих качеством устойчивости.

Объекты и методы исследований. Для анализа приняты леса, отвечающие критериям устойчивости, близкие по фазам динамики к климаксовым лесным сообществам – абсолютно-разновозрастные девственные ельники Кандалакшского лесхоза Мурманской обл.; Северодвинского лесхоза Архангельской обл.; Национального парка парка «Югыд-Ва» Коми Республики (подзона северной тайги) и Центрально-лесного биосферного заповедника (подзона южной тайги). На постоянных пробных площадях проводилась лесоводственная оценка биогеоценозов, сплошной перечёт и нумерация деревьев, бурение у шейки корня с определением возрастов деревьев, определение расположения, типа и стадии развития гнилей, описание состояния деревьев.

Эксперимент и обсуждения. В таблице приведены лесоводственные характеристики биогеоценозов климаксовых, демутационных и дигрессиных фаз динамики. В графической форме представлены показатели возрастных структур древостоев, динамика изменения количества естественного возобновления в градациях его высот от 0,5 до 3,0 м и степень связи этих показателей ($r = 0,67$ при $m_r = 0,06$ и $t = 11,1$), параметры объемов валежа по стадиям разложения, параметры поражённости грибами биотрофного комплекса деревьев в возрастных поколениях, параметры состояния деревьев.

Заключение. Физические параметры структур устойчивых еловых сообществ близки к рассмотренным значениям и могут служить ориентирами при анализе структур ельников других структурных характеристик, оценки их соответствия категории устойчивых лесных сообществ.

Ключевые слова: *устойчивость лесов, возрастные структуры, естественное возобновление, древесный отпад, поражённость древостоев, состояние деревьев.*

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PHYSICAL PARAMETERS OF SELECTED SRTRUCTURES OF INDIGENOUS SPRUCE FORESTS OF THE EUROPEAN PART OF RUSSIAN TAIGA

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Substantial meanings of “sustainability” and “sustainable forest management” used in different ways were discussed in the article.

The aim of studies is to estimate physical (numeric, volumetric) parameters of age structures of stands, dynamics of changes in volumes of natural regeneration, to evaluate volumes of fallen trees focusing on their decomposition stages, and on the degree of damage caused by fungi of biotrophic complex in the course of trees aging, and to assess condition of trees in forests possessing sustainability characteristics.

Research objects and methods. The analysis was made for forests which meet the criteria of sustainability, and which dynamics fazes are close to the climax forests communities’ ones – i. e for virgin spruce forests of different ages of the following areas: Kandalaksha forestry (Murmansk region), Severodvinsk forestry (Arkhangelsk region), National Park “Yugyd-Va” (Republic of Komi, sub-zone of Northern taiga), and Central Forest biosphere reserve (sub-zone of Southern taiga). Silvicultural assessments of biogeocenoses, complete enumeration and inventory of trees, drilling at a root collar to estimate trees age, identification of location, type and development stage of rots and description of trees condition were conducted on the fixed test sites.

Experiment and discussions. Silvicultural characteristics of biogeocenoses of climax, demutational and digressional dynamic fazes are shown in the table. The graphic chart specifies indices of trees stands age structures, dynamics of changes in the volume of natural regeneration in accordance with its heights scale from 0,5 m up to 3,0 m and the ratio of those indices coherence (r = 0,67 when m_r = 0,06 and t = 11,1). The chart also shows parameters of fallen trees volumes focusing on their decomposition stages, parameters of the damage caused by wood-destroying fungi of biotrophic complex to trees of different age generations as well as on parameters of trees conditions.

Conclusion. Physical parameters of structures for stable spruce communities are close to the specified above characteristics and could serve as markers when analyzing spruce forests structures of other structural characteristics and when confirming that they meet the parameters of stable forest communities.

Keywords: forests sustainability, age structures, natural re-generation, woody debris, trees stands damage, condition of trees.

INTRODUCTION

Sustainability of forests can be considered from two perspectives: first, from the position of continuous presence of forests of certain silvicultural, economic parameters and properties in a certain area, and second, from ecosystem, biogeocenotic positions of structural content of forest communities in the same area. In the first case, the term “sustainability” corresponds to the often proclaimed dream of the entire forest industry of sustainable forest management. In the second case, it is connected with the classical notions of the final stages of development of forest communities, their structural and functional optimality.

It must be recognized that in the current conditions of uncertainty of state forest policy in the management of the forest industry there is no condition for a confident combination of these two positions in a single mechanism for managing the country's forest resources. But they must complement each other in content and application in forest practice. At the same time, these two terms, and especially “sustainable forest management”, are never tired of being exploited at all levels as the basic paradigm of forest management in Russia. In our opinion, the concept of “sustainable forest management” should combine these two terms. Sustainable forest management in a certain sense can be represented as a climax stage of forest territorial agglomeration, in which the forest agglomeration is in balance with other agglomerations of a certain territory.

This paper does not consider such extensive and important statements, but focuses on the term “sustainability” as it applies to forest communities. The forest community sustainability paradigm should underlie knowledge about forest structure and dynamics and forest management. But in declaring this provision, one must be prepared to respond to demands to designate the structures of sustainable forest communities in physical terms. The purpose of this research is to determine the physical (numerical, volumetric) parameters of some forest structures that have the characteristic of sustainability. Indigenous, primeval forests of the taiga territories of European Russia are best for studying the physical parameters of sustainable forest communities. The most suitable objects for this study of the structure and dynamics of indigenous stable formations unaffected by anthropogenic impact are primordial spruce forest communities, in which the patterns of evolutionarily formed forest systems are most prominently represented. The presented work considers parameters of age structures, natural regeneration, woody debris (deadwood), infestation of stands of a biotrophic fungi complex, visual assessment of the condition of trees of phytocenosis in indigenous spruce stands.

OBJECTS AND METHODS OF RESEARCH

Before describing the study sites, it is necessary to justify the choice of these objects as forests that meet the content of the term “sustainable forest communities”. According to the classical canons of forest science, “depleted” [9] forest communities in the final stages of successional development correspond to this notion to the greatest extent [3; 9]. Such forests, according to the classification of F. Clements [10], correspond to the concept of “climax”. In previous papers, we have detailed our views on the content of the concept “climax” and closely related formulations [5–8]. We should add that climax is a dynamic phenomenon and is just as “passable” as all other stages of successional development of any forest community. Based on these assumptions, forests that, according to our understanding, meet the criteria of sustainability, both those close to climax forest communities and those in other phases of dynamics – demutational and digressive – were taken as objects of research. Native, different-aged primeval spruce stands of the Kandalaksha district forestry of Murmansk Oblast; the Severodvinsk district forestry of Arkhangelsk Oblast; the Yugyd-Va National Park in the Komi Republic (northern taiga subzone) and the Central Forest Natural Reserve (southern taiga subzone) were used for the analysis.

Sample areas were established in such forests, where an operation cycle was carried out, including edging, silvicultural assessment of biogeocenoses, complete enumeration and numbering of trees, drilling at the root collar and determining the age of trees with a head-mounted magnifier, determining the presence of decay faults with fixing the location recording, type and stage of decay faults, describing the condition of trees on the scale adopted in forestry protection [4]. The entire sample area was divided into 10×10 m sectors, that allowed the more accurate mapping of location of trees, deadwood trunks and natural regeneration on the sample plan. The deadwood trunks have been described according to their wood species affiliation, diameter and stage of decomposition [5; 6; 11]. Species of fomites were identified by their fungal fruits and the types of decay they cause, according to the identification guides [1; 8; 12; 13]. The data obtained using a unified eye and instrumental estimation made it possible to determine the dynamic characteristics of biogeocenoses and calculate the physical characteristics of their consortia.

EXPERIMENT AND DISCUSSION

In accordance with the research objectives, it was necessary to study the parameters of the age structures of the stands, which could confirm (or not) our assumptions about the «depletion» of the forest communities selected for the study, and to describe their dynamic parameters. The characteristics of the age series of indigenous spruce stands are interpreted differently by different researchers. Thus, I. I. Gusev [2] defines one kurtosis in the age structure of indigenous spruce stands of different ages in the North in the middle of the age series. According to our long-term and geographically large-scale studies of taiga spruce stands, the volume values of trees of the climax age generations after the penultimate generation (80 years) should have comparable values up to the first generations (limiting tree ages) [5]. The table shows the silvicultural characteristics of the spruce stands that were analysed.

All of the biogeocenoses represented are indigenous primeval forest communities, unaffected by anthropogenic disturbance and developing according to natural derivative laws.

It is interesting to note two features in the characteristics of forest stands: large values of average stand age in Arkhangelsk Oblast with the smallest values of average diameters and the expected decrease in values of average ages from northern to southern latitudes. In the first case, spruce in the far north and fresh locations can reach the age limit of 400 years for this species, which affects the increase in the average age of stands. In the second case, on the contrary, in the sphagnum growth conditions of the southern taiga, the spruce most commonly has a maximum age of 200–240 years, and reaches an age of 300–320 years only in isolated cases Fig. 1 shows the graphic chart of the age structures of the spruce forests studied.

Although the stands of the climax phases of the dynamics differ in the structure of the age series [2; 5], they belong to the same dynamic category, as indicated by relatively smoothed values of tree volumes in the age generations and similar trend lines of expotential approximation.

The stands have different-aged structures, but are in different phases of dynamics – from demutational (K) to digressive (CR) and climax (A and M) (Fig. 1).

Therefore, the physical parameters of the age structures of stable forest communities lie within the lines of expotential approximation for the climax spruce forests of the taiga. Examples of stand age structures of other dynamics phases refer to absolutely different-aged spruce stands that have passed or have not yet reached the climax phase, the field of climax fluctuation [5].

As well as the different-age structure of stands, the most important criterion for the sustainability of forest biogeocenoses is the presence of sufficient natural regeneration capable of ensuring the formation of new forest generations, the continuity of the age range and the different-age structure of the stand. In indigenous spruce stands, the composition of natural regeneration is mainly represented by spruce, but the admixture of other species (mainly deciduous trees) can vary from single trees to 3–4 in the stand composition. In taiga forests, the undergrowth tends to grow in clumps over the forest area. According to our data, about 80 % of all spruce undergrowth grows on deadwood of 3 to 6 decomposition stages [5]. We counted up to 500 specimens of spruce undergrowth on some deadwood trunks of large-diameter. The confinement of the undergrowth to deadwood can be explained by better water and mineral nutrition conditions of the undergrowth due to the release of wood decomposition products from the deadwood during the process of fungal decomposition of fallen trunks. Figure 2 shows the values of natural regeneration parameters in the biogeocenoses used for analysis.

Analysis of the data in Fig. 2 shows large differences in the amount of regeneration in the represented spruce stands in height gradations up to 1.0 m. Its greatest quantity is observed in the spruce whortleberry-sphagnum stand in the Central Forest Natural Reserve (southern taiga). However, as it grows, the number of undergrowth in this forest community decreases rapidly and within a height gradation of up to 3 m the number is the smallest.

Silvicultural characteristics of spruce stands of different dynamic parameters

Stand composition formula	Dynamics phase	Type of forest	Quality class	Density	Average age	Average diameter	Undergrowth
10 Picea + Betula, Pinus, **A**	DA, climax	Blueberry-blackberry-sphagnum	IY	0.6	216.2	13.2	7 Picea 1 Betula 1 Salix 1 Populus + Sorbus
8 Picea 1 Betula 1Pinus, **M**	DA, climax	Whortleberry-cloudberry-ledum	IY	0.5	185.4	17.3	8 Picea 1 Pinus 1 Betula
8 Picea 2 Betula + Cedrus, Abies, **K**	DA, demutation	Whortleberry-green moss	IY	0.6	146.2	15.7	7 Picea 2 Betula 1 Abies + Pinus pumila
8 Picea 1 Betula 1 Populus + Pinus, **CR**	DA, degradation	Whortleberry-sphagnum	II	0.8	118.4	15.1	7 Picea 3 Sorbus + Betula, Populus

Symbols. A – Arkhangelsk Oblast; M – Murmansk Oblast; K – the Komi Republic (the Yugyd-Va National Park); CR – the Central Forest Natural Reserve. Tree stand structure: DA – different-aged.

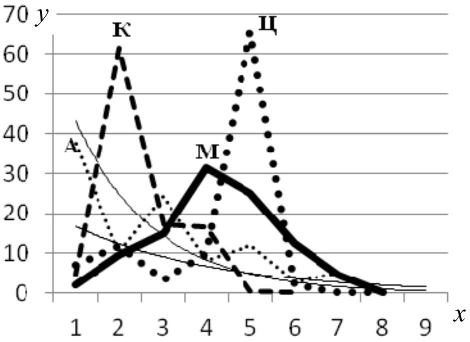

Fig. 1 Parameters of age structures in the taiga spruce stands of European Russia used for analysis:
x – the 40-year-old generation (1 – 360 years);
y – tree volumes (%). A – Arkhangelsk Oblast; K – the Komi Republic; M – Murmansk Oblast; CR – the Central Forest Natural Reserve; ___ – lines of expotential approximation

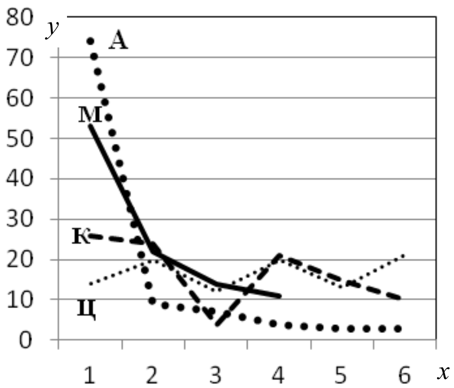

Fig. 2. Parameters of natural regeneration in the taiga spruce stands of the European part of Russia selected for analysis:
x – undergrowth height intervals at 0,5 m (1 – 0,5 m;
6 – 3,0 m); *y* – amount of undergrowth as a % of the total

For the remaining spruce stands, the amount of spruce undergrowth is relatively evened out after grading above 0.5 m in height. In absolute values, the number of undergrowth (including deciduous species) for each of the spruce stands under analysis has the following parameters. Murmansk spruce stand – 1 320 (72) = 1 392; Arkhangelsk spruce stand – 1 988 (52) = 2040); Komi – 1 975 (150) = 2 125; the Central Forest Natural Reserve – 5 933 (87) = 6 080.

The degree of correlation between age and height of undergrowth was calculated for whortleberry-sphagnum spruce stand in subzone of southern taiga (CR) – r = 0.67 with mr = 0.06 and t = 11.1). The correlation is significant and reliable, but not functional, due to the variability of the biogeocenosis silvicultural indicators.

For spruce forests of other taiga sub-zones, the parameters of the undergrowth are close to those described above.

The dynamics of the formation of indigenous spruce stands is based on the continuous inflow of a certain amount of woody debris from the stand to the deadwood structures. The more consistent the volumes of this inflow from year to year and in gradations of decomposition stages, and therefore in the time perspective of up to 50 years, the closer the forest community is to the climax phase. In this paper, we do not provide a description of the trunks related to each stage of decomposition. These data have been published in a series of past papers [5–8]. Fig. 3 shows the time dating and parameters of deadwood volumes by decomposition stages in the analyzed spruce stands.

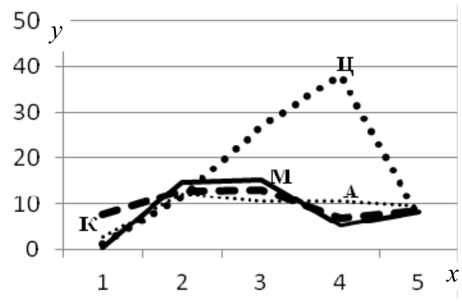

Fig. 3. Parameters of the volume of deadwood by decomposition stages in the taiga forests of the European part of Russia selected for analysis:
x – stages of deadwood decomposition (1 – 3–5 years;
2 – 6–25 years; 3 – 26–35 years; 4 – 36–45 years;
5 – 46–50 (60) years; *y* – volumes of deadwood, m^3/ha

It is clear that the decomposition process of deadwood trunks is ongoing in time and dividing it into fixed time intervals is theoretical. Nevertheless, we do so for the convenience of a variety of calculations. In the chart, the first number is for the southern taiga and the second number for the northern taiga. Figure 3 clearly shows that under northern taiga conditions the volumes of deadwood in the decomposition stages are close and their variation through time is within 5 m3/ha. Such parameters are typical for forest communities close to the climax, and consequently to spruce stands with the most stable structural parameters. Only the biogeocenosis of the Central Forest Natural Reserve in damp whortleberry-sphagnum growing conditions is significantly distinguished by the volume of deadwood. There was a large amount of forest fall in this area between 30 and 45 years ago. This forest community belongs to the degradation phases of the dynamics in terms of age structure (Fig. 1), which determines the possibility of formation of the second increased wave of woody debris from the digressive age generations in a close timeframe. We have not analysed the reasons for these forest falls. They are most likely related to wave changes in the water regime of the area and, as a result, the imbalance in the regeneration processes and the formation of stand age generations.

Wood-destroying fungi of the biotrophic complex play a significant role in the formation of woody debris. In our previous work, we have substantiated the dual functional nature of the involvement of consortia of tree-destroying fungi in the functioning of forest communities.

As a heterotrophic element, this group of fungi is determined by evolution to decompose the biomass accumulated by the phytocenosis in the degradation chain of its cycle. At the same time, all their functioning is determined by the biomass balance concept during its accumulation and decomposition, i.e. the law of formation of a sustainable structural optimum of the forest community [5; 7]. In the dynamics of spruce stand formation (as well as any other stand formation) as the age of trees in the age generations increases, the damage of trees by wood-destroying fungi also increases, which contributes to the fall of trees of older age generations, the formation of younger generations, age diversity of the stand and sustainable forest structure (Fig. 4).

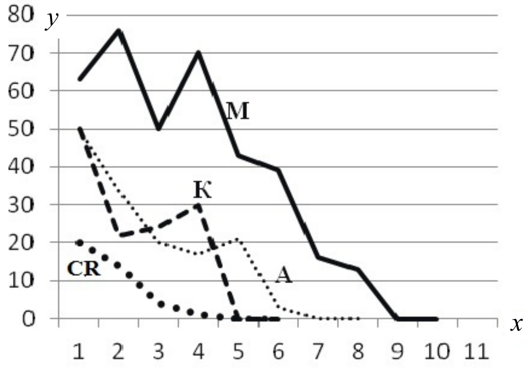

Fig. 4. Parameters of fungal attack ratio of the biotrophic complex of trees in the age generations in the taiga spruce stands of the European part of Russia selected for analysis:
x – age generations (1 – 360 years); *y* – infestation within age generation, %

Fig. 4 clearly shows the trend of increasing fungal attack ratio in the age generations from the last (undergrowth, 10) to the first (limiting tree ages, 1). The rate of correlation between the increase of tree age in generations and the increase of biotrophic fungal attack ratio was calculated: $r = 0.94$; at $mr = 0.006$ and $t = 156$. There is very high, functional correlation. It is clear that the physical values of the fungal attack ratio will be different in different stand structures. This is due to the growth conditions of the stand, its age structure and the dynamic condition of the biogeocenosis: the better the growing conditions and the higher the average age of the stand, the higher the average fungal attack ratio. Spruce stands of climax phases are attacked on average by 25±5 %, demutational by 15±5 %, and degradative by 35±10 %.

Another parameter that characterises indigenous primeval «depleted» forest communities relates to the qualitative estimation of trees and the stand as a whole.

The data in Fig. 5 demonstrates an almost complete correlation between stand degradation trends of different dynamic and zonal characteristics. This shows that the processes of natural degradation of trees in indigenous primeval spruce stands are, in numerical terms, proceeding approximately in close trends.

Some differences can only be noted in the number of externally healthy trees, which is related to the phase parameters of the stands. The spruce forest of the Central Forest Natural Reserve belongs to the degradative phase of the dynamics, there are more old-growth trees that have reached the age limit for the species, and, consequently, there should be fewer externally healthy trees. It should also be noted that this stand is under severe conditions of excessive humidity and older trees, without wood-destroying fungal attack, can be identified as degraded.

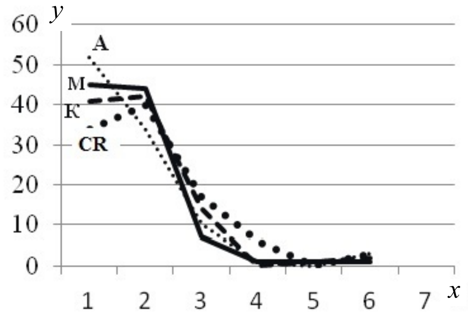

Fig. 5. Tree condition parameters in the taiga spruce stands of the European part of Russia used for analysis:
x – tree condition categories: 1 – externally healthy; 2 – degraded; 3 – severely degraded; 4 – experience partial mortality; 5 – fresh deadwood; 6 – old deadwood; *y* – amount of trees (% of total)

CONCLUSION

The following physical parameters of indigenous primeval, evolutionarily formed spruce biogeocenoses: age structures, indicators of natural regeneration, volumes of deadwood by decay stages, ratio of wood-destroying biotrophic complex fungal attack, tree classification into condition categories, characterise structures of reference (or close to reference) values typical of sustainable spruce stands. They can serve as reference points for comparative analysis of the structures of spruce stands of other silvicultural, pathological and sanitary characteristics, and for estimating their correspondence to the category of sustainable forest communities. We should add that a scale for classifying forests into a certain sustainability category has been developed and published previously [5].

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ФОРМА КРОН ДЕРЕВЬЕВ СОСНЫ ОБЫКНОВЕННОЙ (*Pinus silvestris L.*) В ЧИСТЫХ ВЫСОКОГУСТОТНЫХ НАСАЖДЕНИЯХ МИНУСИНСКОЙ КОТЛОВИНЫ КРАСНОЯРСКОГО КРАЯ

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С целью выяснения некоторых лесоводственных вопросов, касающихся различных форм леса и различных приемов ухода за ним, нужно знать размеры крон деревьев (их длину, поперечное сечение, объем, боковую поверхность). Методы определения указанных элементов еще недостаточно разработаны. Объектом исследования был относительно однородный изолированный лесной массив, в котором произрастают сосновые насаждения. Основной целью нашей работы являлось определение формы кроны сосны обыкновенной различного размера и оценка их объема. Согласно лесорастительному районированию территория исследований относилась к Алтае-Саянскому горнотаежному району лесорастительной провинции кедровых и пихтовых лесов (Сисимский округ горно-таежных пихтовых и кедровых лесов).

Изучая совокупность форм крон сосны обыкновенной, можно выделить несколько групп преобладания той или иной формы. В ступенях толщины 8 и 12 см, имеет наибольшее распространение цилиндрическая форма, редко встречается конус наклонный. Наличие данной формы можно объяснить еще не сомкнувшимся пологом, при этом климатические факторы благоприятно влияют на развитие кроны, не наблюдается выраженной конкуренции. В 28 и 32 ступенях сложно выделить преобладание какой-либо одной формы. В этом случае форма зависит от полноты древостоя, от наличия света и конкуренции. Недостаток света, высокая густота насаждения и видовая конкуренция способствует формированию различных форм крон.

В результате выполненной работы установлено, что сравнить крону с какой либо определенной геометрической формой не представляется возможным, так как габитус крон разнообразен. Такая вариация по ступеням толщины указывала на то, что у сосны крона очень подвержена влиянию ветровой нагрузки. Предложить одну универсальную формулу для определения формы кроны сосны не возможно, так как ошибки в объемах составляют значительную величину. Объем кроны сосны рекомендуется определять отдельно для крупномерных и маломерных деревьев.

Ключевые слова: *форма кроны, сосна обыкновенная, горизонтальная структура, вертикальная структура.*

Conifers of the boreal area. 2022, Vol. XL, No. 7 (special), P. 595–600

CROWN FORMS OF SCOTS PINE (Pinus silvestris L.) IN PURE HIGH-DENSITY PLANTATIONS OF THE MINUSINSK BASIN OF KRASNOYARSK KRAI

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In order to clarify some silvicultural issues concerning the different forest forms and different caring methods, it is necessary to know the dimensions of the tree crowns (length, cross-section, volume, lateral area). Methods for determining these elements have not yet been sufficiently developed. The object of our study was a relatively homogeneous isolated forest area, in which pine trees grow. The main objective of our work was to determine crown forms of Pinus sylvestris in various sizes and to estimate their volume. According to silvicultural zoning, the study area belonged to the Altai-Sayan mountain taiga region of the silvicultural province of pine and fir forests (Sisimsky District of mountain taiga fir and pine forests).

Studying the range of crown forms of Pinus sylvestris, it is possible to distinguish several groups of predominance of one or another form. In steps of 8 and 12 cm in thickness, the cylindrical form has the greatest prevalence, with a slanting cone being rare. The presence of this form can be explained by not yet closed canopy, with climatic factors having a favourable effect on crown development and absence of clear competition. It is difficult to identify the predominance of any one form in steps 28 and 32. In this case the form depends on stand completeness, availability of light and competition. Lack of light, high stand density and species competition contribute to the formation of different crown forms.

As a result of the performed work, it has been determined that it is not possible to compare the crowns with any particular geometric figure, as the crown habitus is diverse. This variation in thickness indicates that the pine crowns are very vulnerable to wind loads. It is not possible to propose one universal formula for determining the form of pine crowns, as volume errors are significant. The volume of pine crowns is recommended to be determined separately for large and small trees.

Keywords: *crone form, (Pinus silvestris L.), horizontal structure, vertical structure.*

INTRODUCTION

Speaking of the degree to which plantation morphology has been researched, and in particular the form of the crowns, we can say that this problem has not been sufficiently studied. As N. D. Skorobogatko noted in his article [6], currently there is no such special branch of knowledge as the morphology of plantings and, consequently, there are no scientifically based indicators characterising their form. The scientific literature provides separate data on the forms of vertical and horizontal projection of crowns, their changes and number depending on age, completeness, age structure and other indicators. At the same time, this problem is very relevant not only for the purposes of automated decoding of space AP (aerial photography), but also for silvicultural, bio-ecological and physiological research.

O. S. Bahur in his article [2] noted that studying the form of tree crowns provides a deeper understanding of the nature of the forest, especially in space and time. It has been established that trees of the same species and age, which have the same crown forms and grow in the same types of forest and forest-vegetation conditions, grow faster than trees with other crown forms. Crown projections within the forest stand differ significantly: each species has its own, typical, predominant form; it varies depending on age, habitat conditions and canopy structure.

Forms of vertical projection of crowns according to G. G. Samoilovich [7] are combined into eight types, and each row, depending on the nature of branching and the form of the upper and lower parts of the crowns, is divided into 3–5 subtypes. The most common species of horizontal projection of crowns are combined into four groups (rounded, ellipsoid, one-sided compressed and irregular), and five subspecies are distinguished in each of them. The diversity of crowns is influenced not only by the biological properties of the tree species and the nature of the branches' location in the canopy, but also by other factors related to sunlight.

T. Rowvinen [5] believes that improving the efficiency of data collection in the forest is one of the cornerstones of forest taxation and forest management. Mobile technologies create a unique opportunity to solve this problem, as well as to improve the accuracy of measurements, ensure the objectivity of data and independent control of results. The Trestim technology is based on obtaining the taxational characteristics of the forest stand, such as the cross-sectional area, trunk diameter, tree height and species composition from photographs of the forest stand and sample trees taken by a mobile phone. Data processing is carried out automatically, and if it's necessary, it can be done with the help of an operator, which makes it possible to automate all subsequent calculations.

The article by O. S. Artemiev [1] presents a method of measuring tree heights based on digital ground photography. Measuring tree heights during the inventory of urban plantings or forest taxation is one of the most time-consuming and expensive operations of field work. In order to increase the efficiency of work, it is proposed not to measure trees in the field, but to measure them in the office conditions by deciphering this taxation indicator according to the materials of ground digital photography.

E. V. Koch [4] studied the vertical structure of phytomass in artificial pine forests. Due to the increasing biospheric role of forests, the study of the vertical fractional distribution of phytomass and the production of various organs of woody plants in the thickness of the forest canopy is becoming increasingly important. The materials of the vertical fractional structure of the forest phytomass serve as the basis for the analysis of the tree canopy layer, which is heterogeneous in many parameters, as a functionally differentiated photosynthetic system and as a screen and filter in the exchange of biogeochemical elements and water in solar radiation fluxes between the components of the forest ecosystem.

In order to clarify some silvicultural issues concerning various types of forest and methods of caring for it, it is necessary to know the tree crowns' dimensions (their length, cross-section, volume, lateral surface). Methods for determining these elements have not yet been sufficiently developed.

RESEARCH PROGRAM AND METHODS

The main purpose of the study was to determine the form of the crowns of the Scots pine trees of various sizes and to estimate their volume. The research program included:

– selection of forest plots (allotments);

– photography of Scots pine trees by steps of thickness (8–44 cm);

– measurement of crown projections by tree diameters;

– desk processing (evaluation of the vertical structure of the tree; identification of patterns of the crown form vertically and horizontally; comparison of the crown form with the correct stereometric shapes; determination of the crown volume using mathematical formulas).

28 sample trees were selected in the forest area of the Kuraginsky forestry. Three trees were selected in each step with a thickness from 8 to 40 cm, two trees – in steps 40–44 cm. The projection of the crown along the cardinal directions was measured for each tree, including the intermediate ones (n-e, s-e, s-w, n-w) (see the table). Therefore, these trees were photographed with a Fujifilm T300 digital camera with a focal length lens of 28 mm.

During the photography, a 3-metre pole was attached to each tree so that the scale could be determined in the photo and further calculations could be performed (Fig. 3). It's necessary to take pictures of trees so that the entire tree is in the frame at a distance of 20–25 metres.

The tree image was entered into the computer memory for estimating the height of the tree. Then, the height of the tree, the height of the first dead bough, the first living bough and the length of the crown were determined on the printed photos. By comparing photos on the computer and the printed ones, a standard crown form was established, which was outlined with a colour filter (Fig. 1). The vertical scale was determined using a 3-metre pole. The height of the pole was divided by its length, measured from a photo. The horizontal scale was calculated as the ratio of the maximum length in the cardinal directions to the maximum diameter in the photo.

OBJECT OF RESEARCH

According to the forest-growing zoning of cedar and fir forests made by the Institute of Forest and Woods SB RAS (Sisimsky district of mountain taiga fir and cedar forests).

The object of research was a relatively homogeneous forest area.

The type of the forest is green–mossy-mixed pine, 2nd class of bonitet, completeness is 1.0. Two studied sites were identical to each other in bonitet, completeness, composition, type of forest and stock.

RESEARCH RESULTS AND DISCUSSION

The form of the crown projections within the stand varies. Each species is characterised by its own, typical, predominant form; it changes depending on the age, the growing conditions and the structure of the canopy. The variety of forms of horizontal crown projection is influenced not only by the biological properties of the species and the pattern of crowns in the canopy, but also by other factors related to sunlight. An analysis of the crown transection is necessary in order to study the form of the crowns more completely. It is needed for understanding what geometric figure will be represented by a transection, which will further help to understand whether the crown can be reduced to any correct geometric figure for the subsequent determination of the volume. The maximum radius of each sample tree was measured along the cardinal directions. Since we will need not only the radius, but also the diameter to determine the volume, it was also set and was the maximum for the horizontal projection of the crowns.

In order to identify the stability of the correlation between crown diameters (CD) and sizes ($d_{1,3}$) of pine trees, a graph was constructed (Fig. 2).

The diagram shows that the field of points is divided into two zones: before and after 16 cm. The ratio of diameters may depend on the lighting conditions, location and canopy density. Therefore, we can conclude that trees up to the 16th step have a sufficient level of solar energy. On this basis, the crown diameter in these steps is even greater than that of large-sized trees:

CD = 0,177 · $d_{1.3}$ + 0,136,

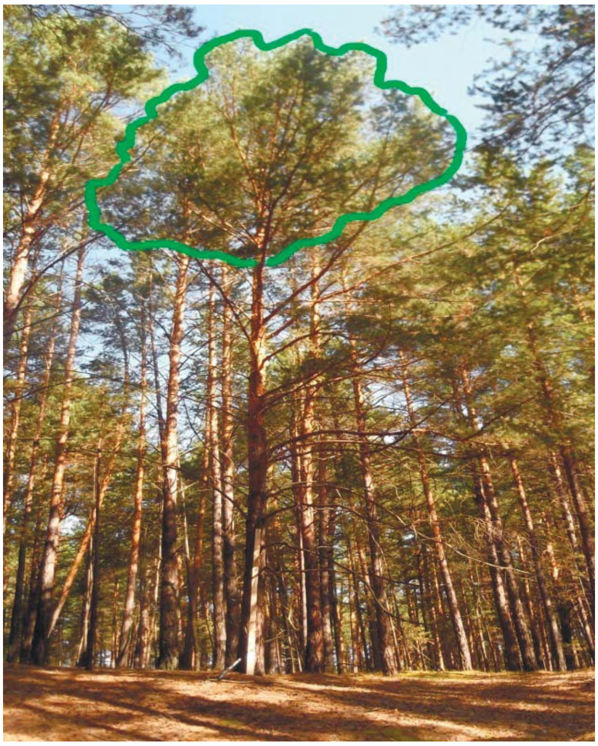
R 2 = 0,534 – diameter up to 16 cm;

CD = 0,270 · $d_{1.3}$ – 3,600,

R2 = 0,534 – diameter 16 cm or more.

The table of average crown projection radii was obtained by statistical analysis (see table).

To determine the statistical significance of differences in mean figures, Student's t -test was used.



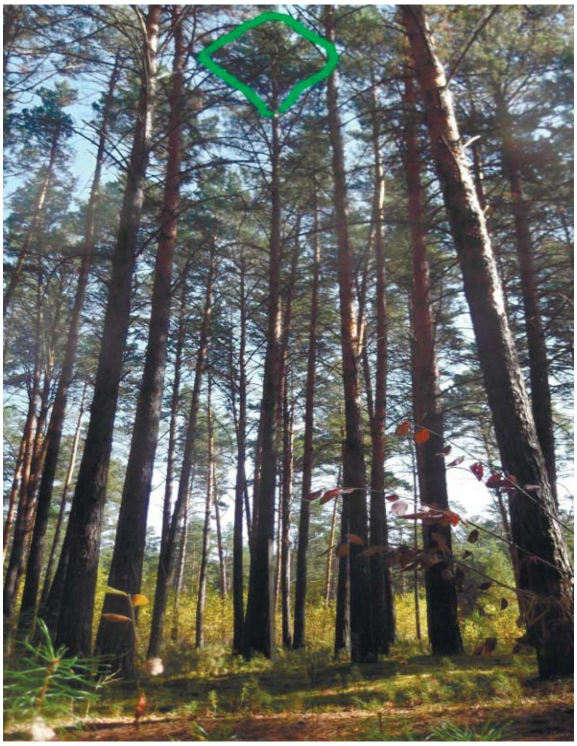


Fig. 1. Model tree with crown form – spherical sector

$$t_f = \frac{|\bar{x}_1 - \bar{x}_2|}{\sqrt{m_1^2 + m_2^2}}, \quad (1)$$

where x_1, x_2 are the average values of the compared figures; m_1, m_2 are standard errors.

t_f n-s = 0,47;

t_f e-w = 0,68;

t_f ne-sw = 0,35, t_{tab} = 2,03;

t_f nw-se = 0,81.

For comparison, we take a table figure of two. The figures of the calculated Student's *t*-tests is less than the tabular ones ($t_f < t_{tab}$), which means that the differences in the figures are not statistically significant. As there are no significant differences between the radii, it is advisable to consider the projection as a circle. This allows to compare the crowns with the correct three-dimensional figures, such as a cylinder, a ball, a cone, etc.

Further, three vertical zones were marked on digital photographs on each sample tree: the height of the first dead bough, the first living bough and the length of the crown (Fig. 2).

For each part of the vertical structure of the tree, its own graph of the correlation of the height of these elements and the thickness steps was constructed (Fig. 3). The coefficient of variation of indicators was in the range from 21 to 50 % (the variability is large). The heights of the first dead and living bough are approximately identical to each other (they change insignificantly with increasing diameter). At the same time, due to the intensive growth of trees in height, the growth of the crown length is evident. If we study this indicator from a forestry point of view, then trees with maximum diameters perform a more significant carbon-storage function, and larger trees should be left for economic use.

Form of crowns are important for the growth and development of trees, so studying of them allows to determine AP taxonomic indices more accurate using the automatic interpretation method (T. Rouvinen [5]). The most common forms of horizontal crown projection are divided into four groups (rounded, ellipsoid, one-sided compressed and irregular). In turn, studying the vertical structure of the form of the crowns of the Scots pine, our own classification was proposed. For each sample tree, the form of the crown was determined from digital photographs, having previously marked the crown contour with a colour filter (Fig. 1). Comparing each crown, 5 types of crowns were identified with any particular form (cylinder, inclined cone, ball, spherical sector and hemisphere). To confirm the form, the crown was measured at three points, in the upper and lower parts of the crown at a distance of one metre, taking into account the scale and the middle of the crown length.

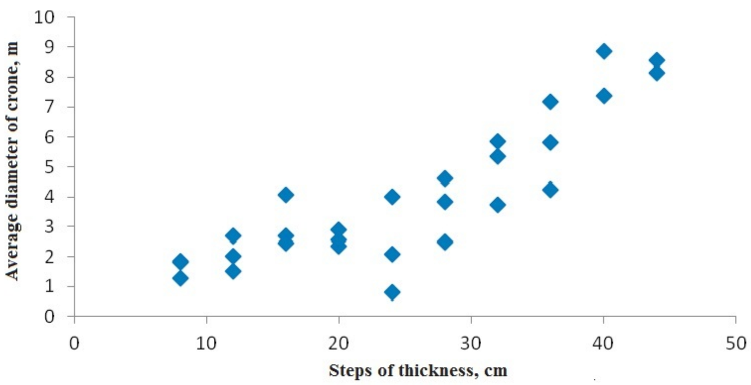


Fig. 2. Correlation between average crown diameter and steps of thickness

Statistical analysis of the maximum crown radii by cardinal points

Statistical indicators	North	N-E	East	S-E	South	S-W	West	N-W
Average	2,1	2,0	2,3	2,0	1,9	1,9	2,0	1,7
Standard error	0,3	0,3	0,3	0,3	0,3	0,2	0,3	0,3
Median	1,6	1,7	1,9	1,8	1,5	1,6	1,5	1,6
Mode	1,6	0,5	0,7	0,5	1,6	0,7	0,6	0,7
Standard deviation	1,4	1,4	1,6	1,4	1,4	1,3	1,5	1,3
Sample variance	2,1	1,9	2,6	1,8	2,1	1,7	2,4	1,8
Excess	1,6	1,3	0,3	1,4	2,2	0,0	0,3	2,9
Asymmetry	1,3	1,2	1,0	1,3	1,6	1,0	1,2	1,7
Interval	5,8	5,3	5,7	5,4	5,8	4,5	5,2	5,3
Minimum	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4
Maximum	6,2	5,7	6,1	5,8	6,2	4,9	5,6	5,7
Accuracy of experience	13,1	13,0	13,3	12,6	14,4	13,3	14,6	14,6
Coefficient of variation	69,5	68,8	70,5	66,9	76,4	70,4	77,2	77,0

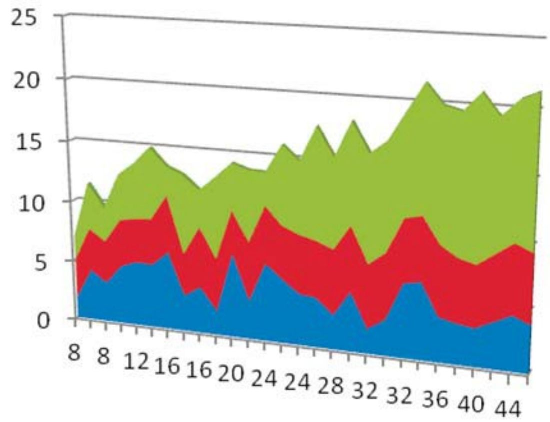


Fig. 3. Vertical structure of wood and pine plantations

The difference between these parts has allowed to determine whether the crown is adequately formed. For example, the upper and lower parts in a spherical shape should be approximately equal to each other, and the middle should be larger; measurements at these points in a cylinder form are approximately equal to each other.

Comparing the crown forms visually determined by photographs and measurements, it can be said that the errors were insignificant, and this allows the crown to be considered a regular geometric figure with a high degree of probability.

Having studied the aggregate crown forms of the Scots pine, several groups of predominance of one form or another can be distinguished. In steps with a thickness of 8 and 12 cm, the cylindrical form is most common, an inclined cone is rarely found. The presence of this form can be explained by the canopy that has not yet closed, while climatic factors favourably affect the development of the crown, there is no marked competition.

Trees of 16 and 20 steps are dominated by a spherical form, with a rare cone form. Such a form as a spherical sector occurs singly in 20 and 24 steps, this form was most likely formed due to species competition, since the spherical sector is a figure with a narrow base and an increasing diameter. The presented crown contour contributes to greater absorption of solar energy.

In the 24th and 28th steps, the spherical form of the crown is clearly distinct.

In the 28th and 32nd steps, it is impossible to distinguish any predominant form. In this case, the form depends on stand completeness, the availability of light and competitor trees. Lack of light, high completeness of planting and species competition promotes the formation of various crown forms.

Starting from the 36 cm step and ending with 44 cm, the spherical form is predominant, the hemisphere and the spherical sector are rare.

After necessary calculations it was established that the horizontal projection of the Scots pine crowns is a circle. This allows a crown to be seen as a stereometric figure and its volume to be calculated. (I. N. Vetoshkina, A. A. Weiss [3]).

A separate stereometric formula was applied for each crown form determined earlier:

$$V = \frac{1}{4}\pi d^2 h, \text{ circular cylinder;} \quad (2)$$

$$V = \frac{1}{12}\pi d^2 h, \text{ circular cone;} \quad (3)$$

$$V = \frac{1}{6}\pi d^2, \text{ sphere;} \quad (4)$$

$$V = \frac{1}{12}\pi d^2, \text{ hemisphere;} \quad (5)$$

$$V = \frac{2}{3}\pi r^2 h, \text{ sphere sector.} \quad (6)$$

where d – crown diameter, m; h – crown length, m; r – crown radius, m; $h,$ – sector height, m.

According to the radii measured earlier and the calculated diameters, the crown volume of each sample tree was determined by the thickness gradation. To do this, we used stereometric formulas for calculating the volume (2)–(6). In order to determine the dispersion degree of dots by volume, a graph of the volume on diameter dependency at chest height was drawn. The diagram shows that the spread of points is insignificant up to the 20th degree of thickness. Therefore, a linear equation was used for small-sized trunks. The model type is as follows: V = 0.951 · d1,3. The correlation coefficient is 0.922, the standard error is 6.1 m3. The equation is reliable and trustworthy, F > 3(62), the coefficient of the equation turned out to be significant. To create the final table, the initial model was calibrated in degrees of thickness (8–20 cm).

Determining the volume of the crown for large-sized trees requires taking into account a number of values: the diameter of the trunk, the place of the tree in the canopy, the vertical structure of the crown, adjacent trees competition, etc.

CONCLUSION

It has been determined that the form of crowns within a tree stand varies considerably. At the same time each tree species is characterised by its own typical, predominant form of the crown. Therefore, by studying the form of the crowns of Scots pine in the Kuraginsky forestry, it was discovered that the form of the crowns of small trees is close to cylindrical. Trees up to 28 cm have the form of a sphere, as well as a spherical sector. It is not possible to determine any form for trees with diameter from 28 to 32 cm, as the crown habitus is diverse. Large trees (36-44 cm) have a sphere form. Such diversity of crowns at different steps of their thickness indicates that pine crowns are very likely to be affected by wind loads.

It is difficult to suggest one universal formula for determining the crown volume of a pine tree, as errors are very common. It is recommended to calculate crown volume separately for large and small trees.

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РЕЗУЛЬТАТЫ СРАВНЕНИЯ НИЗКОТЕМПЕРАТУРНЫХ ЭКЗО- И ЭНДОТЕРМ ПРИ ЗАМЕРЗАНИИ ВОДЫ И ПЛАВЛЕНИИ ЛЬДА В ТКАНЯХ 2-ЛЕТНЕЙ ХВОИ У НЕКОТОРЫХ ВИДОВ ХВОЙНЫХ ДЕРЕВЬЕВ*

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Описаны результаты сравнительного исследования вечнозеленых хвойных видов Сибири (Picea obovata Ledeb., Pinus sibirica Du Tour., Pinus sylvestris L., Abis sibirica Ledeb.) по характеру низкотемпературных экзотерм и эндотерм при замораживании до –80 ºС и оттаивании 2-летней хвои, проведенного с помощью дифференциальной сканирующей калориметрии (ДСК). Установлено, что хвоя деревьев перечисленных видов, собранная в начале-середине осени, отличается как по температуре начала и окончания кристаллизации воды, так и по температуре начала плавления льда, количеству выделившегося и поглощенного тепла, количеству связанной воды. Оценена индивидуальная изменчивость хвои перечисленных видов деревьев по температурам начала, пиков и окончания кристаллизации воды при ее охлаждении, а также температурам начала, пика и окончания плавления льда при нагревании. Отмечен общий характер изменений ДСК-профилей большей части образцов при охлаждении их до –80 ºС. В образцах чаще наблюдались 2 экзотермических пика, реже – 1 или 3–5 пиков. Анализ данных свидетельствует о непрерывной быстрой кристаллизации воды в 2–3 разных тканях хвои при скорости охлаждения образцов 10 ºС·мин$^{-1}$. Различия по температурам поглощения тепла при плавлении льда в образцах, в целом, согласуются с отмеченными различиями по температурам выделения тепла при кристаллизации растворов. Более высокая физиологическая морозостойкость выявлена у хвои ели сибирской и пихты сибирской, а также деревьев сосны обыкновенной из Якутии. Полученные результаты подтвердили возможность использования варианта ДСК с быстрой скоростью охлаждения для оценки морозостойкости деревьев, позволяющего увеличить объем выборки деревьев.

Ключевые слова: *хвойные виды, устойчивость хвои к низким температура, дифференциальная сканирующая калориметрия.*

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THE RESULTS OF COMPARISON OF LOW-TEMPERATURE EXOTHERMS AND ENDOTHERM DURING FREEZING AND MELTING WATER IN THE TISSUES OF 2-YEAR-OLD NEEDLES IN SOME SPECIES OF CONIFEROUS TREES

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The results of a comparative study of evergreen coniferous species of Siberia (Picea obovata Ledeb., Pinus sibirica Du Tour., Pinus sylvestris L., Abis sibirica Ledeb.) are described in terms of low-temperature exotherms and endotherms during freezing to –80 ºC and thawing of 2-year-old needles carried out using differential scanning calorimetry (DSC). It has been established that the needles of the trees of the listed species, collected in early-mid-autumn, differ both in temperature of the beginning and end of water crystallization, and in temperature of the beginning of ice melting, the amount of released and absorbed heat, and the amount of bound water. Individual variability of the needles of the listed tree species was estimated in terms of the temperatures of the beginning, peaks, and end of water crystallization during its cooling, as well as the temperatures of the beginning, peak, and end of ice melting during heating. General character of changes in the DSC profiles of most of the samples when they are cooled to –80 ºC is noted. In the samples, 2 exothermic peaks were observed more often, than 1 or 3–5 peaks. Analysis of the data indicates a continuous rapid crystallization of water in 2–3 different tissues of needles at sample cooling rate 10 ºC min^{-1}. Differences in heat

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absorption temperatures during ice melting in the samples, on the whole, are consistent with the noted differences in the temperatures of heat release during crystallization of solutions. A higher physiological frost resistance was found in the needles of Siberian spruce and Siberian fir, as well as Scots pine trees from Yakutia. The results obtained confirmed the possibility of using the DSC variant with a fast-cooling rate to assess the frost resistance of trees, which makes it possible to increase the sample size of trees.

Keywords: *coniferous species, needle resistance to low temperatures, differential scanning calorimetry.*

INTRODUCTION

Study of the resistance of woody plant species to adverse environmental factors remains relevant for both fruit growing and forestry. It is known that coniferous species growing in Siberia are generally resistant to low temperatures [16; 17]. However, "swaying" of weather observed in the last decade, which manifests itself in sudden changes in temperature over short time intervals, in an increase in the amplitude and frequency of changes within a year/season [10], disrupts the established course of phenological rhythms in coniferous species. In particular, there are changes in timing of onset of phenological phases in different species of woody plants [1; 9 and others]. It was noted that, due to global climate change, abnormally warm winters led to a change in the timing of onset of stages in the development of coniferous pollen and, as a result, to a greater irregularity of their seed production (in terms of quantity and quality of seeds) [8; 11; 13]. Earlier pollen emergence by 10–18 days in common pine was also noted in the south of the Krasnoyarsk Territory and in Khakassia (in the period 2003–2015 compared to 1996–2001, except for 2009 and 2013). Along with this, in the period from 2001 to 2005 in the same place, a high content of underdeveloped and empty seeds was observed in the cones. It should be noted that unidirectional trends in climate change for such intrazonal species as Siberian larch, Scotch pine, Siberian spruce, Siberian cedar pine, Siberian fir, in general, do not pose a great danger compared to increase in fluctuations within seasons, when long warm periods in autumn, in winter or spring are replaced by quick freeze. Reproductive tissues are especially sensitive to low temperatures during their formation, development and growth. It is known, that during the evolution, species have developed mechanisms to protect hibernating tissues from damage by freezing water crystals, such as the formation of ice crystallization centers in the extracellular space, changes in the structure of cell membranes, the synthesis of compounds that lower the freezing point of water, an increase in content of bound water, partial dehydration and others [2; 6; 12; 14; 15; 19; 20; 24; 27]. Differential scanning calorimetry (DSC) methods provide great opportunities for studying frost resistance of plants [3]. However, most of the works known that use these methods to study frost resistance of woody plants were performed on wood tissues and buds [6; 7; 18; 19; 22; 23; 24; 26].

The needles of evergreen coniferous species have been underexplored in this regard. In connection with the above, the purpose of the research was to study the process of ice crystallization and melting during freezing and thawing of tree needles in order to assess the possibility of a wider use of DSC methods in predicting the response of coniferous species to quick freeze and negative temperatures in early autumn, on a significant sample of trees.

MATERIALS AND METHODS

The studies were carried out using the methods of differential scanning calorimetry on 2-year-old needles. Samples were collected in early to mid-September from Scots pine trees (*Pinus sylvestris)*, Siberian cedar pine (*Pinus sibirica)*, Siberian spruce (*Picea obovate)*, Siberian fir (*Abis sibirica)*, spruce Siberian form blue *(Picea obovata f. glauca)*, also from common juniper (*Juniperus communis)* and American arborvitae (*Thuja occidentalis)*, growing in the Arboretum of the V.N. Sukachev Forest Institute of the Siberian Branch of the Russian Academy of Sciences in Krasnoyarsk [5]. For comparison, samples of needles were collected in the Scots pine population in the Priobsky forest of the Altai Territory and on the river Orosu in Yakutia; Siberian spruce (in the same place, in Yakutia); Siberian cedar pine and Siberian fir in Turukhansk, on the northern border of the distribution of species. The total sample was 35 trees. For analysis, the middle part of intact needle was cut out, weighed with an accuracy of 0.0001 g, and placed in an aluminum crucible with a lid. An empty aluminum crucible served as a reference. Mass of a sample varied from 1.13 to 6.55 mg. All measurements were performed on a DSC 204 F1 instrument (NETZSCH, Germany). The sample in a helium atmosphere was subjected to gradual cooling from +10 to –80 ºC, and then to heating to +30 ºC at a rate of 10 ºC min/min^{-1} (flow rate of protective gas is 40 ml/min^{-1}, purge gas flow rate is 70 ml/min^{-1}. This cooling rate, according to L.K. Lozino-Lozinsky [4], is considered to be borderline between "slow" and "fast". The instrument was calibrated according to the instructions using the reference substances supplied with the instruments.

Processing of the measurement results – determination of temperature of the beginning and end of water crystallization in needles, the amount of heat released (absorbed) in cooling-heating cycle, glass transition temperature and change in heat capacity, temperature of the beginning and end of melting – was carried out using the software package, "NETZSCH Proteus Thermal Analysis 4.8.4".

RESULTS AND DISCUSSION

When analyzing the results, we took into account that, at cooling rate used in the experiment, living tissues usually die at the initial temperature of water crystallization [6; 19]. Despite this, with the help of analysis and others listed above indicators of DSC profiles, it is possible to obtain additional information on the potential frost resistance of tree needles (their pre-adaptation in early autumn), without taking into account the ability to adapt and harden off with gradual temperature changes over several days to weeks.

It is necessary to note general nature of changes in thermodynamic values under conditions of fairly rapid cooling of most samples of Scots pine needles and some samples of Siberian spruce, Siberian fir and common juniper needles (Fig. 1, *a*). In most samples, 2 exothermic peaks stand out. In contrast, 1 Siberian spruce tree, 2 Siberian fir trees, and all 6 Siberian stone pine trees from Turukhansk, as well as 2 Scotch pine trees from Yakutia, have 3-5 peaks on the exotherm (Fig. 1, *b*). Obviously, each of the subsequent peaks of curve reflects the involvement of new cellular structures and solutions in crystallization process – the more diverse they are, the more obstacles there seem to be for formation and spread of growing ice crystals and the more diverse the composition of the samples according to their physicochemical properties (crystallization temperature of solutions). The curves obtained are significantly different from those for slow freezing of buds at a rate of –5…–10 ºC/h^{-1} [6], where one first main maximum stands out, associated with a large separate low-temperature spike in the curve – with a change in state of supercooled water inside cells and cell membranes. All samples of Siberian spruce form needles of 2 Siberian fir trees from Turukhansk, needles of 1 Siberian spruce tree from Yakutia, and needles of 2 Scotch pine trees from Priobsky forests are more similar to them (Fig. 1, *c*).

The observed exotherms testify to continuous rapid crystallization of water in 2–3 different tissues of needles. The first peak is probably associated with freezing of water in cells of the xylem, phloem, and in intercellular spaces of vascular bundle, which contain a larger amount of free water compared to other needle tissues (Fig. 2). The second is associated with crystallization of water inside the cells of parenchyma. These two peaks are rarely equivalent in terms of rate of heat release per unit fresh mass of the sample mW/g, more often the second one prevails over the first one or the first one over the second one. The second peak was higher in the samples of most Scots pine trees and individual trees of other species, the first peak was higher in the needles of most Siberian spruce trees and individual Siberian fir and Siberian stone pine trees.

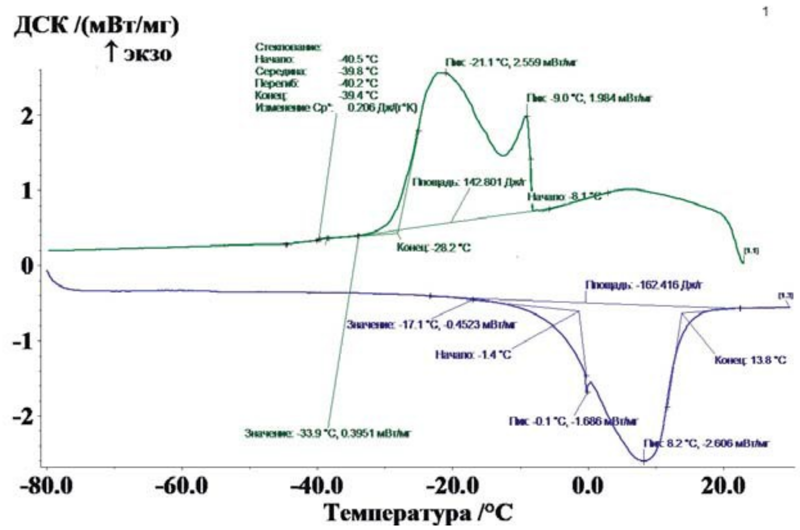
It should be noted that with slower cooling of the needles, the value of the first peak will be much larger than the second one due to outflow of free water from cells to centers of ice crystallization in extracellular space and establishment of thermodynamic equilibrium with ice at –17–25 °C [6], when water remaining in cells (about 25–30 %) can be preserved in a supercooled state up to a temperature homogeneous nucleation, down to –80 °C [25]. In cryopreservation, on the contrary, higher cooling rates (1000 ºC/min^{-1}) are used, at which formation of ice crystals that disrupt the intracellular structure is unlikely [3].

Along with an increase in number of exothermic peaks, some samples exhibit lower peak onset temperatures and a larger range of freezing temperatures for water in the sample. At the same time, in Siberian fir and individual samples of Siberian spruce, which significantly differ in lower temperatures of the onset of water crystallization (see table), 1–2 main high-temperature exothermic peaks and 1 small low-temperature peak predominate in the sample. The literature also provides conflicting information: a single exothermic peak can be observed both during slow cooling in living tissues of the most frost-resistant plants, and in plants that have already died as a result of rapid cooling [3].

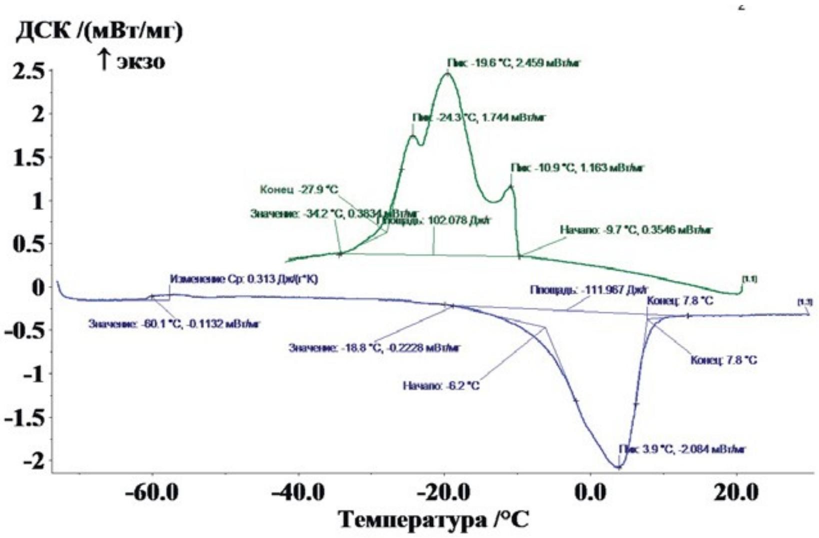
It was found that the temperature of the onset of water freezing in a high-temperature part of the DSC profile (T1) in live needle samples varies from –6.1 to –17.7 ºC. The main distinct peaks of heat release are observed at temperatures of –9.7…–16.4 ºC (T2) and –11.2…–27.3 ºC (T3), respectively. The temperature of the end of a heat release process varies from –23.5 to –39.0 ºC (T5); in some samples, a slight release of heat was observed at low temperatures – from –38.8 to –58.2 ºC. In addition, in a low-temperature part of DSC profiles of 29 out of 35 samples, from 1 to 3 changes in heat capacity associated with the glass transition of supercooled water were revealed. They were observed mainly at temperatures of –37.8…–39.3 ºC, in some trees at temperatures of –40.7…–68.4 ºC. Obviously, if the number of peaks in the high-temperature exotherm indicates differences between the species in anatomical structure of the needles, then the values of the listed temperatures are more related to the biochemical differences in the composition of solutions in the samples. Thus, the differences between needle samples are 11.6 ºC (according to T1), 6.7 ºC (T2), 16.1 ºC (T3) and 15.5 ºC (T5), i.e., the smallest differences are observed in the temperature of the first peak (T2) and 2 times greater - in other temperatures. In one of the review works on cryobiology, it was also noted that, unlike animals, plant cells are characterized by a large freezing temperature range, up to 9 ºC [21].

At a rough estimate of variability of DSC profiles within a tree, we also compared 3–4 samples each in 5 Scots pine trees (one of the most heat-loving species) and 2 samples each in 2 Siberian stone pine trees, 1 Siberian fir tree, and 1 Siberian cedar pine from the Arboretum of the IL SB RAS (Fig. 3). Preliminarily, it can be noted that the largest range of values within a tree was revealed for temperatures T3 and T5. For clarification, additional studies are required on needles collected in different parts of a tree crown.

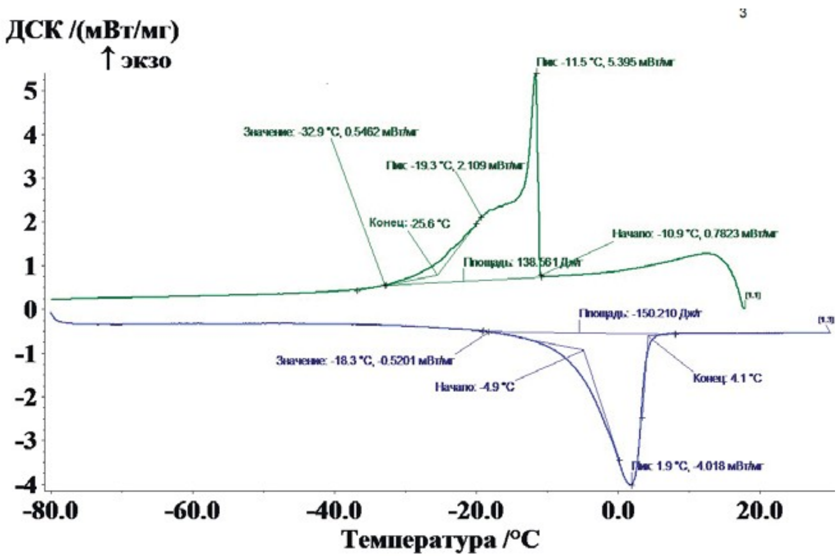
As a result of comparing the used characteristics of DSC profiles, lower temperatures ($t = 2.67–32.56$, $p < 0.0000–0.048$) for the start and end of heat release (T1 and T5) during cooling of samples of fir needles Siberian fir from the Arboretum of the IL SB RAS, Siberian fir from Turukhansk, and Scots pine and Siberian spruce from Yakutia, as well as lower temperatures for the end of heat release in the needles of all forms of Siberian spruce from the Arboretum (table) were established reliably. Higher temperatures for the beginning and end of water crystallization were obtained from the analysis of samples of Siberian pine (of different origin) and most of the samples of Scotch pine from the Altai Territory. It is interesting that minimum temperature of the beginning of water crystallization (–17.7 ºC) and glass transition temperature (–68.4 ºC) were observed in the North American species, American arborvitae. Differences within species between samples from geographic populations (lower temperatures of beginning and end of heat release in needle samples from northern habitats) turned out to be unreliable for all species, except for Scotch pine ($t = 6.09$, $p < 0, 0005$). Scotch pine was also distinguished by greater variability of the temperatures of the beginning and end of water crystallization within the species.



a



b



c

Fig. 1. DSC profiles of freezing (upper line) and defrosting (lower line) of needles:
a – Scotch pine; *b* – Siberian pine; *c* – Siberian spruce f. blue

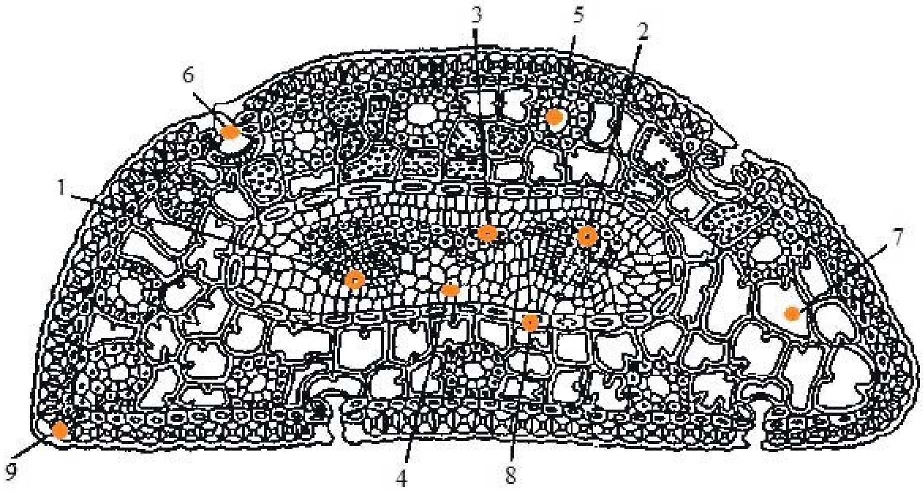


Fig. 2. Cross section of Scotch pine needles:
1 – xylem; 2 – phloem; 3 – sclerenchyma; 4 – transfusion tissue of the conducting bundle; 5 – resin channel; 6 – stomata; 7 – folded parenchyma; 8 – endoderm; 9 – epidermis and hypodermis

Average values (first row) and limits (second row) of exo- and endotherm temperatures when freezing and thawing 2-year-old needles of compared evergreen species

Tempreture, °C	Types of conifers					
	Pinus sylvestris	*Pinus sibirica*	*Picea obovata*	*Abis sibirica*	*Juniperus communis*	*Thuja occidentalis*
Water crystallization						
T1*	–9,0 –14,1…–6,1	–9,4 –10,2–8,8	–11,9 –14,0–9,1	–13,5 –14,9–12,0	–10,2	–17,7
T2	–10,2 –16,4…–9,7	–10,3 –11,2–9,2	–12,8 –14,9–10,4	–17,2 –27,3–13,1	–13,0	–22,4
T3	–19,8 –26,3–12,4	–14,3 –19,6–11,4	–20,1 –22,9–13,5	–20,4 –22,7–18,7	–17,9	–
T4	–20,9 –23,7–17,2	–21,1 –24,3–14,1	–25,0 –26,1–23,3	–	–19,5	–
T5	–32,8 –39,0–22,0	–29,6 –34,2–23,5	–35,3 –38,8–32,9	–34,4 –37,9–29,4	–35,0	–31,6
Q1, Дж/г	127,4 57,6–173,6	116,8 82,7–157,4	133,6 127,1–140,5	112,2 76,5–145,7	109,7	156,3
Ice melting						
T6	–18,2 –28,0–13,4	–18,1 –18,8–16,3	–19,6 –23,2–18,3	–19,8 –21,7–15,8	–21,3	–18,3
T7	+5,8 +0,2+10,2	+2,6 +0,2+5,2	+3,5 +1,9+5,8	+1,5 –1,2+4,6	+2,5	+0,8
T8	+14,5 +4,6+23,4	+8,7 +4,3+13,6	+10,3 +7,7+14,5	+6,9 +2,6+11,6	+9,1	+6,0
Q2, Дж/г	–141,9 –57,3–181,2	–129,3 –99,8–167,0	–148,9 –139,3–157,3	–119,5 –76,3–148,5	–111,8	–125,5
Q2–Q1, Дж/г	29,9 9,7–48,0	33,0 15,6–43,1	27,9 20,8–31,3	29,7 19,1–40,9	30,4	9,0

Notice. T1 is the start temperature; T2 is the temperature of the first peak; T3 is the temperature of the second peak; T4 is the temperature of the third peak; T5 is the temperature of the end of heat release; T6 is the start temperature; T7 the temperature of the first peak; T8 is the end temperature of ice melting. Single samples of *J. communis* and *T. occidentalis* were used.

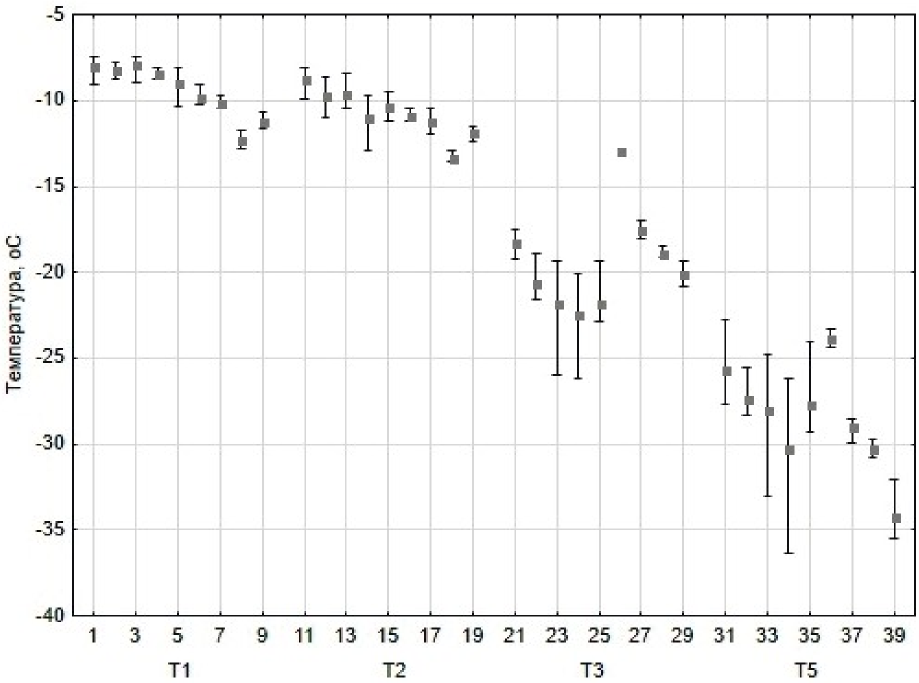


Fig. 3. Limits of temperature values (T1–T5, symbols see in the table) of exothermic curves in samples inside trees: 1–5 Scotch pine; 6–7, Siberian pine; 8 - Siberian fir; 9 - Siberian spruce

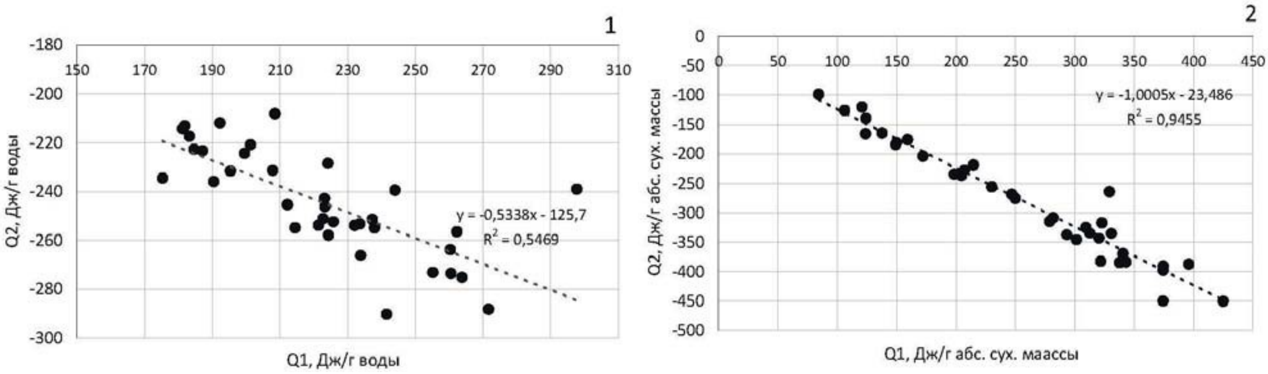


Fig. 4. Dependence of the amount of heat absorbed during ice melting on the amount of heat released during crystallization per unit mass of water (1) and unit of absolutely dry mass of needles (2)

Differences in the temperatures of heat absorption during melting of ice in the samples (T6-T8), in general, are consistent with the noted differences in T1-T5. However, in Scotch pine, the needles of some trees were characterized by the lowest temperature of the beginning and peak of heat absorption during ice melting (T6, T7), and in Siberian pine – low peak temperature of heat absorption (T7).

As can be seen from fig. 4, there is a negative correlation between the amount of heat (Q1) released during crystallization and absorbed (Q2) during ice melting, which is closer to Q values per absolutely dry mass of the sample and weaker for Q per unit mass of water. This also indicates a greater variability of the samples in terms of the composition of solutions and the proportion of bound water in them than in terms of the thermodynamic characteristics of mechanical and other tissues of dry matter of needles. At the same time, the range of Q1 and Q2 values per unit of absolutely dry mass of needles was 4 times wider. In general, samples of needles of different tree species are distributed in one series of Q2 versus Q1 dependence, with the exception of American arborvitae, whose leaf structure is very different from other coniferous species.

CONCLUSIONS

As a result of the studies, it was found that evergreen coniferous species are characterized by high intraspecific variability of DSC profiles, both in shape of the curves (by the number of peaks) and in the listed temperatures, reflecting differences in composition and amount of the compound, lowering freezing point of liquid in the samples of needles. Taking into account the needles collected in the southern, central and northern regions of Siberia in early autumn, the differences between the samples of coniferous species in terms of temperatures of exo- and endothermic curves were 7–21 ºC: the minimum differences were in the temperature of the first peak of water crystallization (6.7 ºС), higher - by the temperature of the beginning (11.6 ºС), the second peak (16.1 ºС) and the temperature of the end of water crystallization (15.5 ºС), as well as by the temperature of the beginning (14.6 ºС), peak (11 .4 ºС) and the end (20.9 ºС) of ice melting.

The general nature of changes in the DSC profiles of most of the samples upon cooling to –80 ºС at a rate of 10 ºС/min^{-1} was noted: more often 2 exothermic peaks, less often 1.3–5 peaks. The observed exotherms testify to the continuous rapid crystallization of water in 2–3 different tissues of needles at a cooling rate of samples of 10 ºС/min^{-1}. The first peak is presumably associated with the crystallization of water in the cells and intercellular spaces of the conducting bundle, the second peak is associated with the crystallization of water inside the cells of the parenchyma. Of the two main peaks, in Scotch pine, more often, the second peak prevails over the first in terms of the rate of heat release per unit wet weight of a sample; in Siberian pine and Siberian spruce, the first peak more often prevails.

In general, a higher frost resistance was noted for the needles of Siberian spruce and Siberian fir, as well as for Scotch pine trees from Yakutia. Higher temperatures for the beginning and end of water crystallization were obtained from the analysis of Siberian pine samples (of different origin) and most of the samples of Scotch pine from the Altai Territory. The minimum temperature of the beginning of water crystallization (–17.7 ºС) was observed at American arborvitae. This sample also significantly differed from the others in terms of the ratio of the amount of released and absorbed heat.

The conducted studies indicate the possibility of using the DSC variant with a fast cooling rate to assess frost resistance of trees, which makes it possible to increase a sample size of trees. Further research is needed to clarify the value of endogenous and individual variability of trees according to the listed characteristics.

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ЭФФЕКТИВНОСТЬ РАЗНОГУСТОТНОГО РЕЖИМА ЛЕСОВЫРАЩИВАНИЯ КУЛЬТУР СОСНЫ В ЮЖНОЙ ТАЙГЕ СРЕДНЕЙ СИБИРИ

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Исследованы 35-летние экспериментальные разногустотные посадки сосны обыкновенной (Pinus silvestris Ledeb) 18 вариантов густоты в подзоне южной тайги (Красноярский край). Рассмотрены особенности динамики роста и продуктивности разногустотных ценозов, начиная с момента создания. Доказано, что плотность посадок культур изначально определяет индивидуальный сценарий хода роста и развития ценозов в процессе формирования. Получены густотно-зависимые характеристики изменения запаса, диаметра, высоты культур. Доказано, что с возрастом очень густые ценозы утрачивают приоритет по показателям продуктивности, а оптимальная густота культур постепенно смещается на более низкие густоты посадки.

Ключевые слова: *Pinus silvestris Ledeb., густота посадки, возрастная динамика, таксационные показатели, южная тайга, Красноярский край.*

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EFFICIENCY OF REAFFORESTATION REGIME OF PINUS PLANTATIONS OF DIFFERENT DENSITIES IN SOUTHERN TAIGA OF CENTRAL SIBERIA

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Are investigated 35-years experimental plantations of pine (Pinus silvestris Ledeb) at 18 variants of densities in the southern taiga subzone (Krasnoyarsk Krai). The peculiarities of growth dynamics and productivity of dense-variety cenoses, starting from the moment of their planting, were considered. It has been proved that the density of planting cultures initially determines the individual scenario of the course of growth and development of cenoses in the process of formation. Density-dependent characteristics of changes in stocking, diameter and height of cultures are obtained. It is proved that with age, very dense cenoses lose priority in terms of productivity, and the optimal density of cultures gradually shifts to lower planting densities.

Keywords: *Pinus silvestris Ledeb, planting density, age-related dynamics, inventory parameters, southern taiga, Krasnoyarsk Krai.*

INTRODUCTION

Stand density is the most important in productivity among biocenotic indicators. In sparse stands, due to insufficient use of environmental resources, stands are formed with decreasing productivity. The tree experiences a growth depression in dense and excessively dense stands, which inevitably causes a loss of growth and reduced productivity. In other words, the density of the stand is adjusted by natural regulators to the resource potential of the particular ecotope environment. There is a reason to believe that it is possible to achieve the maximum possible total productivity of wood of the desired size and quality by regulating the density [5; 8; 7; 11; 17].

Judging by the current density and fullness of our forests, the average fullness of which is 0.65, we can conclude that the forest stands significantly under-utilise the resources of the environment to form timber products. Studies and calculations show that more wood products in 1.5–2 times can be obtained from a unit area only by increasing the density of stands with the same climatic and edaphic resources compared to its available supply in the current stand [1; 2]. Consequently, the conclusion about a large reserve for increasing productivity through low- and medium-height stands is confirmed, and the idea that increasing the density of green cover will allow to sharply increase its biological productivity at the energy input to the biosphere [6; 18] materializes.

The issue of planting density of forest cultures has been discussed for more than 150 years and is still important in forestry. V. N. Sukachev [16] believed that the form and direction of competitive relations between plants, determined mainly by plant density, significantly change the lifetime state of forest phytocenoses and determine the morphostructure and productivity of different density cultures.

Until recently, the effect of planting density in pine cultures has been judged by a large number of studies, but mainly in the European part of the country. The first significant experience with planting cultures of different densities was established in the forestry dacha of the Timiryazev Agricultural Academy, when the optimum density of pure and mixed pine, spruce and larch cultures for the middle belt of Russia was found on the basis of experimental data.

Noteworthy is the long-term 65-year monitoring of experimental pine cultures in the Serebryanoborsky experimental forestry area with planting densities of 2, 4, 8, 16, 32 thousand pieces/ha. By the age of 30 years, the most productive pine plants here were those with planting density of 4 and 8 thousand spices/ha. Later, thinning was carried out in all plots [3; 9; 12].

35-year experimental cultures of pine with seven variants of density (from 2.5 to 30 thousand pieces/ha), created in 1940 in Boyarsky FES of the Ukrainian Agricultural Academy are of great interest. During the systematic observations it turned out that pine crops with planting density from 2.5 to 7 thousand had good growth, high productivity and stability. The planting density of 5 thousand was proposed as a recommendation. [15].

A review by A. P. Ryabokon [14] on optimising the density of pine stands shows that the variability in planting density norms is due to different methodological approaches to the study of the density of coniferous cenoses.

The undoubted value have the materials summarised over a century on pine plantations of different densities in the former Soviet Union, where the criteria for optimisation in terms of productivity and sustainability were discussed [19].

Most foresters clearly recognise that natural factors play a dominant role in determining optimum densities, and recommendations for optimum planting densities are regional by natural and climatic zone.

Planting of variable-density cultures in the taiga zone of Siberia is very limited, although pine forest cultures are being established over large areas [4]. The considered multivariant experience of pine cultures is yet the only one.

The aim of the work was to assess the reaction of pine cultures to planting density in the dynamics of their structure and productivity over a 35-year growth period.

OBJECTS AND METHODS OF RESEARCH

Experimental plantations of *Pinus sylvestris* L. were laid in 1982 by workers of the Forest Institute of the Siberian Branch of the Academy of Sciences under the direction of A.I. Buzykin in the southern taiga subzone (Bolshemurtinsky forestry, Krasnoyarsk Krai) on grey forest soils from agricultural use in homogeneous upland forest conditions.

The experiment with planting with 2-year-old seedlings was an ascending row consisting of 18 density variants: (Variant No. – density, thousand pcs./ha):

1	2	3	4	5	6	7	8	9
0,5	0,75	1	1,5	2	3	4	6	8

10	11	12	13	14	15	16	17	18
10	12	14	16	24	32	64	96	128

The collecting of field materials included a total estimation of trees on each section, measuring heights and diameters on the surveyed trees (at least 25 pieces). Cultures heights were determined from height curves with reference to the average diameter of the stand. Stem stock was calculated using volume tables for young pine trees [10]. The data was processed in Excel. Unfortunately, one variant (No. 8) with a planting density of 6,000 pieces/ha was excluded from the analysis because it was damaged.

Only direct (immediate) measurements and counts were used in the taxation and statistical processing, then the totals and averages of each density variant were analysed and the effect of density on growth and productivity of young stands at each age was assessed., The marginal planting rows in contact with gaps were excluded from the processing to eliminate its effects. The methodology is described in more detail in previous publications [2].

The different densities of the studied cultures represent an example of different use of the productivity of the same growing conditions. This kind of data allows to be interpreted as “density curves” of changes in stock, height, diameter, phytomass and other parameters [1; 20; 21; 22]. Density curves make it possible to find the density that ensures the maximum bioproductivity of stands.

RESULTS AND DISCUSSION

Changes in stand density and decline with age. Studies have shown that as a result of natural thinning of cultures with age, there was a unidirectional and gradual decrease in the current density of the remaining living part of the cenosis by variants of the experiment. If the initial density between the rarest and densest variant in pine plantations (0.5 and 128 thousand pcs./ha) differed 256 times, then at the age of 35 years it differed 48 times (0.56 and 11.75 thousand pcs./ha) (Fig. 1).

The survival rate of pine seedlings after planting was very high in all experiment variants (on average 82 %), and the total number of healthy plants averaged 60 % (see Fig. 1).

Three years after planting, the intensity of fall-off of 5-year-old pine trees had a random stochastic character. In subsequent years, the role of the regulator of their density was determined by the competitive relationship between the trees and the natural thinning increased as the cenoses grew and the crowns closed.

Tree elimination was more intensive in dense planting variants. So, in the interval of planting density of 0.5–16 thousand pieces/ha, the initial density decreased by 35 years approximately 2 times. It decreased 4 times in the interval of planting of 24–32 thousand pieces/ha; 6 times – at planting density of 48 thousand pieces/ha; 10–11 times – in the interval of 64–128 thousand pieces/ha (Fig. 1, a).

There was no further thinning after the accidental fall-off in single sparse stands and their density has remained virtually unchanged since 12 years of age.

Age-related changes in the average diameter of stands. The average diameter of pine trees, from 12 to 35 years of age, increased most intensively in single-growing trees (6–9 times), the increase in sparse stands (2–4 thousand pcs./ha) was 4–5 times. It was about 3–4 times in thickened and dense stands (8-128 thousand pcs./ha).

The tightness of the correlation between the average diameter and density of pine cenoses during the formation of young stands was high and increased with growing age. Thus, closeness of correlation between average diameter of stands and density (R^2) at the age of 12 years, was 0.74, at 15 years – 0.89, at 20–35 years – 0.9-0.98 (Fig. 2).

The difference between the maximum and minimum values of the average diameter in the dense row of pine trees at 12 years was 1.7, at 15 years – 2.5, and at 20–35 years – 3.3–3.8.

With increasing age, the range between the extreme values of average diameters widened. Thus, the amplitude of pine diameters at 12 years of age ranged within 1.7 cm (2.4)–(4.1), at 15 years – 5.3, at 20 years – 11.0, at 25 years – 14.8, at 30 years – 18.5, at 35 years – 19.9 m. The diameter range for 23 years increased by 11.7 times.

The figures of the average cenosis diameters increased with decreasing of current density. However, the effect of density on tree distribution by thickness was limited to a certain range of current density figures at each studied age. While at 12 years, the average and maximum stand diameters depended on the current density in the interval up to 30 thousand pieces/ha, at 35 years – up to 8, after which virtually the same figures were observed.

The thinnest trees marked the boundary beyond which they began to die off. The diameter of such trees at 12–15 years of age did not exceed 1 cm. With age, due to the natural process of thinning growth, the lower limit of diameters shifted upwards and at 35 years of age, the diameter of thin trees was 6–9 cm.

The change in the average height of stands from the current density was not unambiguous. Regardless of age, the average height of trees from the free-growth state to the cenosis one initially increased as the crowns were closing in, but decreased with further increase in stand density (Fig. 3). Compared to the average diameter, the closeness of the correlation between tree height and culture density is low, as tree height responds poorly to changes in cenosis density than diameter does.

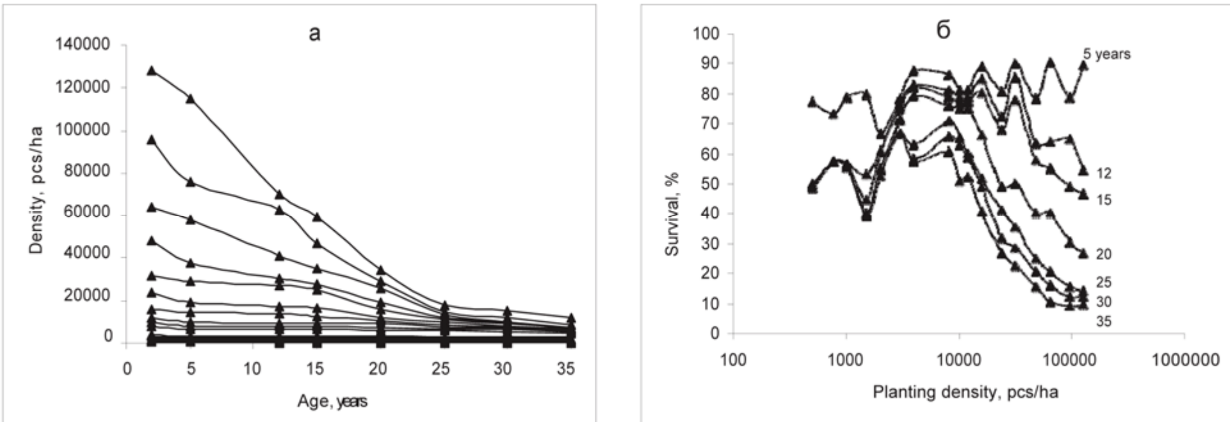

Fig. 1. Change in densities amplitude with age (*a*) and post-planting survival (*b*) in pine cenoses

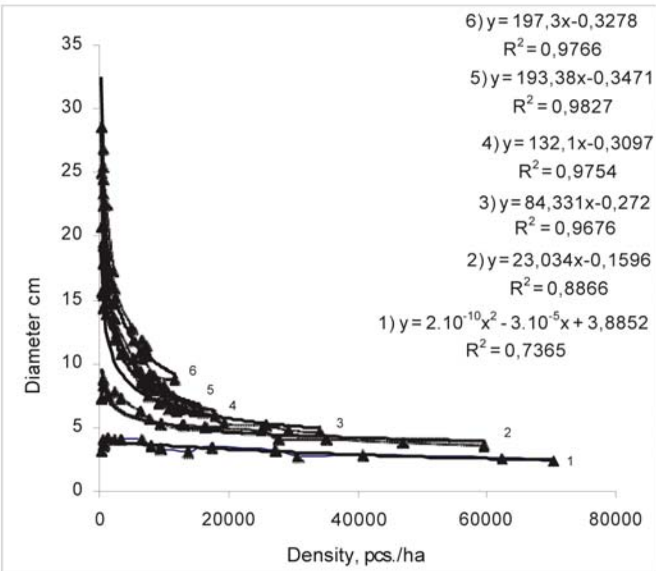

Fig. 2. Dependence of average diameter of pine cenoses on their current density at ages:
1 – 12 years; *2* – 15 years; *3* – 20 years; *4* – 25 years; *5* – 30 years; *6* – 35 years

The difference between the maximum and minimum figures of average heights from 12 to 35 years was almost constant, averaging 1.2 to 1.3 times, while for diameter the difference varied from 2 to 4 times.

The interval between the extreme figures of average heights increased with age. Thus, the range of heights of pine trees at age 12 was 1.0 m (2.5–3.5), at age 15 years – 1.3, at age 20 years – 1.4, at age 25 years – 1.8, at age 30 years – 2.7 and at age 35 years – 3.7. The height amplitude increased 4 times in 23 years, from 1.0 to 3.7 m: the amplitude of the average diameter increased almost 12 times.

Changes in stocking and current growth of stands with age. It follows from the above that planted cultures of sparser density have an advantage in terms of average stocking rates over denser ones. However, the growth in stock per hectare has a different pattern due to the number of remaining trees in the area. At different age stages, the maximum stock of the stand was formed by different number of trunks.

From 12 to 20 years there was a proportional increase in the stock with cenosis density, with its maximum occurring in the most dense variant. After 25 years, the stock increased with growing cenosis density to a certain maximum, followed by a gradual decrease. In each time interval, these indicators had a parabolic dependance. Over time, the maximum stock gradually shifted towards lower density. At 25 years, the maximum stock occurred at the current density of 11.3 thousand pieces/ha, at 30 years – at a density of 9.1, and at 35 years – at a density of 6–7 thousand pieces/ha and amounted to 500 m^3/ha (Fig. 4).

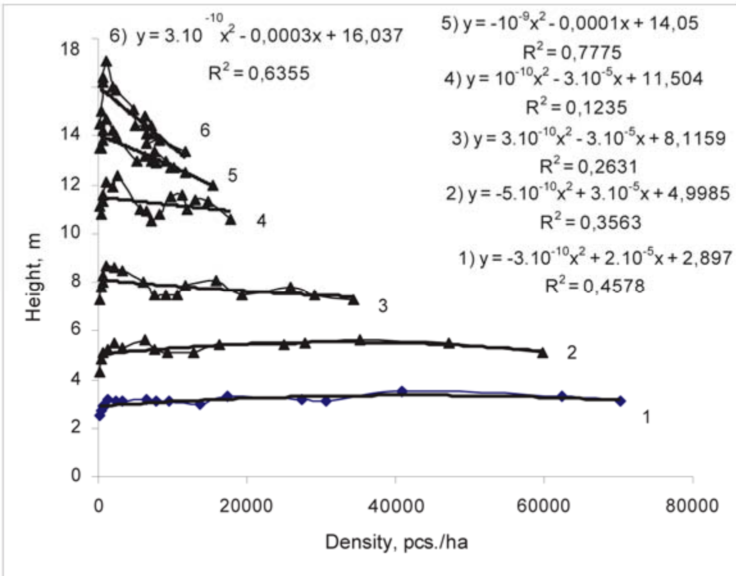

Fig. 3. Dependence of average height of pine cenoses on their current density at age:
1 – 12 years; *2* – 15 years; *3* – 20 years; *4* – 25 years; *5* – 30 years; *6* – 35 years

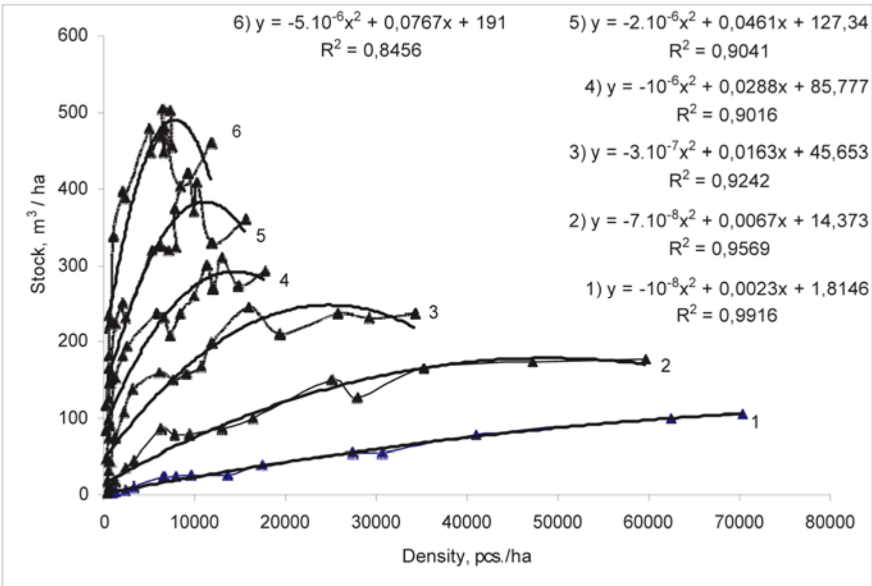

Fig. 4. Dependence of the stem stock of pine cenoses on their current density at ages:
1 – 12 years; *2* – 15 years; *3* – 20 years; *4* – 25 years; *5* – 30 years; *6* – 35 years

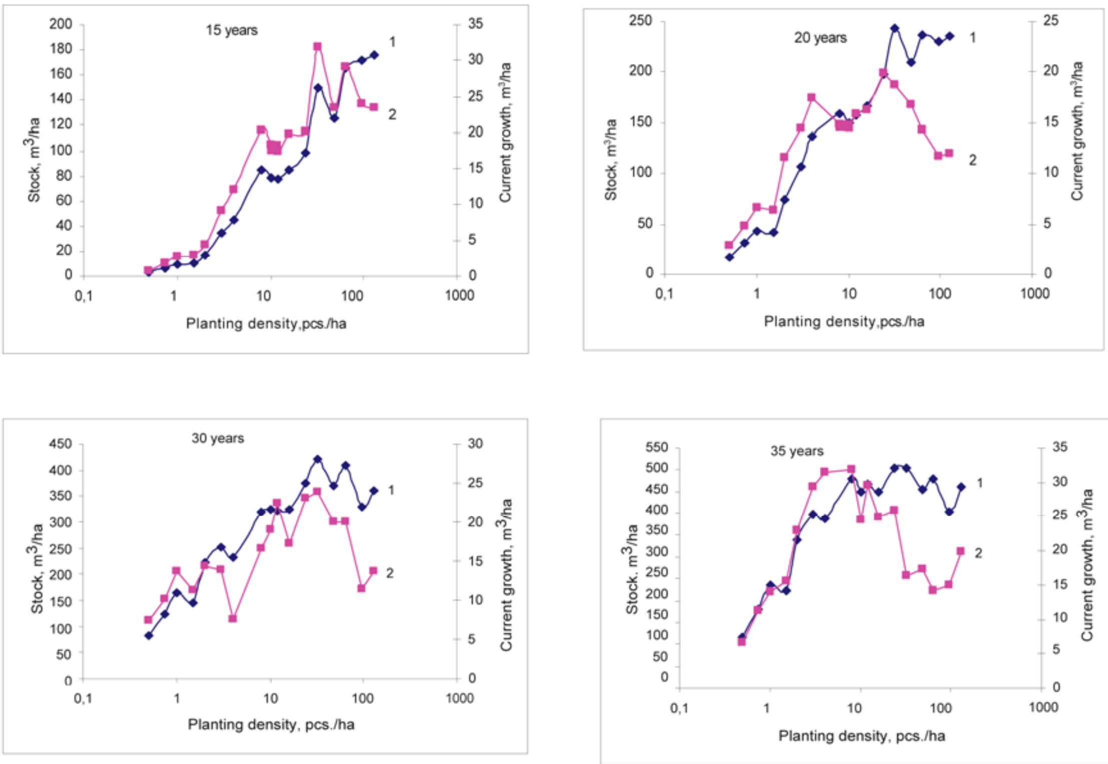

Fig. 5. Variation of stock with age (*1*) and current growth (*2*) depending on planting density in pine cenoses

For comparison, in Fig. 5 stem stock is correlated with current wood growth in relation to planting density. The figure shows that the cultures stock in 15 years was proportional to planting density, and the current growth reached a maximum at planting density of 32,000 pcs/ha, then decreased. At the age of 20, the stock increased intensively up to planting density of 32,000 plants/ha, and the peak of current growth corresponded to planting density of 24,000 plants/ha. At the age of 30–35 years stocking leveled off, and even slightly decreased, starting from planting density of 24 and 8 thousand pieces/ha respectively; the current growth increased intensively up to planting density of 12 and 4–8 thousand pieces/ha. Thus, by the age of 35 years the maximum figures of current growth and stocking were observed at planting density of 8 thousand pieces/ha, which corresponded to the actual density of 4.9 thousand pieces/ha. With further densification of planting, the stock figures leveled off, i.e. fluctuated within insignificant limits, and the current growth decreased.

CONCLUSION

Thus, the results of the 35-year experience indicate a continuing influence of pine planting density on the main productivity indicators of cenoses. Changes in density and thinning of cenoses during the formation of young trees are regulated in accordance with the volume and supply of vital environmental resources through changes in the number and size of individuals. For normal growth and development, a woody plant needs some optimal living space (feeding area), the amount of which changes with growth and depends on the size of the tree. The older the stand, the lower the optimum density.

At the end of observations, the variant with planting density of 8 thousand pieces/ha turned out to be the most optimal in terms of productivity out of 18 variants of planting density. This variant had a survival rate of 86 % after planting, resulting in an initial density of 6,900 pieces/ha. At the age of 35 years, the fall-off was 39 %, and the planting density decreased to 4.9 thousand pieces/ha. Due to the low age of the cultures, it can be argued that the process of shifting the optimal silvicultural and taxation indicators to less dense variants of cultures will continue until the end of the phase of young stands formation.

Based on the preliminary results of the experiment, it is possible to increase the criterion for planting density suggested in the “Guideline...” [13] for economic reasons by the amount of expected drop-off (up to 40 %) to 6–8 thousand seedlings per ha in similar regional conditions of the taiga zone. in similar regions. [13]. Compared to sparse planting density, such denser cenoses in the process of formation are closer to natural forest plantations in terms of growth and development, as natural self-regulation, biological stability increases and there is no need to supplement cultures. Thinning is possible in correcting excessive densities.

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Хвойные бореальной зоны. 2022. Т. XL, № 7 (специальный). С. 616–619

ПОКАЗАТЕЛИ 50-ЛЕТНЕЙ СОСНЫ КЕДРОВОЙ СИБИРСКОЙ ПОСЛЕ ДЕКАПИТАЦИИ КРОНЫ НА ПЛАНТАЦИИ «ЛЭП-1» (ПРИГОРОДНАЯ ЗОНА ГОРОДА КРАСНОЯРСКА)

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Приведены данные о росте и семеношении декапитированных деревьев сосны кедровой сибирской на плантации «ЛЭП-1» в Караульном лесничестве Учебно-опытного лесхоза СибГУ им. М. Ф. Решетнева. Обрезка крон проведена у деревьев в 28-летнем биологическом возрасте с удалением от 4 до 10 мутовок на высоте от 1,7 до 2,8 м. Через 9 лет деревья были подвергнуты повторной декапитации с удалением 6–8 мутовок лидирующих побегов. В 50-летнем возрасте контрольные деревья достигли высоты 8,9 м. Средняя высота декапитированных деревьев составила 7,9 м, что на 12,6 % меньше, чем в контроле. Коэффициент изменчивости показателей декапитированных деревьев выше, чем у контрольных. Диаметр ствола контрольных и декапитированных деревьев в 50-летнем возрасте не имеет существенных различий. После обрезки кроны на деревьях формируются в основном по 1–2 лидирующих побега. По три лидирующих побега образовалось у 47 % деревьев, по четыре – всего у 3 % деревьев. В 2017 г. шишки образовались на 34 % контрольных деревьев, 46 % – декапитированных.

Ключевые слова: *сосна кедровая сибирская, декапитация кроны, изменчивость, Сибирь.*

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INDICATORS OF 50-YEAR-OLD SIBERIAN CEDAR PINE AFTER DECAPITATION OF THE CROWN ON THE PLANTATION “LEP-1”(SUBURBAN AREA OF THE CITY OF KRASNOYARSK)

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The results of studies about the growth and yield of dekapitation trees pine Siberian Cedar at plantation “LEP-1” in the Karaulny territory of the Training and Experimental Forestry SibSU are given. Trim crowns held at the 28-year-old in the biological age trees from 4 up to 10 interstitial site at a height of 1.7 to 2.8 m. Through 9 years trees were subjected to repeated delete 6–8 interstitial site of leading shoots. Control trees aged 50 years reached a height of 8.9 m. The average height of the cropped trees amounted to 7.9 m, which at 12.6 % lower than in control trees. Coefficient variability of cropped trees is higher than of the control trees. The diameter of the trunk control and cropped trees in a 50-year-old has no significant differences. After trimming crown trees are formed mainly by 1–2 leading the escape. Three leading escape was formed at 47 % of the trees, four – in 3 % of the trees. In 2017 g. bumps were formed on 34 % of control trees, 46 %-cropped trees.

Keywords: *pine Cedar Siberian, crown dekapitation, variability, Siberia.*

INTRODUCTION

The main way to reduce the height of trees today is decapitation, that is, cutting the upper part of the crown at different intensities. Reducing the height of trees at breeding sites, i.e., creating low-growing plantations, can make it possible to make cuttings, collect cones, hybridize, and other work without climbing to a great height into the crown of a tree [1; 6; 9; 17; others]. In Russia, crown decapitation is carried out with Sukachev's larch, Norway spruce, Scotch pine and Siberian pines [2; 3; 8; 16].

The issue of the possibility of decapitation of the crowns of cedar pines was studied not only by domestic scientists, but abroad too: Jae-Seon Yi et al. [18] noted an increase in the production of Korean pine by 1.4–2.2 times after decapitation.

At the time, N. P. Bratilova and S. S. Shamova [2; 3] studied the effect of crown decapitation of cedar pines at the age of 42–57 years.

Although numerous experiments have been conducted, the question of the benefits or harms of deciduous conifers topping remains unanswered. Opinions on the effectiveness of decapitation of the crown of conifers, as well as its effect on growth and productivity, are different. A.I. Iroshnikov [8] noted that pruning the upper part of the central shoot of Siberian larch stimulates seed production, but excessive removal of the crown can, on the contrary, reduce the production of the tree.

Stimulation of the onset and increase in the intensity of seed production after crown decapitation in Scots pine was noted also in the works of Y. A. Danusyavichus [6], V. I. Dolgolikov [7], E. P. Prokazin [11] and others.

D. Y. Girgidov [5], A. I. Sidor [14], V. V. Tarakanov and others [13], V. L. Cherepnin, N. A. Kuzmina [15] noted the negative effect of crown decapitation on seed production of trees in the first few years after pruning. M.P. Sinkevich, M.A. Klinov [12] pay attention to a possible decrease in the viability of trees by 70–75 % due to crown pruning. According to V.V. Tarakanov and others [13], controversial results regarding the data obtained after decapitation of conifers are associated with the variety of crown pruning regimes used by them, as well as the peculiarities of development of decapitated trees depending on the type of tree species, area of growth, etc. He noted that the crown pruning at the age of stable seed production is most effective for conifers, for Scotch pine in particular.

OBJECTS AND METHODS OF RESEARCH

The object of the study was Siberian cedar pine trees growing on the plantation “LEP-1”, located on the territory of the Karaulny territory of the TTraining and Experimental Forestry of the Reshetnev Siberian State University. The planting was carried out in 1977 using 10-year-old seedlings. Pruning of tree crowns was carried out in 1996 with removal of 4 to 10 whorls at the height from 1.7 to 2.5 m. In 2005, the trees were subjected to repeated decapitation with the removal of 6–8 whorls from the leading shoots [10].

The research program included a comparison of biometric indicators of Siberian cedar pine trees with a decapitated crown and without decapitation (control trees) in height, trunk diameter at a height of 1.3 m, shoot growth in height for 2016–2018, and the number of cones. The study data were statistically processed using the Microsoft Office software package.

RESULTS AND DISCUSSION

By the age of 50, non-decapitated trees (control) reached a height of 8.9 m with a low level of variation. The average height of decapitated trees was 7.9 m, which is 12.6 % less than in the control. The level of variability is high. At the same time, the coefficient of variability of decapitated trees is higher than that of the control ones (Table 1).

The diameter of the trunk of decapitated trees and the control ones differs slightly (tf = 0.93), which is consistent with the data of N.P. Bratilova, S.S. Shamova [2]. The level of variation of the indicator is high in both variants.

Growth of leading shoots in height in 2016–2018 was 16.4–19.4 cm without significant differences between decapitated and control trees. The growth variability coefficient of decapitated trees is higher than that of control trees. The central shoot of decapitated trees after pruning the crown is replaced by the shoots of the whorl closest to the cut. Basically, 1–2 leading shoots are formed on the tree. Three leading shoots were formed in 47 % of trees, four shoots had only 3 % of trees. The average diameter of one best shoot was 9.5–10.9 cm. A significant difference in the diameter of shoots was found only in trees with one and three leading shoots (Table 2).

Decapitated trees, which form a larger number of leading shoots, are also distinguished by a large diameter of shoots.

Analysis of the distribution of decapitated trees by trunk diameter showed that it is symmetrical ($A < 0.5$) with a shift to the right, the distribution is peaked ($E < 0.5$ in modulus). The distribution in height is peaked, extremely asymmetric with a shift to the right, the asymmetry is negative (Table 3).

In control trees, the range of distribution along the diameter of the trunk is peaked, the asymmetry is weak. 71 % of the trees are in the range of 9–18 cm. In terms of height, the asymmetry is positive, with a shift to the left, 76 % of the trees are in the range of 7.5–8.9 m.

The influence of the cutting height on the trunk diameter was traced (Table 4).

Table 1
Comparative analysis of biometric indicators of decapitated and control trees

Trees	$\bar{x}$	±σ	±m	V, %	$t_ф$ with t_{05} = 2,01
Height, m					
Not decapitated (control)	8,9	0,98	0,18	11,3	–
Decapitated	7,9	1,69	0,19	21,3	3,82
Diameter of trunk, cm					
Not decapitated (control)	16,2	4,13	0,75	25,5	–
Decapitated	15,4	3,88	0,42	25,2	0,93
A sprouted shoot 2016, cm					
Not decapitated (control)	17,6	5,13	0,93	29,1	–
Decapitated	16,4	7,09	1,29	43,2	0,75
A sprouted shoot 2017, cm					
Not decapitated (control)	19,4	4,89	0,89	25,2	–
Decapitated	16,6	5,87	1,07	35,4	2,01
A sprouted shoot 2018, cm					
Not decapitated (control)	19,2	6,35	1,37	33,1	–
Decapitated	16,4	5,82	1,27	35,4	1,50

Table 2
Diameter of leading shoots on decapitated trees with different numbers of them, cm

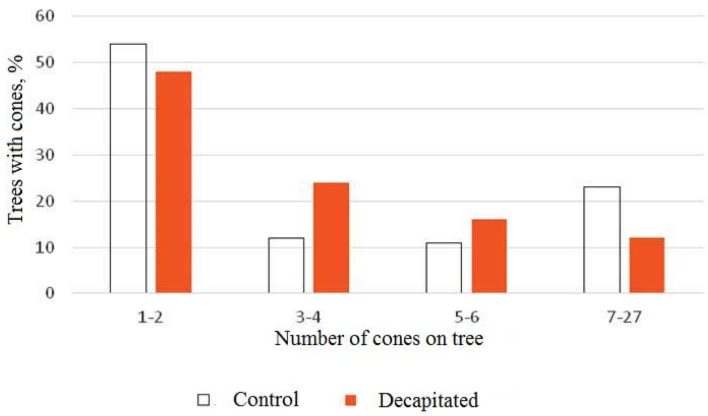
Trees having leading shoots, pcs.	$\bar{x}$	±a	±m	*V*, %	t_f
1	9,5	3,23	0,34	34,0	2,32
2	9,9	3,30	0,38	33,3	1,59
3	10,9	3,25	0,50	29,8	–

Table 3
Characteristics of the distribution of decapitated trees by trunk diameter and height

Indicator	Decapitated		Control		Critical value at 95th probability level
	in diameter of trunk	in height	in diameter of trunk	in height	
Mediana	16,1	9,0	16,0	8,2	
Mode	16,0	10,1	14,0	8,0	
Excess	–0,20	0,34	0,01	3,01	0,814
Asymmetry	–0,48	–1,11	0,19	0,28	0,163
Minimum	6,0	3,0	8,1	7,4	
Maximum	25,0	11,3	25,0	11,4	

Table 4
Stem diameter depending on the number of removed whorls and cutting height

Number of removed whorls, pcs.	Cutting height, m	Min, cm	Max, cm	$\bar{x}$, cm	% to x
9–10	1,7	6,0	22,0	14,9	96,7
7–8	2,0	7,1	24,1	15,9	108,2
4–6	2,8	10,1	24,3	16,6	100,6



The formation of cones on trees in the control and experimental variants

It has been established that the diameter of the trunk differs insignificantly according to the prunning options. There is no correlation between the cutting height and trunk diameter (r = 0.06).

In 2017, cones were formed in 34 % of control trees, 46 % of decapitated trees, 1–27 pcs. of cones on a tree. Basically, 48–54 % of the trees formed 1–2 cones each (see the picture).

CONCLUSION

Studies have shown that when the crown of 28-year-old Siberian Cedar pine trees is decapitated, biometric indicators decrease: height, growth of the leading shoot, trunk diameter of 50-year-old trees, but their reproductive capacity increases.

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АНАЛИЗ ФЛОРЫ СООБЩЕСТВ С УЧАСТИЕМ *JUNIPERUS EXCELSA* SUBSP. *POLYCARPOS* (C. KOCH) TAKHT. ПРЕДГОРНОГО ДАГЕСТАНА

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Представлены результаты анализа растительных сообществ Предгорного Дагестана с участием краснокнижного вида Juniperus excelsa subsp. polycarpos (C. Koch) Takht. Рассмотрена таксономическая и биоморфологическая структура флоры, проведен географический анализ, выявлены эндемичные, реликтовые и охраняемые виды, занесенные в Красные книги России и Республики Дагестан.

Выявлено 239 видов высших растений, относящихся к 163 родам и 58 семействам, определен спектр семейств (As-Po-Ro), характерный для ксерофитностепного флороценотического комплекса среднеевропейского типа. Биоморфологический спектр можжевеловых редколесий Предгорного Дагестана относится к гемикриптофитно-терофитному типу, соответствующий в целом аридной флоре. Высокая доля реликтов и эндемиков (21,3 и 21,5 %, соответственно) от общего числа видов в составе можжевеловых редколесий свидетельствует об их реликтовом характере, значительном своеобразии и существенной роли автохтонных процессов в формировании флоры арчовых редколесий Предгорного Дагестана.

Анализ структуры флоры можжевеловых редколесий Предгорного Дагестана показывает его приграничное положение, на стыке бореального и древнесредиземнорского подцарств Голарктики, в зоне контакта евро-сибирской и ирано-туранской областей, характерной в целом и для Кавказа с более глубокой и древней связью с ирано-туранской флорой.

Ключевые слова: *флора, аридные редколесья, географический анализ, эндемики, реликты, биоморфологический анализ, Juniperus excelsa subsp. polycarpos, Предгорный Дагестан.*

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ANALYSIS OF THE FLORA OF COMMUNITIES WITH THE PARTICIPATION OF JUNIPERUS EXCELSA SUBSP. POLYCARPOS C. KOCH FOOTHILL DAGESTAN

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The paper presents the results of the analysis of plant communities of Piedmont Dagestan with the participation species of the Red Book Juniperus excelsa subsp. polycarpos (C. Koch) Takht. The taxonomic and biomorphological structure of the flora was considered, a geographical analysis was carried out, endemic, relict and protected species identified in the Red Books of Russia and the Republic of Dagestan were identified.

239 species of higher plants belonging to 163 genus and 58 families have been identified, the spectrum of families (As-Po-Ro) characteristic of the xerophytic-steppe florocenotic complex of the Central European type has been determined. The biomorphological spectrum of juniper open woodlands of Piedmont Dagestan belongs to the hemicryptophyte-terophytic type, corresponding generally to the arid flora. The high proportion of relicts and endemics (21.3 and 21.5% of the total number of species, respectively) in the composition of juniper open woodlands indicates their relict nature, significant peculiar and role autochthonous processes in the formation of the juniper forests of Piedmont Dagestan.

Analysis of the structure of the flora of juniper open woodlands of Piedmont Dagestan shows its cross-border position at the junction of the boreal and ancient Mediterranean kingdom of the Holarctic, in the zone of contact of the Euro-Siberian and Iranian-Turanian regions, characteristic generally and for the Caucasus with a deeper and ancient connection with the Iranian-Turanian flora.

Keywords: *flora, arid open woodlands, geographical analysis, endemics, relicts, biomorphological analysis, Juniperus excelsa subsp. polycarpos, Piedmont Dagestan.*

INTRODUCTION

The analysis of cenoflores, in contrast to the territorial flora analysis, is more informative and allows to reveal the ecological and geographic patterns of community formation.

This paper presents the results of the research of cenoflores in Foothill Dagestan with the rare species Juniperus excelsa subsp. polycarpos C. Koch. The issues of taxonomic and biomorphological structure of communities, geography, endemism, and relict plant species that determine the originality of floras and directly correlate with their genesis and transformation are considered.

Analysis of cenoflores with J. excelsa subsp. polycarpos is important not only for revealing the mechanism of their genesis, but also for solving the issues of ex situ conservation of the species populations and reproduction of its gene pool.

RESEARCH METHODS

Communities with J. excelsa subsp. polycarpos were studied in two areas of Foothill Dagestan: Talginsky and Gubden.

1. The Talginsky area is situated in the south-west, 20 km from Makhachkala at the foot of Kukurtbash mountain in the Istisu-Kaka gorge or Talginsky gorge at heights from 400 to 600 m above sea level on slopes of southern and northern exposures with steepness from 5 to 50°. Soils are light-chestnut to brown, depending on altitude level, formed on fine- and medium-clastic limestone with rocky outcrops up to 30 %.

2. The Gubden area is located in the Central Foothill Dagestan, 5 km from the village of Gubden, on the southern spurs of Chonkatau Ridge and the northern spurs of Shamkhaldag Ridge (Gubden area) at a height of 785–910 m above sea level on western, south- and northwestern slopes with a steepness of 25 to 45°, on chestnut low-humus, clastic-rubbly, clay-carbonate soils with outcrop of parental rocks and presence of de-alluvial hillocks, 10–15 cm deep.

The flora of the communities was analyzed according to generally accepted methods of floristic research [21]. The taxonomic belonging and nomenclature of species are given according to the "Dagestan Flora List" [16]. The analysis of geographical elements was performed using the classification of elements of the Caucasian flora developed by A.A. Grossheim [5–7]. The analysis of life forms was carried out according to the H. Raunckier's system [2; 15]. The Red Book of the Republic of Dagestan [12] and the Red Book of the Russian Federation [13] were used to identify rare and protected species. The list of endemics was compiled according to the annotated list of endemics of the Caucasus by S.A. Litvinskaya and R.A. Murtazaliev [14]. The relics were identified according to the analytical lists of relics of the flora of Dagestan [1] and the abstracts of the floras of the North Caucasus republics [8; 9; 19; 23].

RESULTS AND CONSIDERATION

Systematic flora structure.

Taxonomic analysis is the most important part of flora analysis, where the composition and order of families in the spectrum reflect the features of the flora. The first 10 families are considered most informative, of which the first three reflect the most important regional features of the flora [10; 22]. The next three families are used in the assessment when the first three families in the compared floras are too heterogeneous.

239 species of higher plants belonging to 163 genera and 58 families were identified in the flora of juniper (J. excelsa subsp. polycarpos) sparse woodlands of Foothill Dagestan. The families *Asteraceae* (33 species), *Poaceae* (23), and *Rosaceae* (16 species) are leading by the number of species (see Table 1).

The families *Asteraceae* and *Poaceae* retain their position in the head part of the spectrum, which is a typical feature of Eurasian boreal floras, in connection with which this flora type can be referred to the *Rosacea*e type, since the flora type in the Holarctic floristic realm is determined by the third member of the first triad of families [22].

Table 1
The number of species in the spectrum of juniper woodlands flora families
(*J. excelsa* subsp. *polycarpos*) of Foothill Dagestan

Families	Rank	Number of genera	Number of species	%
Asteraceae	1	24	33	13,8
Poaceae	2	14	23	9,6
Rosaceae	3	12	16	6,7
Lamiaceae	4	11	15	6,3
Fabaceae	5	6	14	5,6
Brassicaceae	7	10	12	5,0
Caryophyllaceae	6	7	12	5,0
Apiaceae	8	6	7	2,9
Boraginaceae	9	6	7	2,9
Rubiaceae	10	2	7	2,9
Ranunculaceae	12	4	5	2,1
Dipsacaceae	11	2	5	2,1
Cistaceae	13	2	4	1,7
Crassulaceae	14	2	4	1,7
Papaveraceae	15	3	4	1,7

This spectrum of families (As-Po-Ro) slightly differs from the As-Po-Fa spectrum typical for the Caucasus and represents a xerophytic steppe florocenotic complex of the Central European type. The family Rosaceae in the first triad of leading families indicates the proximity to the Central European floras, and juniper woodlands of Foothill Dagestan in their formation, probably, as in general, arid woodlands of Foothill Dagestan, experienced a distinct influence of boreal floras [20].

The floristic spectrum of the second triad of leading families is headed by *Lamiaceae*, followed by *Fabaceae* and *Brassicaceae* with the number of species ranging from 12 to 15. The leading position of *Lamiaceae* and the presence of *Brassicaceae* in the second triad is generally characteristic of the flora of the Caucasus. Whereas the shift of *Fabaceae* into the second triad indicates a decrease in the influence of Mediterranean and Central Asian flora [22], whereas, on the contrary, *Fabaceae* occupies the leading position for juniper woodlands of High Mountain Dagestan [18].

The difference in the participation of the families *Rosaceae* and *Fabaceae* in the taxonomic spectrum of the flora of juniper woodlands may also indicate a change in the steppe and forest-steppe zones (10).

Overall, the leading families account for 146 species comprising 61 % of the flora. Small families (4–5 species) account for 9.2 % of the flora. These are such families as *Ranunculaceae, Dipsacaceae, Cistaceae, Crassulaceae, Papaveraceae*. The number of oligotypic (22) and monotypic (21) families is significant (21.0 and 8.8 %, respectively).

Geographical analysis. A special place in the flora analysis is occupied by the comparison of spectra of geographical elements. Geographical analysis of the flora allows to obtain information on the history of flora formation, its relationship with the surrounding flora, and the ways of species migration, and can be a fundamental factor in the sociological evaluation of rare and endangered plant species.

For the geographical analysis of the cenoflora of juniper woodlands (Table 2), the areal classification of A.A. Grossheim was used [5].

Thus, in the studied communities, the greatest number of species of xerophilic type of areal (75 species, 33.8 %), of which species of the Mediterranean class (45 species, 20.3 %) are predominant. The Nearctic class includes 28 species and the Central Asian class includes 2 species.

Species of boreal type (70 species, 31.5 %) are also well represented. Palaearctic (34) and European (25) species prevail here.

The high percentage of xerophilic type species in the area is associated with their migration to the Caucasus from Asia Minor, Iran, and Central Asia, which were the centers of development of xerophytic elements, while the distribution of boreal elements is associated with the migration of species from the north in the Quaternary period and close links with the floras of Europe and Palaearctic in general [3].

In the flora of the studied juniper communities, a significant role is played by species of the Caucasian type of the areal (49 species, 22.1 %), which indicates a important role of autochthonous processes and is an indicator of a high level of endemism [17]. The steppe type of the areal is represented by 22 species: 13 species belong to the Sarmatian and 8 to the Pontic classes of the areal.

Species of desert (3) and ancient forest (3) types are singularly represented here.

The weak representation of species of these types of areal is associated with their young age in the flora of the Caucasus and their appearance in the Caucasus only at the beginning of the Quaternary period as a result of marine regression.

Biomorphological analysis. The biomorphological structure of flora serves as an indicator of environmental conditions, reflecting the nature of plant adaptation to them.

Table 2
Geographical analysis of the flora of juniper woodlands (J. excelsa subsp. polycarpos) of Foothill Dagestan

Areal type	Areal class	Number of species	% of total number of species
1. Ancient (Tertiary) Forest	Minor Asian-Mediterranean Ancient	1	0,5
	Hyrcanian	2	0,9
	Total	**3**	**1,4**
2. Boreal	Holarctic	11	5,0
	Palearctic	34	15,3
	European	25	11,3
	Total	**70**	**31,5**
3. Steppe	Pannonian	1	0,5
	Pontic	8	3,6
	Sarmatian	13	5,8
	Total	**22**	**9,9**
4. Xerophilic	Mediterranean	45	20,3
	Trans-Asian	28	12,6
	Central Asian	2	0,9
	Total (%)	**75**	**33,8**
5. Desert	Turanian	3	1,3
6. Caucasian	Caucasian	49	22,1

The biomorphological analysis of the flora of the studied juniper communities, carried out by C. Raunckier classification, revealed the absolute dominance of hemicryptophytes – 124 species (55.6 %). Percentage of therophytes is significant – 44 species (19.7 %), which survive the unfavorable season of the year as dormant seeds. The large number of hemicryptophytes is a feature of the temperate-cold Holarctic flora, and the significant number of therophytes is a feature characteristic of the xeric territories of the Ancient Mediterranean [11].

The proportion of phanerophytes in the flora of the studied communities is 13.1 %, among which microphanerophytes (Phm) is 5.8 % (Table 3). The number of chameophytes and cryptophytes is equal (5.8 %). Chameophytes are mainly represented by families *Lamiaceae* (*Thymus daghestanicus* Klok. et Shost., *Thymus marschallianus* Willd., *Ziziphora serpyllaceae* Bieb, *Satureja subdentata* Boiss. etc.), *Cistaceae* (*Helianthemum grandiflorum* (Scop.) DC., *Helianthemum daghestanicum* Rupr.ex Boiss., *Fumana procumbens* (Dun.) Gren. et Godr.), *Asteraceae* (*Anthemis fruticulosa* Bieb., *Artemisia salsoloides* Willd.) Cryptophytes are represented by the families *Alliaceae* (*Allium atroviolaceum* Boiss., *Allium rotundum* L.), *Asparagaceae* (*Asparagus verticillatus* L., *Asparagus officinalis* L.), *Liliaceae* (*Tulipa biebersteiniana* Schult. et Schult. f., *Gagea bulbifera* (Pall.) Salisb.), *Orchidaceae* (*Orchis militialis* L., *Orchis morio subsp. picta* (Lois.) K. Richt.), *Iridaceae* (*Iris pumila* L., Iris notha Bieb.) and 3 monotypic families *Convallariaceae*, *Hyacinthaceae*, *Asphodelaceae*.

Thus, the biomorphological spectrum of the flora of juniper woodlands of High Mountain Dagestan is heterogeneous, revealing the features of plant adaptation to soil and climatic conditions. In general, the biomorphological spectrum of juniper woodlands of High Mountain Dagestan is of the hemicryptophytic-terophytic type, corresponding to arid flora in general (Table 5).

Rarity analysis. There are 10 species included in the Red Books of the Russian Federation and the Republic of Dagestan in the composition of juniper woodlands of Foothills Dagestan: *Artemisia salsoloides*, *Eremurus spectabilis* Bieb, *Hedysarum daghestanicum* Rupr. ex Boiss., *Iris notha*, *Iris pumila*, *Juniperus excelsa ssp. polycarpos*, *Orchis militaris*, *Orchis morio subsp. picta*, *Stipa pennata* L., *Stipa pulcherrima* C. Koch. In addition, 5 species (*Celtis caucasica* Willd., *Crambe gibberosa* Rupr., *Matthiola caspica* (Busch) Grossh., *Psephellus galushkoi* Alieva, *Salvia verbascifolia* Bieb. are included in the Red Book of the Republic of Dagestan.

Endemism analysis. Endemics are of particular importance in the analysis of the flora, indicating the originality of the flora and the directionality of florogenetic processes [4; 11].

48 endemics are represented in the communities with *J. excelsa subsp. polycarpos*, of which 20 species (41.7%) are endemics of the Caucasus (*Astragalus denudatus* Stev., *Bromopsis biebersteinii* (Roem. et Schult.) Holub, *Campanula sarmatica* Ker Gawl., *Cerastium ruderale* Bieb., *Dictamnus caucasicus* Sims, *Koeleria luerssenii* (Domin) Domin, *Onobrychis petrea* (Bieb. ex Willd.) Fisch., *Haplophyllum villosum* (Bieb.) G. Don. fil., *Galium brachyphyllum* Roem. et Schult. etc.) and 8 species are endemics of the Greater Caucasus (*Elytrigia gracillima* (Nevski.) Nevski, *Pedicularis daghestanica* Botani, *Polygala sosnowskyii* Kem.-Nath., *Salvia canescens* C. A. Mey, *Scorzonera filifolia* Boiss., *Thymus daghestanicus*, *Rosa elasmacantha* Trautv., *Cerastium holosteum* Fisch. ex Hornem.) (table 4).

There are 20 species of endemics of the Eastern Caucasus (*Anthemis fruticulosa, Astragalus alexandri* Char., *Fraxinus excelsior* L., *Hypericum asperuloides* Czern. ex Turcz., *Kemulariella rosea* (Stev.) Tamamsch., *Matthiola caspica, Milium vernale* Bieb., *Onobrychis bobrovii* Grossh., *Oxytropis dasypoda* Rupr. ex Boiss., *Psephellus boissieri* (Sosn.) Sosn.), of which 8 are endemics of Dagestan (*Campanula daghestanica* Fomin, *Dianthus awarica* Char., *Helianthemum daghestanicum*, *Satureja subdentata*, *Psephellus daghestanica* Sosn., *Psephellus boissieri*, *Psephellus galushkoi*, *Scabiosa gumbetica* Boiss.).

The high degree of endemism (21.5 % of the total number of species) indicates a significant role of autochthonous processes in the formation of the flora of juniper woodlands of Foothill Dagestan.

Table 3
Biomorphological spectrum of flora of communities with *J. excelsa* subsp. *polycarpos*

Biomorph	Ph				Ch	HK	K	T
	Phmg	Phms	Phm	Phn				
Number of species	1	4	13	11	13	124	13	44
% of total number	0,5	1,8	5,8	5,0	5,8	55,6	5,8	19,7

Table 4
Endemics in the flora of juniper woodlands (*J. excelsa* subsp. *polycarpos*) of Foothill Dagestan

Endemic groups	Number of species	% of total number of endemics
Greater Caucasus endemics	8	16,7
Caucasus endemics	20	41,7
Eastern Caucasus endemics	20	41,7
Dagestan endemics	8	16,7

Table 5
Relicts in the flora of juniper woodlands (*J. excelsa* subsp. *polycarpos*) of Foothill Dagestan

Relict group	Number of species	% of total number of relicts
Rt	24	47,1
Rg	5	9,8
Rx	22	43,1

Relict analysis. The relict analysis reflects historical stages of species contribution in the formation of the flora, as well as the relationship through them with other floras. To identify relics A.A. Grossheim's classification [7] was used, according to which the relics of Tertiary (Rt), Glacial (Rg) and Post-Glacial (Rx) periods are represented in the studied area.

There are 51 relict plant species in the flora of communities with *J. excelsa* subsp. *polycarpos* belonging to 43 genera and 29 families. One third of them (16 species) are represented by woody plants (*Cerasus incana* (Pall.) Spach, *Cotinus coggygria* Scop., *Cotoneaster integirrimus* Medic., *Fraxinus excelsior*, *Ligustrum vulgare* L., *Pyrus salicifolia* Pall., *Quercus petraea subsp. Petraea* ex Liebl., *Ephedra procera* Fisch. et C. A. Mey., *Juniperus communis* subsp. *oblonga* (Bieb.) Galushko, *J. polycarpos, Rhus coriaria* L.*, Rhamnus pallasii* Fisch. et Mey.*, Spiraea hypericifolia* L., *Ephedra procera*, *Viburnum lantana* L.).

Tertiary (24 species) and xerotermic (22 species) relicts are represented in almost equal proportions. Tertiary relicts are: *Alyssum daghestanicum* Rupr.*, Asparagus verticillatus, Asplenium ruta-muraria* L.*, Bromus briziformis* Fisch. et Mey.*, Campanula daghestanica, Ceterach officinarum* Willd.*, Geranium robertianum* L.*, Hedysarum daghestanicum, Helianthemum daghestanicum, Hypericum asperuloides, Juniperus excelsa ssp. polycarpos, Ligustrum vulgare, Medicago daghestanica* Rupr.*, Onobrychis bobrovii, Primula macrocalyx* Bunge, *Salvia canescens*, *Salvia verbascifolia, Scabiosa gumbetica, Thalictrum foetidum* L.*, Thesium ramosum* Kaune etc.

The relicts of the xerotermic period are remnants of floras characteristic of the Caucasus during interglacial arid epochs. In the investigated flora they are represented by the following species (43.1 %): *Artemisia salsoloides*, *Astragalus onobrychioides* Bieb., *Eremurus spectabilis*, *Festuca ovina* L., *Fumana procumbens*, *Haplophyllum villosum*, *Helianthemum grandiflorum*, *Iris pumila*, *Koeleria cristata* (L.) Pers., *Onobrychis cornuta* (L.) Desv., *Scabiosa micrantha* Desf., *Stipa capillata* L., *Thymus daghestanicus*, *Astragalus brachylobus* DC., *Euphorbia szovitsii* Fisch. et Mey., *Euphorbia glareosa* Pall. ex Bieb. etc.

There are 5 species (9.8%) of glacial relics: *Trisetum rigidum* (Bieb.) Roem. Et Schult., *Sedum subulatum* (C. A. Mey.) Boiss., *J. oblonga*, *Cotoneaster integirrimus*, *Sorbus torminalis* L.

CONCLISION

Structure analysis of the flora of juniper woodlands of Foothill Dagestan shows its border position at the junction of the boreal and ancient Mediterranean sub-regions of the Holarctic, in the contact zone of Euro-Siberian and Iranian-Turanian regions, which is also typical of the Caucasus in general [17] with a deeper and older connection with the Iranian-Turanian flora.

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ГЕНЕТИЧЕСКАЯ ДИФФЕРЕНЦИАЦИЯ ПОПУЛЯЦИЙ *PICEA OBOVATA* L. В РЕГИОНАХ СИБИРИ

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Представлены результаты исследования генетического разнообразия ели сибирской, произрастающей в регионах Сибири. Установлено, что основная доля генетической изменчивости приходится на внутрипопуляционную изменчивость (93 %). Четко прослеживается распределение исследованных популяций на 2 основных кластера по генетическим дистанциям.

Ключевые слова: *ель сибирская, генетическое разнообразие, дифференциация.*

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GENETIC DIFFERENTIATION OF *PICEA OBOVATA* L. POPULATIONS IN THE REGIONS OF SIBERIA

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The results of the genetic diversity study of Siberian spruce growing in the regions of Siberia are presented. It was revealed that major share of genetic variability accounts for intra-population variation (93%). The distribution of the studied populations into 2 main clusters at genetic distance is apparent.

Keywords*: Siberian spruce, genetic diversity, differentiation.*

INTRODUCTION

Siberian spruce (*Picea obovata* Ledeb.) is one of the dominant species of dark coniferous forests in Russia. Its distribution area extends from the north of the European part of Russia to the Pacific coast (Cherepanov, 1995). However, in spite of the wide area and studies of genetic variability of the species, many questions concerning the structure, genetic diversity, intra- and interspecific differentiation of *P. obovata* remain open. Currently, different types of genetic markers are most commonly used to study genetic variability and geographical subdivision of species [5; 6; 11]. Among them, microsatellite DNA loci are widespread. They are tandem repeats of short nucleotide motifs relatively evenly dispersed throughout the genome. They can be used to obtain data on multilocus genotypes of individuals, calculate the main indicators of intraspecific variability, and describe population processes [4; 8; 11; 12; 16].

The aim of this work was to obtain data on genetic diversity, population structure and differentiation of Siberian spruce growing in Siberia using nuclear DNA microsatellite analysis.

STUDY MATERIALS AND METHODS

Samples from 9 populations of Siberian spruce growing in natural stands on the territories of Krasnoyarsk Krai, Tomsk, Kemerovo, Irkutsk Oblasts, and the Tyva Republic were used as objects of the study. The names of the samples and their locations are presented in Table 1 and Fig. 1.

The volume of population samples was 32 trees. Total DNA was isolated from 100-200 mg of dried needles. DNA isolation was performed using the modified CTAB method [9].

The isolated DNA was used for polymerase chain reaction (PCR) with five pairs of microsatellite primers – EATC1B02, EATC1B03, UAPgAG105, Pa 33, Pa 36. PCR was performed using a commercial reagent kit “ScreenMix” (Evrogen Joint Stock Company, Russia). Amplification was performed on a T100 Thermal Cycler (BioRad). Characteristics of the microsatellite loci selected for the study and conditions of PCR amplification are shown in Table 2.

Amplification products were separated by electrophoresis in 6 % polyacrylamide gel using tris-EDTA-borate electrode buffer and stained in ethidium bromide solution. PCR products were visualized in ultraviolet light using a gel-documentation system. Data analysis was performed using

Vilber Lourmat Bio Capt v.12.5.0.0 software. Genetic diversity parameters were calculated using GenAlEx6 software [15].

Table 1
Geographical location of the studied samples of Siberian spruce

Sample name	Location area	Geographic coordinates	Forest vegetation zones and their composition (Ministry of Natural Resources and Environment, Order No. 367 of 18 August 2014)
Khor-Tagnanskaya	Irkutsk Oblast, Zalarinsky Forestry	53,13 N 101,28 E	South Siberian mountain zone, Altai-Sayan mountain-taiga region
Nazimovskaya	Krasnoyarsk Krai, Yeniseysk Forestry	59,66 N 90,80 E	Taiga zone, West Siberian southern taiga plain area
Stepnaya	Krasnoyarsk Krai, Karatuzsky Forestry	53,56 N 92,54 E	South Siberian mountain zone, Altai-Sayan mountain-taiga region
Kuraginskaya	Krasnoyarsk Krai, Kuraginsky Forestry	53,80 N 93,86 E	South Siberian mountain zone, Altai-Sayan mountain-taiga region
Izhmorskaya	Kemerovo Oblast, Izhmorsky Forestry	55,94 N 86,52 E	Taiga zone, West Siberian southern taiga plain area
Argat-Yulskaya	Tomsk Oblast, Ulu-Yulskoye forestry	57,83 N 86,09 E	Taiga zone, West Siberian southern taiga plain area
Nybegskaya	Tomsk Oblast, Verkhneketsky Forestry	58,28 N 84,74 E	The taiga zone, West Siberian middle taiga plain area
Balgazinskaya	Tyva Republic	50,91 N 95,01 E	South Siberian mountain zone Altai-Sayan mountain forest-steppe region
Todjinskaya	Tyva Republic	52,33 N 95,97 E	South Siberian mountain zone, Altai-Sayan mountain-taiga region

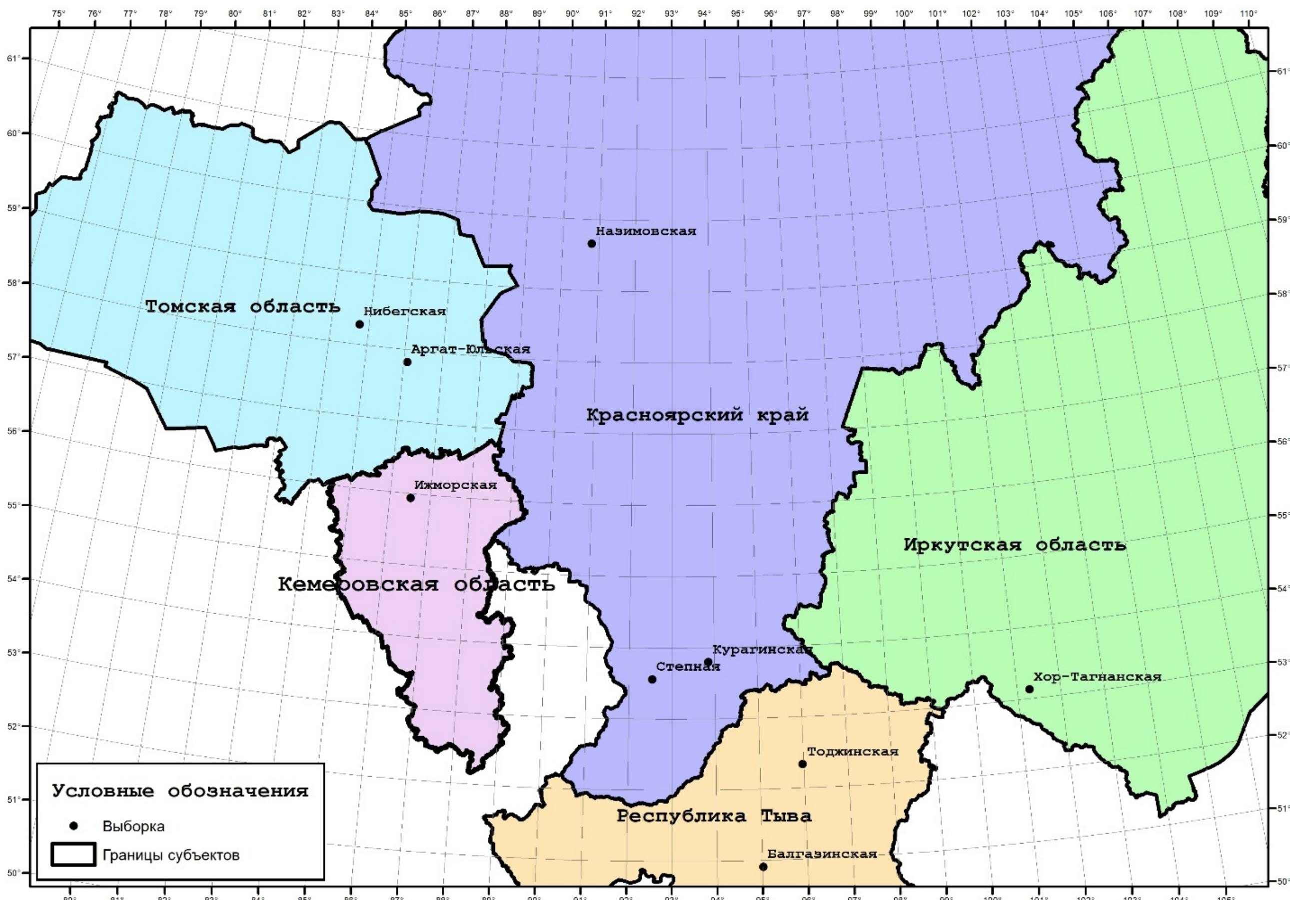

Figure 1. Schematic map of the sample locations of *P. Obovata*

Table 2
Characteristics of microsatellite loci selected for genetic variability analysis of Siberian spruce

№	Locus	Motif	*t*, ºC of annealing	Expected amplicon size, p.n.	Number of alleles	Literary resource
1	EATC1B02	$(ATC)_7 (AT)_3$	57	197–215	5	Scotti ea, 2002; Ekart et al., 2014
2	EATC1E03	$(CAT)_4 CGT(CAT)_8$	57	134–209	5	Scotti ea, 2002
3	UAPgAG105	$(AG)_{11}$	53	161–171	5	Hodgetts ea, 2001; Rungis ea, 2004; Ekart et al., 2014
4	Pa 33	$(CGG)_n$	62	107–119	2	Fluch ea, 2011
5	Pa 36	$(CGG)_n$	62	185–197	4	Fluch ea, 2011

RESULTS AND THEIR DISCUSSION

Analysis of the electrophoretic spectra of the amplicons of five nuclear microsatellite loci in 9 samples of Siberian spruce revealed from 2 to 8 allelic variants. All 5 analyzed loci were polymorphic. Examples of electrophoregrams demonstrating the variability of the studied microsatellite loci are shown in Fig. 2. The highest allelic diversity was found at the EATC1E03 and UAPgAG105 loci. The locus Pa 33 was the least variable, the heritability of which was determined by two allelic variants. The mean number of alleles per locus ranged in the samples from 2.6 to 4.4, the effective number of alleles from 1.765 to 2.398, the values of observed and expected heterozygosity from 0.344 to 0.525 and from 0.307 to 0.510 respectively (Table 3).

The average values of these indicators for the studied samples were: N_A = 3.511; N_E = 2.157; H_O = 0.438; H_E = 0.428. The highest effective number of alleles per locus was detected in the Khor-Tagnanskaya sample (2.398), and the lowest in the Todjinskaya sample (1.765). A deficit of heterozygous genotypes was detected in five samples of Siberian spruce.

The structure and degree of genetic subdivision of Siberian spruce samples were determined using Wright's F-statistics [10]. For each of the 5 polymorphic loci, coefficients of inbreeding of the individual relative to the population (F_{is}), inbreeding of the individual relative to the species (F_{it}) and inbreeding of the population relative to the species as a whole F_{is} were calculated. Using the data shown in Table 4, we see that the value of F_{is} coefficient at *EATC1B02, EATC1E03*, *UAPgAG105*, *Pa 33* are negative, indicating an excess of heterozygous genotypes. The Pa 36 locus indicates a deficiency of heterozygous genotypes. Analysis of the population structure using the F_{st} index showed that inter-population genetic variation accounts for 7 % of the variability detected in the samples.

The remaining variability (93 %) is represented within samples (Table 4). It has been noted that such a low level of interpopulation differentiation is generally characteristic of conifers [1; 2; 7].

The estimate of genetic differences between the studied samples was calculated using the Nei (DN) method [13]. The value of this index in the studied samples ranged from 0.014 to 0.143 (Table 5). According to Krutovskiy et al. [3], the value of genetic distance between populations in general for conifers is in the range 0.008-0.013. Thus, the results indicate a high level of genetic differentiation of the studied samples (Fig. 3).

Based on genetic distances (D), a dendrogram showing the genetic relationships between the studied samples of Siberian spruce (Fig. 4) was constructed. According to this diagram, the samples are distributed in two main clusters. The first cluster is formed by the Argat-Yulskaya and Nybegskaya samples (Tomsk Oblast), the second cluster is formed by all other samples, which are divided into 3 groups. The first group includes the Khor-Tagnanskaya sample growing in the Irkutsk Oblast, the second group includes samples located in the north of Krasnoyarsk Krai and Kemerovo Oblast, the third group includes samples from the Tyva Republic and southern districts of Krasnoyarsk Krai.

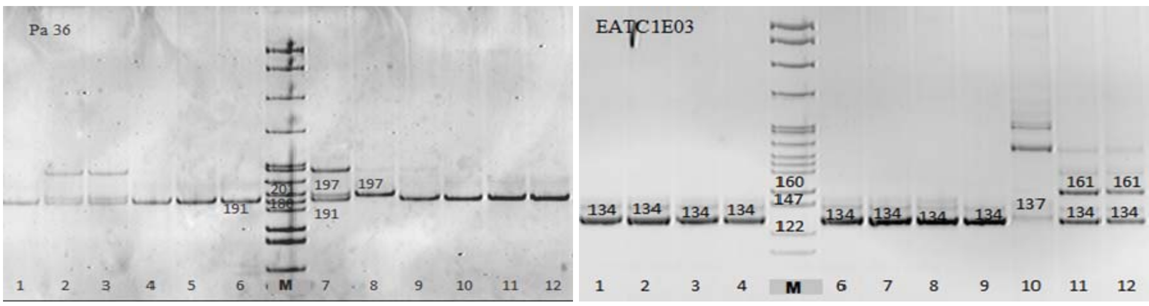

Figure 2. Electrophoregrams of nuclear microsatellite loci Pa 36 and EATC1E03 of Siberian spruce. Numbers 191, 197, 134, 137, 161 in the electrophoreograms of Pa 36 and EATC1E03 indicate alleles of amplified DNA fragments; M – electrophoretic standard

Table 3
Indicators of genetic variability in the studied samples of Siberian spruce

Samples	N_A	N_E	H_O	H_E	F
Argat-Yulskaya	3,000	1,949	0,394	0,365	0,065
Balgazinskaya	3,200	2,004	0,425	0,410	–0,047
Izhmorskaya	3,800	2,306	0,438	0,450	0,002
Kuraginskaya	4,400	2,310	0,481	0,490	0,007
Nazimovskaya	3,200	2,280	0,500	0,462	–0,052
Nybegskaya	3,400	2,101	0,400	0,406	0,039
Stepnaya	3,800	2,302	0,431	0,456	0,036
Todjinskaya	2,600	1,765	0,344	0,307	–0,067
Khor-Tagnanskaya	4,200	2,398	0,525	0,510	–0,033
On average for all studied samples	3,511±0,257	2,157±0,156	0,438±0,039	0,428±0,036	–0,006±0,026

Note: N_A – number of alleles per locus; N_E – effective number of alleles per locus; H_O – observed heterozygosity; H_E – expected heterozygosity; F – Wright fixation index; ± – standard error.

Table 4
Values of Wright's F-statistics

Locus	F_{IS}	F_{IT}	F_{ST}
EATC1B02	–0,077	0,077	0,143
EATC1E03	–0,022	0,062	0,083
UAPgAG105	–0,039	–0,029	0,010
Pa 33	–0,040	–0,011	0,028
Pa 36	0,102	0,181	0,088
average	–0,015±0,031	0,056±0,037	0,070±0,024

Table 5
Genetic distances of M. Nei (DN) between the studied samples of Siberian spruce

Samples	Nazimovskaya	Khor Tagnanskaya	Izhmorskaya	Argat-Yulskaya	Nybegskaya	Balgazinskaya	Todjinskaya	Stepnaya	Kuraginskaya
Nazimovskaya	0,000								
Khor-Tagnanskaya	0,075	0,000							
Izhmorskaya	0,034	0,057	0,000						
Argat-Yulskaya	0,099	0,050	0,063	0,000					
Nybegskaya	0,136	0,082	0,094	0,014	0,000				
Balgazinskaya	0,026	0,051	0,028	0,086	0,114	0,000			
Todjinskaya	0,069	0,055	0,049	0,080	0,123	0,025	0,000		
Stepnaya	0,077	0,052	0,081	0,117	0,134	0,025	0,042	0,000	
Kuraginskaya	0,060	0,048	0,059	0,112	0,143	0,025	0,035	0,016	0,000

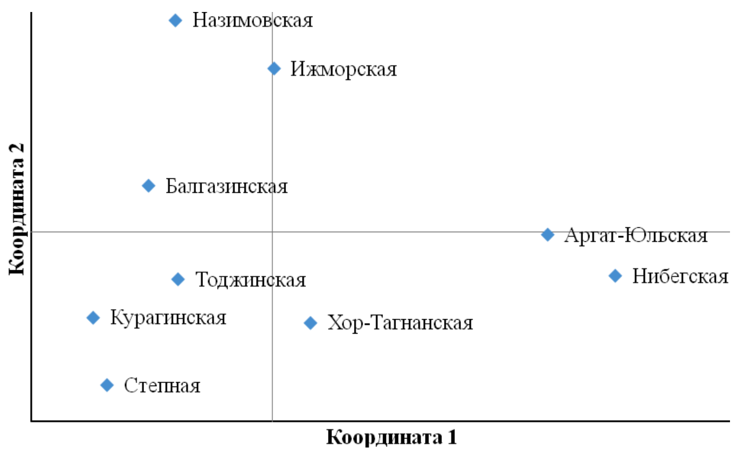

Figure 3. Projection of Siberian spruce populations on a two-coordinate plane (PSA analysis)

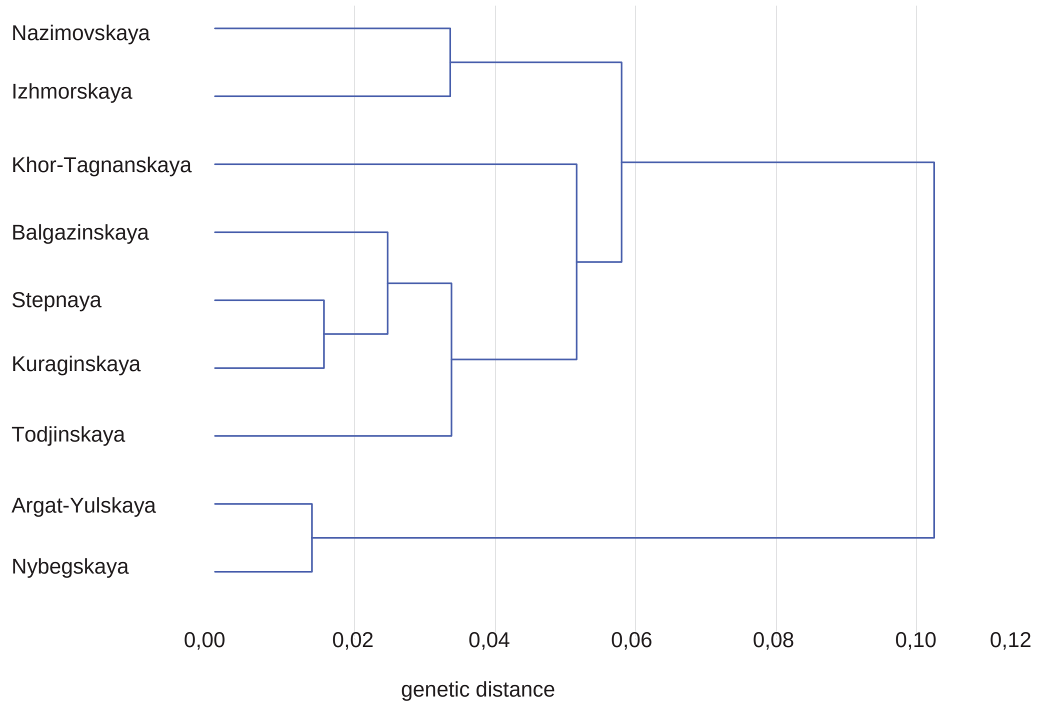

Figure 4. Dendrogram based on Nei's genetic distances [14] using pairwise unweighted method of clustering (UPGMA)

CONCLUSION

Thus, a study of DNA polymorphism of nine samples of Siberian spruce growing in Irkutsk, Kemerovo, Tomsk Oblasts, Krasnoyarsk Krai and the Tyva Republic revealed their genetic diversity at five nuclear microsatellite loci and a high degree of genetic differentiation. Intra-population variability (93%) accounted for the bulk of the identified genetic variability. There is a clear distribution of the studied samples into 2 main clusters by genetic distances. There is a significant differentiation of samples from Tomsk Oblast from all others.

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ОСОБЕННОСТИ ИСПОЛЬЗОВАНИЯ КОМПЛЕКСНОГО ОЦЕНОЧНОГО ПОКАЗАТЕЛЯ ПРИ ХАРАКТЕРИСТИКЕ ФОРМИРОВАНИЯ ДРЕВОСТОЕВ ЛИСТВЕННИЦЫ СИБИРСКОЙ

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В лесной таксации и лесоводстве используется значительное число методов и приемов оценки состояния динамики древостоев. Одним из них является применение так называемого комплексного оценочного показателя имеющего еще название «коэффициент напряженности роста», который рассчитывается как отношение средней высоты древостоя (Н, м) к площади поперечного сечения среднего дерева в древостое (G, см^2) на высоте 1,3 м. Целью работы явилось установление величины этого критерия и особенностей его динамики в нормальных и модальных древостоях лиственницы сибирской в Сибири. На основе материалов натурной таксации 434 выделов, а также анализа девяти таблиц хода роста нормальных и модальных древостоев лиственницы сибирской зеленомошной группы типов леса для различных регионов Сибири, установлена динамика средних величин показателя, осуществлена оценка степени опосредованности величины комплексного оценочного показателя таксационными характеристиками древостоев. Рассмотрены возможности использования данного показателя для сравнительной характеристики особенностей формирования древостоев в различных лесорастительных условиях.

Ключевые слова: *комплексный оценочный показатель, лиственница сибирская, модальные древостои, нормальные древостои, особенности формирования.*

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FEATURES OF USE OF THE COMPLEX ESTIMATED INDICATOR AT CHARACTERISTIC OF FORMATION OF FOREST STANDS OF THE LARCH SIBERIAN

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In forest valuation and forestry the considerable number of methods and receptions of assessment of a condition of dynamics of forest stands is used. One of them is application of the so-called complex estimated indicator having still the name "coefficient of tension of growth" which pays off as the relation of average height of a forest stand (N, l) to the cross-sectional area of an average tree in a forest stand (G, cm^2) at the height of 1.3 m. The purpose of work was establishment of size of this criterion and features of its dynamics in normal and modal forest stands of a larch Siberian in Siberia. In work on the basis of materials of natural valuation 434 having manufactured and also the analysis of nine tables of the course of growth of normal and modal forest stands of a larch of the Siberian zelenomoshny group of types of the wood for various regions of Siberia, dynamics of average sizes of an indicator is established, assessment of degree of an oposredovannost of size of a complex estimated indicator is carried out by taxation characteristics of forest stands. The possibilities of use of this indicator for comparative characteristic of features of formation of forest stands in various forest vegetation conditions are considered.

Keywords: *complex estimated indicator, larch Siberian, modal forest stands, normal forest stands, features of formation.*

INTRODUCTION

The considerable number of methods and techniques are used in modern scientific practice of research in forest inventory and forestry to assess the condition of dynamics of forest stands. One of them is the so-called complex estimated indicator (CEI).

The purpose of this work is to establish the criteria and its dynamics in normal and modal tree stands of Siberian larch in Siberia.

To accomplish this task we analyzed 9 tables of the growth of Siberian larch stands in various forest regions of Siberia. We also analyzed data from field-taxation of 434 modal stands formed in stable (climax) forests.

The object of the research is Siberian larch forest stands growing in the Velminsky district forestry of the Severo-Yeniseysk forestry of Krasnoyarsk Krai.

Nowadays, the forests of the Velminsky district forestry are experiencing the least anthropogenic impact, compared to the forests of adjacent territories. It is assumed that the growth and formation of forest stands of the forest massif, which was the object of the study, are due only to environmental factors. The forest vegetation of this region is typical for the forests of the Yenisey Range, which is the basis of the Central Siberian Plateau taiga forest region.

The Yenisey Range is a high southwestern part of the Central Siberian Plateau, stretching from the basin of the river Kan in the south to the mouth of the river Podkamennaya Tunguska. The climate of this area is sharply continental. The average annual rainfall ranges from 500 to 700 mm. The average annual temperature is about –5 ºC. There are 121 days with temperatures over +5. The height of the snow cover exceeds 1 m.

The Yenisey Range, together with the East Sayan Plateau, is a part of the Baikalid system [1]. The prevailing heights are 700–900 meters above sea level, with the highest point being the Yenisey Polkan (1104 m a.s.l.). The valleys of the rivers cutting through the range (Velmo, Bolshoy Pit, Teya, etc.) are of considerable width and are often swampy.

Soddy-calcareous soils are typical for the studied area.

Vegetation is described in the works of A. Ya. Tugarinov [2], K. N. Igoshina [3], E. N. Falaleev [4] and others. Pine-larch forests predominate. In the detailed typological classification of larch forests, E.N. Falaleev [4] identified four groups of forest types: larch forests on stony soils, including one type of forest, Ledum larch forest; green moss larch forests, combining two types of forest: lingonberry larch and green moss larch forest; larch forests are herbaceous, also uniting two types of forest: forb larch forest, coastal larch forest. The fourth group of types of larch forests is long-moss-sphagnum larch forests which includes blueberry larch and sphagnum larch.

RESEARCH METHODS

The Complex Estimated Indicator (CEI), also known as the “tension coefficient of growth” for stands is calculated as the ratio of the average stand height (H, m) to the cross-sectional area of an average tree in the stand (G, cm^2) at the height of 1.3 m:

$$CEI = H \cdot 100 / G_{1,3}. \quad (1)$$

Accordingly, it is calculated for a single tree as the ratio of the height of the tree to the cross-sectional area at a height of 1.3 m, expressed in centimeters.

The physical meaning of the complex estimated indicator is in the characteristic of the size of the part of the tree trunk, the formation of which is provided by a unit of cross-sectional area.

This indication was proposed by K.K. Vysotsky [5] more than half a century ago and has found application in various aspects of the study of forest stands and single trees.

It is used to assess the vital state of stands [6; 7], the coefficient is used in the study of the hydrophysical properties of wood [8], to characterize the degree of thinning of natural and artificial forest stands [8–10], etc.

CEI calculations are made both for forest stands and for individual trees with the division of the latter by size, which, in our opinion, is not entirely justified, since it would be more logical to rely on the differentiation of trees by age, which mediates the dynamics of the main taxation features as single trees, and tree stands.

Often the use of CEI to characterize the state of single trees makes it difficult to take into account all the factors that determine its value. For example, noting that the lowest CEI is characteristic of edge or park trees [7], they attribute this only to an increase in their nutritional area and moisture supply, forgetting about the light regime, which largely determines the height and shape of tree trunks.

There is an assumption that the indicator of the state of CEI is appropriate for characterizing forest stands, when average taxation signs are used for its calculation.

The influence of regional forest conditions on the growth and development of forest stands does not require any evidence. Such factors as climate, soil, orography determine the nature of changes in the size of trees, as well as the processes of renewal and thinning of forest stands. Forest growth, forest management, forest inventory zoning are based on regional growth patterns and the quality of forest stands. It is very likely that both regional peculiarities of growth should be reflected in the values of the CEI.

Statistical characteristics of the main average inventory indicators of Siberian larch forest stands, which were the object of the research, are given in table 1.

Thus, natural, rather old-aged, large-sized stands of Siberian larch were assessed. The maximum age of stands reaches 220 years. Modal forest stands have maximum relative density 0.9. The CEI value was calculated for individual stands by dividing the average height of the main species of Siberian larch, by the cross-sectional area corresponding to the average stand diameter of this forest element.

RESULTS AND THEIR DISCUSSION

The analysis of the peculiarities of the dynamics of the complex estimated indicator was started by determining the dependence of its value on the inventory characteristics of stands at different age stages. For this purpose, the values of the coefficient of pair correlation between the CEI and the main inventory characteristics of forest stands in the studied area of different age groups were calculated (Table 2).

Table 1
Statistical characteristics of some inventory indicators of larch stands

Statistical indicators	Age, years	Height, m	Diameter, cm	Stock m^3/ha
Average	138	18,9	23,0	158
Standard error	1,9	0,3	0,3	2,4
Median	160	20	26	160
Mode	170	23	28	190
Standard deviation	54,2	7,5	8,1	70,4
Accuracy of experience, %	1,4	1,4	1,2	1,5
Coefficient of variation, %	39,3	40,0	35,3	44,7

The analysis of the data from Table 2 shows that there is a trend towards a decrease in the value of the correlation coefficient between the CEI and the average age of the stand with an increase in the latter.

The interdependence of CEI and the average height of forest stands is somewhat different. It is relatively low (–0.17; –0.22) at the stages of middle age and maturation of stands, i.e., during periods of intensive growth and thinning. At the ripeness stage, the interdependence of traits reaches a maximum (–0.69), then, with a decrease in the growth rate of trees in height and continued growth in diameter, it decreases.

With the average diameter of forest stands, CEI has a significant stable correlation from –0.80 to –0.96. For the array as a whole, without dividing forest stands into age groups, the correlation coefficient between these indicators is –0.92.

The correlation of CEI with the stock is not high, since its assessment does not take into account the degree of influence on the stock of forest stands.

In the works of V. D. Shul'ga and others [11; 12], based on the analysis of data from tables of the growth course of normal plantations of class I bonitas of the main forest-forming species of the country, the statement is made that "the ratio of the height of a tree to the cross-sectional area at the inventory diameter (complex estimated indicator – CEI) or a single average volume of a tree trunk, is practically the same for all species according to age classes" (Article 24).

Table 3 shows a fragment of data characterizing the CEI values for larch, as well as the average values of the indicator for normal and modal (obviously stable – climax) forest stands.

To establish the peculiarities of the dynamics of the CEI value in normal forest stands of Siberian larch of class I bonitet, three tables of the growth were used, compiled by V. S. Zolotukhin for Gorny Altai and E. N. Falaleev [13] for the regions of Central Siberia, which were subjected to mathematical modeling by A. Z. Shvidenko and others [14] (Picture 1).

The limited number of tables taken for analysis is explained by the fact that most of these standards built for different regions of Siberia do not have enough data on the forest stands of class I bonitet's patterns of growth, since these stands are quite rare.

The average dynamics of CEI with a high degree of adequacy is displayed by the Weibull function of the type.

$$y = a - b \cdot e^{-cx^d} \qquad (2)$$

while a = 17,916; b = 15,843; c = 451,502; d = –1,816.

The resulting data (Table 4) are quite similar to those given in [11; 12] (Table 3), from which the conclusion about the relative stability of the dynamics of CEI in normal stands of different forest plantations may be made.

Unfortunately, the works of V. D. Shulga et al. [11; 12] do not specify which tables of the growth rate of normal stands were used in the calculations, and, therefore, if even one table coincides with the one used in this work, the comparison cannot be considered correct.

The dynamics of the complex estimated indicator in modal (stable) stands of Siberian larch was established on the basis of the data from the six growth rate tables made for different regions of Siberia (Table 5).

Table 2
Paired coefficients' correlation between CEI and indicators of inventory

Age groups	Average inventory indicators			
	Age, years	Height, m	Diameter, cm	Stock m^3/ha
Middle – aged 41–80 years old	–0,51	–0,17	–0,84	–0,14
Ripening 81–120 years old	–0,59	–0,22	–0,96	–0,33
Ripe 121–160 years old	–0,24	–0,69	–0,93	–0,44
Overmatured 161–200 years old	–0,37	–0,44	–0,89	–0,17
Overmatured 201 and more years old	–0,08	–0,34	–0,80	–0,22

Table 3
The value of the complex estimated indicator according to V. D. Shulga (2007)

An object	CEI, cm/cm^2, at the age, years				
	20	30	50	70	100
Larch	22.9	12.6	7.3	5.0	3.8
Average for normal stands	20,7	12,3	6,6	4,5	3,2
Average for obviously stable stands	4,0	3,5	3,5	3,5	2,0

Table 4
Dynamics of average CEI values in normal stands of Siberian larch

Age, years	10	30	50	70	90	110	130	150	170	190	210
CEI cm/cm^2	17,9	11,7	7,0	5,0	4,0	3,4	3,1	2,9	2,6	2,4	2,3

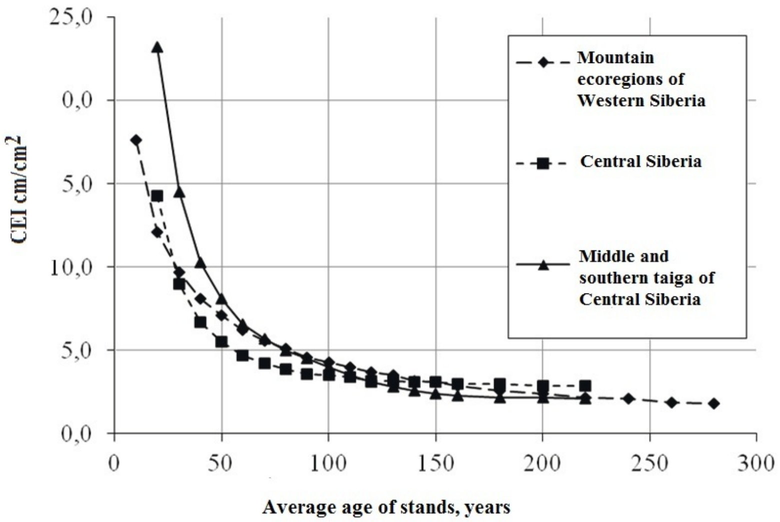

Fig. 1. Dynamics of a complex estimated indicator in normal stands of Siberian larch

Table 5
Growth progress tables used to calculate the CEI

№	Region, year of publication	Author
1	The Khantyka River Basin, 1971	A. A. Dzezyulya
2	South Yakutia, 1975	I. F. Shurduk
3	Mountain Altai, 1958	V. S. Zolotukhin
4	Lake Baikal Basin, 1973	A. E. Tetenkin, V. T. Busoedov, Y. M. Popova
5	Southern districts of the Krasnoyarsk Krai, 1969	E. N. Falaleev, V. S. Polyakov
6	Tyva, 2013	S. L. Shevelev, I. I. Krasikov

Table 6
Dynamics of average values of CEI in modal stands of Siberian larch calculated by growth tables

Age, years	10	30	50	70	90	110	130	150	170	190	210	230	250	270
CEI cm/cm^2	23,2	14,7	9,3	6,8	5,4	4,4	3,8	3,0	2,9	2,7	2,4	2,3	2,1	2,0

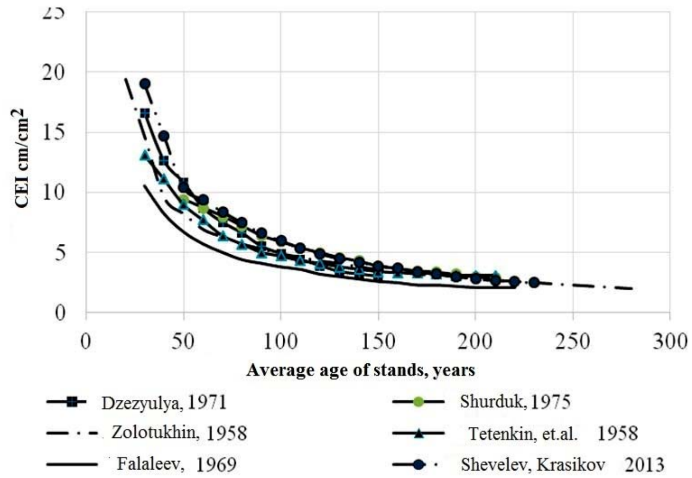

Fig. 2. Values of CEI cm/cm^2 of modal stands of Siberian larch

The graph in Fig. 2 illustrates the change in the value of the CEI in modal larches of different ages.

It turned out that the indicators calculated for regions differing in forest conditions, especially in the period up to 100 years, have significant differences. Although it was not possible to establish an obvious dependence of the CEI value on forest growing conditions, there is a tendency to decrease the value of the indicator with a simplification of growing conditions.

The larch forests of the mountainous regions in the Republic of Tyva and the Khantayka River basin are characterized by the highest value of the CEI, the larch forests of the southern regions of Krasnoyarsk Krai have the lowest value of the indicator.

Of course, the question of the correlation of the average value of the CEI with forest-growing conditions requires more detailed study using not only the data of the growth tables, but also the materials of full-scale inventory, as well as climatic, soil, and other characteristics of forest-growing areas.

The dynamics of the average values of the CEI for modal stands, obtained using growth tables, is approximated by equation (2), the adequacy of which corresponds to $r^2 = 0.998$.

The coefficients are equal:

$a = 30{,}153$; $b = 29{,}677$; $c = 31{,}820$; $d = -1{,}149$.

Table 6 shows the results of tabulating the equation. Thus, based on the analysis of the tables of the Siberian larch stand's growth, the series characterizing the dynamics of the complex estimated indicator in normal and modal stands were obtained. However, it should not be forgotten that the data characterizing the change in the initial values for the CEI – average heights and average diameters, according to which the cross-sectional area of the average in the tree stand was established when constructing growth tables, were subjected to mathematical or graphical alignment (depending on the method of constructing the table), therefore, the dynamics of the CEI obtained on the basis of field-taxation data are of some interest (Table 7).

It should be noted that the value of the CEI in the young trees of the first class of age reaches 63.8 cm/cm^2, however, they are not included in the processing, since they are taken into account in the forest in insignificant quantities.

The graph in Fig. 3 illustrates the dynamics of a complex estimated indicator of modal stands of Siberian larch, obtained by various methods. It turned out that the values of the CEI found according to the full-scale taxation slightly exceed the values of the indicator established using the growth tables of modal larch trees, however, they fit perfectly into the data field shown in Fig. 2.

The nature of the dynamics of the CEI modal larch forests of Siberia differs greatly from the data for obviously stable stands of larch given in the works [11; 12]. Perhaps “obviously stable stands” in these works meant a slightly different plant formation, sparse stands of park type, where the value of the CEI is insignificant.

Table 7
Dynamics of average values of CEI in modal stands of Siberian larch of the Velminsky district forestry

Age, years	10	30	50	70	90	110	130	150	170	190	210
CEI cm/cm^2	–	19,4	11,4	8,2	6,6	5,5	4,9	4,5	4,1	3,8	3,6

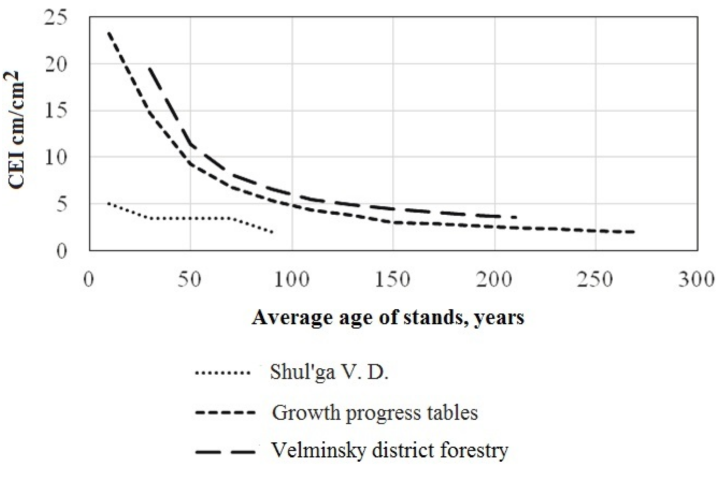

Fig. 3. Comparison of the dynamics of the complex estimated indicator in the modal stands of Siberian larch

CONCLUSION

It must be admitted that the complex estimated indicator (CEI) currently has not found wide application in domestic forestry practice. The reason for this is the lack of knowledge about the values and dynamics of this indicator for various forest-forming species in different forest conditions. Knowledge of the general patterns of the dynamics of a complex estimated indicator, the establishment of regional standardized CEI values will make it possible to use it not only in characterizing the dynamics of forest stands, but also in forest inventory zoning.

As a result of the study, some peculiarities of the dynamics of the complex estimated indicator in the stands of Siberian larch were established, the average series of the indicator for normal and modal stands were found, and the degree of mediation of the CEI by the main taxation characteristics of the stands was established.

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ОЦЕНКА ОБЪЕМОВ ТОПЛЯКОВОЙ ДРЕВЕСИНЫ В РЕКЕ ЕНИСЕЙ НА УЧАСТКЕ ОТ УСТЬ-МАНЫ ДО КРАСНОЯРСКА

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С 1931 по 1991 годы лесоперерабатывающим предприятиям и целлюлозно-бумажному комбинату города Красноярска основной объем древесины поставлялся водным путем в кошелях со Слизневского рейда и рейда Красноярского лесоперевалочного комбината (ЛПК). Древесина на Слизневский рейд поступала из реки Мана по молепроводу, исключающему выход леса проплывающей древесины на судовой ход. Поэтому основная масса топляковой древесины располагалась на дне узкой полосой вдоль правого берега р. Енисей, ширина которой не превышала 100 м. Древесина, поступающая по реке Мана в молепровод теряла часть запаса плавучести при сплаве непосредственно по реке Мана, при прохождении по молепроводу, нахождении ее в запани, в процессе сортировочных работ, формировании кошелей. Поэтому часть ее осела на дно реки Енисей в молепроводе и в акватории действующих в то время предприятий. Приведена оценка объемов затонувшей древесины на реке Енисей на участке от поселка Усть-Мана до города Красноярска, полученная при выполнении натурных обследований прибрежной акватории реки Енисей в месте действовавшего ранее молепровода. В соответствии с проведенными исследованиями в прибрежной акватории правого берега реки Енисей на участке от устья реки Мана до участка Красноярский ЛПК в черте города Красноярска затоплено от 65 до 88 тыс. м^3 *древесины. Исследования по оценке качества затопленной древесины показывают, что имеющиеся запасы затопленной древесиной массы могут быть вовлечены в промышленное производство. Вовлечение в производство значительных объемов древесиной массы позволит не только получить экономическую выгоду, но и ощутимый экологический эффект от очистки акватории прибрежной зоны реки Енисей.*

Ключевые слова: *лесосплав, топляковая древесина, лесосплавной рейд, водный транспорт леса, молевой лесосплав, кошель.*

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ESTIMATION OF VOLUME OF FLOODED WOOD IN R. YENISEI FROM THE ESTUARY OF R. MANA TO THE STATION KRASNOYARSK FOREST COMPLEX

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From 1931 to 1991, timber processing enterprises and the pulp and paper mill of the city of Krasnoyarsk were supplied mostly by water in bag booms from the Sliznevsky raid and the raid of the Krasnoyarsk timber-handling plant (THP).

Wood on the Sliznevsky raid came from the river Mana through the loose wood line, excluding the exit of the forest of passing wood on the ship channel. Therefore, the bulk of the sinker wood was located at the bottom of a narrow strip along the right bank of the r. Yenisei, the width of which did not exceed 100 m. Wood flowing through the Mana River to the mall pipe lost part of its buoyancy margin when rafting directly along the Mana River, passing through the loose wood line, finding it in the pool, in the course of sorting works, forming bag booms. Therefore, part of it settled on the bottom of the Yenisei River in the loose wood line and in the waters of the enterprises operating at that time. The article provides an estimate of the amount of sunken wood on the Yenisei River in the area from the village of Ust-Mana to the city of Krasnoyarsk, obtained when performing full-scale surveys of the coastal water area of the Yenisei River at the site of the previously loose wood line. In accordance with the studies carried out in the coastal waters of the right bank of the Yenisei River, from 65 000 to 88 000 m^3 *of timber were flooded in the section from the mouth of the Mana River to the Krasnoyarsk THP site within the city of Krasnoyarsk. Studies assessing the quality of flooded wood show that existing stocks of flooded wood mass may be involved in industrial production. The involvement in the production of significant volumes of wood mass will not only provide economic benefits, but also a tangible environmental effect from cleaning the waters of the Yenisei coastal zone.*

Keywords: *timber floating, sinker wood, booming ground, water transport of the forest, loose floating timber, bag boom.*

INTRODUCTION

In 2017 the volume of logging in Russia exceeded 200 million m^3, in the Krasnoyarsk Territory – 23.1 million m^3 and it tends to increase [1; 2]. More than 60 % of forest resources are located near waterways. Thus, during the period of the largest volumes of timber harvesting in 1985–1990, the volume of water timber transport reached 24 % of the whole volume of timber transportation. Loose floating accounted for about 30 % of the total volume of water timber transport [3].

With all the economic efficiency of timber floating, in comparison with other types of timber transport, for various reasons, losses of wood are inevitable, which during loose floating amounted to 3–4 % [4]. In the river beds of the rivers of Krasnoyarsk Territory and the Irkutsk Region previously used for timber floating, there are 452 thousand m^3 of sunken wood [4], among which 85 % is larch wood.

For the period from 1931 to 1991 the volume of the loose floating along the Mana River in the Krasnoyarsk Territory amounted to 40 million m^3 according to archival materials.

For many years, timber processing enterprises and the pulp and paper plant in Krasnoyarsk were supplied with the main volume of wood by water in bag booms from the Sliznevsky booming ground (Fig. 1) and the booming ground of the Krasnoyarsk timber-handling plant (THP).

Timber for the Sliznevsky booming ground came from the Mana River through a loose wood line, which excluded the exit of the floating timber to the ship channel. Therefore, the main mass of sunken wood is located at the bottom of the Yenisei River in a narrow strip along its right bank. The width of the strip did not exceed 100 m.

From the lower reaches of the Yenisei timber was delivered to the Krasnoyarsk THP in barges and unloaded mainly by heeling into the boom of the sorting ground. Timber was delivered to the Krasnoyarsk Woodworking Plant (WWP) by barges and unloaded by cranes at the mooring facilities of the booming ground.

Timber coming from the Mana River through the loose wood line lost part of the buoyancy reserve when rafting directly along the Mana River, passing through the loose wood line, being in the boom, in the process of sorting work, and forming bag booms. Therefore, part of it settled on the bottom of the Yenisei River in the loose wood line and in the water area of enterprise grounds (Fig. 2).

Fig. 1. Sliznevsky booming ground on the Yenisei River in 1990

Initially an assessment of the volumes of sunken wood and the development of a technology for its salvage in the the stretch of the Yenisei River from Ust-Mana to Otdykha Island was carried out by the Department of Forest Water Transport of the Siberian Technological Institute in 1987. The volume of sunken wood was estimated with the help of divers. In 1989-1990 the British company "RosBRI" was engaged in timber salvage. It worked on timber salvage for only one navigation along the right bank at a distance of 10 km from the mouth of the Mana River in the place of the most intense accumulation of timber. About 7 thousand m^3 of timber was salvaged. Later on no one was engaged in sunken wood salvage.

Fig. 2. Survey area diagram

In this regard, there is a need to conduct field studies to assess the available stocks of sunken wood in the area under consideration.

RESEARCH RESULTS

Throughout the considered section of the river, the firewood is placed unevenly. Most of the wood has settled in areas with low flow rates.

The volumes of flooded wood were determined on the sites located within 27.0...25.2 km, 25.2...24.0 km from Krasnoyarsk; in the area of the Sliznevsky booming; in the area of the “Shaluninsky byk” rock and the Krasnoyarsk THP and WWP booming grounds.

The length of the surveyed stretch was divided into distances equal to 50 m. At the same time, stretches with separately located logs (rarely), stretches of accumulation in 1...2 layers and 2...3 layers were observed. The results of the examinations are given in Table 1.

The volume of sunken wood in the stretch was determined according to the data in Table 1 as follows. The volume of wood per 1 m^2 was determined with its single-row placement with an average diameter of a log d = 0.31 m, the length of a log segment 1 m.

Three segments of 1 meter long can be placed on 1 m^2 stretch with a gap of 7 cm on the curvature of logs, bark, and protruding uncut branches:

$$V = \frac{\pi d^2}{4} l = \frac{3{,}14 \cdot 0{,}31^2}{4} \cdot 3 = 0{,}226\,\text{m}^3/\text{s}. \qquad (1)$$

The average log volume V_l at l = 6.5 m, d = 0.31 m is 0.49 m.

The volume of wood in a stretch with a rare location:

$$V_1 = \frac{S}{S_{1l}} V_l = \frac{62350}{40} 0{,}49 = 764\ m^3, \qquad (2)$$

where S is the area of timber accumulation (Table 1); S_{1l} is the area per one assortment (according to observations, it is 40 m^2).

The volume of timber on the area with the arrangement of timber in 1 ... 2 layers:

$$V_2 = S \cdot V_l \cdot 1{,}5 = 42\ 920 \cdot 0{,}226 \cdot 1{,}5 = 14\ 550\ m^3. \quad (3)$$

On the area with the arrangement of timber in 2…3 layers:

$$V_3 = S \cdot V_l \cdot 3 = 13\ 800 \cdot 0{,}226 \cdot 3 = 9356\ m^3. \qquad (4)$$

Thus, on the area of 27,0...25,2 km the volume of sunken wood will be 24670 m^3.

The volumes of sunken wood in other areas were determined by a similar method. The results of determining the volumes of occurrence of sunken wood are presented in Table. 2.

In the process of surveying the first stretch, a comparison was made of the estimated volume of sunken wood occurrence with the actual volume. 7200 m^3 of sunken wood was salvaged on trial area of 15,720 m^2. According to the calculation, 5320 m^2 of wood was flooded in this area, i.e. in fact, the calculated volume is underestimated by 1.35 times. If this factor is extended to all sites, the expected volume of sunken wood is 88,520 m^3.

There are two ways to solve this problem. The first one is to leave the sunken wood at the bottom of the Yenisei as an invisible monument to the costs of timber floating in the 1970-s and 1980-s. The second is to salvage the sunken wood and use it in industrial production, clearing the bottom of the Yenisei from this wood.

Table 1
The intensity of the location of sunken wood in the area from 27.0 to 25.2 km

Distance from the city of Krasnoyarsk, km	Area of accumulation, m^2		
	rarely	1–2 layers	2–3 layers
27,00–26,00	40 000	–	–
26,00–25,95	2000	1850	–
25,95–25,90	3400	5070	–
25,90–25,85	4100	4500	–
25,85–25,80	3500	4300	–
25,80–25,75	1750	3700	1700
25,75–25,70	1500	4000	1200
25,70–25,65	900	4300	450
25,65–25,60	2000	1600	750
25,60–25,55	600	1300	1750
25,55–25,50	–	1300	1750
25,50–25,45	–	1600	750
25,45–25,40	–	2000	1750
25,40–25,35	200	2400	1200
25,35–25,30	1800	500	–
25,30–25,25	400	1500	1000
25,25–25,20	200	3000	1500
Totally	62 350	42 920	13 800

Table 2
Volumes of sunken wood occurrence in the study zone

Zone name	Distance from the city of Krasnoyarsk	Volume, m^3
Zone of the Yenisei River	27,0–25,2	24 670
	25,2–24,0	19 000
Sliznevsky booming ground	20,5–18,8	13 000
Shaluninsky byk	13,0–12,0	800
Booming ground of the Krasnoyarsk THP	9,0–7,0	5300
Booming ground of the Krasnoyarsk WWP	7,0–6,5	2800
Totally		65 570

Studies evaluating the quality of sunken wood show:

– species composition of sunken wood in the zones under consideration is: larch – about 50–60 %; conifers (pine, spruce, fir) – 35–45 %; birch and aspen – about 5 % (data of the Department of Transport, Construction and Water Use, SibGTU);

– spruce, pine, fir, cedar, larch are the most susceptible to changes in initial properties during prolonged exposure to water [5];

– spruce wood, when in water for more than 7–10 years, acquires a blue or gray-blue colour [5], fir changes colour in the sapwood part of the trunk, pine is subject to changes in the sapwood part [6];

– the colour of the larch does not change if it is in the water for less than 10 years; when the larch is in the water for more than 20 years, the end parts are covered with a sticky mass of black colour from 1 to 3 mm, the rest of the part changes its colour to darker one compared to freshly cut [7];

– mechanical tests of larch that has lain in water for about 50 years have shown that the tensile strength in static bending has decreased by 23.4 %, the compressive strength along the fibres has decreased by 22.9 % in comparison with wood not subjected to loose floating [8].

It is noted in [7] that birch sunken wood has no restrictions on its use in the woodworking industry; larch can be used without restrictions; the rest of the wood can be used in the production of wood concrete.

CONCLUSION

Thus, in the zone under consideration the volume of sunken wood is more than 65 000 m^3.

Cleaning the river bed from sunken wood will allow not only improving the ecological state of the water body, its hydrological and recreational conditions, but also involving additional volumes of wood raw materials into production without increasing felling.

The timber salvage technology does not require the manufacture of special equipment, since the timber is salvaged at shallow depths. To salvage timber, it is proposed to use the LS-41 sunken timber salvage unit or a floating crane, barges with a carrying capacity of 500 to 1000 tons, an Angara-type tugboat and a boat KS-100D. The cost of sunken wood salvage and its unloading on the bank in Krasnoyarsk is 2...2.5 times lower than the cost of logging.

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К ВОПРОСУ ПОСТРОЕНИЯ НОРМАТИВОВ ПО МАТЕРИАЛАМ ГОСУДАРСТВЕННОЙ ИНВЕНТАРИЗЦИИ ЛЕСОВ НА ПРИМЕРЕ НАСАЖДЕНИЙ ЛИСТВЕННИЦЫ ДАУРСКОЙ

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Род лиственница – один из наиболее распространенных на Российском Дальнем Востоке представителей семейства сосновые. Проведенная государственная инвентаризация лесов показала, что в Хабаровском крае площадь, занимаемая лиственницей даурской, составляет – 33,7 % от общей площади лесов, лиственница Каяндера – 0,2 %. В Дальневосточном таежном лесном районе лиственница формирует преимущественно лесные насаждения, в Приамурско-Приморском хвойно-широколиственном лесном районе практически везде встречается с примесью березы или ели. В целом по краю отмечается низкое качество древесины лиственницы. Из общего числа учтенных деревьев – 3747666,7 тыс. шт. меньше половины (46,6 %) отнесено к деловым стволам, 29,8 % – к полуделовым и 27,1 % – дровяным. Лиственница даурская – одна из наиболее изученных древесных пород в регионе. Для этой породы в прошлом столетии была разработана обширная нормативная база. В качестве экспериментального материала привлекали пробные площади, таксационные выделы. Точность оценки запаса с помощью этого материала варьировала от ±10–35 %. Низкая точность исходного материала, как следствие, давала низкую точность разработанных нормативов. При государственной инвентаризации лесов основной таксационный показатель – запас древостоя, в зависимости от лесного района, определяют с заранее заданной точностью (±2,5–5 %). Точность разработанных на этой основе нормативов по определению запаса будет аналогичной. По материалам государственной инвентаризации лесов изучены взаимосвязи таксационных показателей лиственницы даурской. Для расчета отбирались регрессии с наиболее высокими коэффициентами детерминации. Дано обоснование известному соотношению 3/2, использующемуся для определения оптимального количества стволов.

В качестве примера на одном и том же экспериментальном материале построены две таблицы хода роста, в которых динамика средних значений таксационных показателей рассчитана по разным уравнениям регрессии. Разные регрессии оказали влияние на динамику запаса древостоев лиственницы даурской.

Ключевые слова: *таксационный показатель, модельные деревья, лиственница, нормативы.*

Conifers of the boreal area. 2022, Vol. XL, No. 7 (special), P. 642–646

TO THE ISSUE OF BUILDING STANDARDS FOR MATERIALS OF THE STATE INVENTARIZACII FORESTS BY THE EXAMPLE OF PLANTATIONS OF LARIX DAHURICA

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Genus Larix – one of the most common in the Russian far East representatives of the pine family. The conducted GIL showed that in the Khabarovsk territory the area occupied by Larix dahurica is 33.7 % of the total forest area, Kayanader larch is 0.2 %. In the far Eastern taiga forest area, larch forms mainly forest plantations, in the Amur-Primorsky coniferous-deciduous forest area, it is found almost everywhere with an admixture of birch or spruce. In General, the edge is marked by low quality Larix dahurica wood. Of the total number of trees accounted for – 3747666.7 thousand pieces. less than half (46.6 %) attributed to business trunks, 29.8 % – to poludelovym and 27.1 % – wood. Larix dahurica is one of the most studied tree species in the region. This led to the development of an extensive regulatory framework for this breed. The involvement of unsystematic experimental material indicated its low accuracy and, as a consequence, low accuracy of the developed standards. At the state inventory of the woods the basic taxation indicator – a stock of a stand define with the predetermined accuracy (2,5–5 %). Therefore, the accuracy of standards developed on the basis of these materials will be similar. According to the materials of the state inventory of forests, the interrelations of taxation indicators of Larix dahurica are studied. Regressions with the highest determination coefficients were selected for practical calculations. The justification of the known ratio 3/2, used to calculate the optimal number of barrels, is given. As an example, on the same experimental material, two tables of the growth course *are constructed, in which the dynamics of the average values of taxation indicators is calculated according to different regression equations. Different regression had an impact on the dynamics of the stock of forest stands of Larix dahurica*

Keywords: *taxation indicator, model trees, larch, standards.*

RELEVANCE OF THE ISSUE

According to the Federal Forestry Agency Act on March 9, 2011 № 61 "On Approval of the List of Forest Zones of the Russian Federation and the List of Forest Areas of the Russian Federation", the forests in Khabarovsk Krai are referred to the 2-nd forest zone and the 2-nd forest areas. The Taiga zone includes the Far East Taiga forest area, and the Coniferous-Leaf forest area includes the Priamursko-Primorsky Coniferous-Leaf forest area. The total size of these areas is 78.858 million hectares. Daurian larch predominates in the Far Eastern taiga forest area. At present, the first cycle of the State Forest Inventory (hereinafter referred to as SFI) has been completed for the forest areas of the country. The SFI sample area is a statistically reliable information base on forest plantations of forest areas, obtained with a certain accuracy and which is an information databank, based on which new regulations can be developed, including growth progress tables (hereinafter referred to as GPTs).

The first Russian "Experimental Tables of Stock and Growth of Normal Plantations", constructed on sample plots, were published in 1846 [1]. For more than 170 years of forest research their number has increased many times, but the essence has remained the same – age-related changes in numerous qualitative and quantitative characteristics of the taxation features of forest stands. As a rule, several variants of growth progress tables (modal, norma, optimal) are compiled for the same species. They reflect not only the stock of trunk wood, but also the stock of the entire phytomass of stands. This is due to the fact that many forestry programs are implemented on the basis of GPT: productivity forecasts, calculations of ripeness ages, size of forest use during thinning, assessment of general and biological productivity [2–5]. The analysis of methods for compiling GPTs shows that depending on the goals and objectives faced by researchers, the volume of experimental material, and the methods of obtaining it, the accuracy of the developed standards varies considerably. For example, GPT drawn up on the basis of taxation divisions have the accuracy of determining the stock within ±35 %, and on the basis of sample areas laid down in accordance with OST 56-69-83 – within ±10 %, even if they belong to the same class of bonitet. Few of the researchers paid attention to the accuracy of determining the stock of plantations, analyzing the accuracy of the description by different regression equations of the taxation indicators that make up the stock [6]. Accuracy of description of regression line of taxation characteristic ultimately influences the dependent variable – stock of plantation, which is determined by the multiple of the sum of section areas and species height. In other words, if we describe tree height and diameter with errors, the errors will affect stand stock.

Permanent sample areas of the SFI, depending on the forest area, are laid in such numbers that allow us to determine the stock of stands with an accuracy of ±2–5 %. But the stock is determined by at least two independent indicators – species height and the sum of cross-sectional areas. We have tested the accuracy of the final indicator, the stock of stands, using different functions to describe the heights, diameters, and volumes of trunks in the sample plots of the SFI laid in the Far East Forest Region in 2012–2018.

OBJECTS AND RESEARCH METHODS

The article is based on data from permanent sample plots laid during the SFI in the Far Eastern taiga forest area (Khabarovsk Krai) in the period from 2012 to 2018. A total of 1,249 permanent sample plots were used. Sites for analysis were selected by predominance or concomitance of larch Dahurian (Larix dahurica). Analysis of changes of Dahurian larch taxation indicators with age was carried out with the help of mathematical models, using the methods of biometry. In searching for optimal regression equations, the independent indicator was the age of the model trees, the dependent indicators were: diameter at 1.3 m, tree height, tree volume. Development of mathematical models was performed using non-linear functions [7]. In modelling the phyto-mass components of trees, a stepwise growth function was used, the general form of which is $y = a \cdot x^b$. It carries biological meaning and has high flexibility [8]. The connection of trunk volumes with heights and diameters at the height of 1.3 m was described with its help. The adequacy of the equation and accuracy of the model was checked by value of determination coefficient (R^2) [9].

Regression correlations are important for phytomass calculations:

– between height and diameter at 1.3 m;

– between the height of the live crown base and the diameter at a height of 1.3 m;

– height of live crown base and tree height;

– the height of the maximum diameter of the crown and the diameter at the height of 1,3 m;

– the height of the maximum diameter of the crown and the height;

– the maximum crown width and the diameter at the height of 1,3 m;

– maximum crown width and height.

Crown width not only reflects the competitiveness of trees in the stand, but is also an important parameter for the interpretation of aerial photographs, since it has a close connection with most taxonomic indicators [10]. There is no close correlation between stand height and crown extent, but there is a close correlation between height, crown diameter and trunk diameter in this sample. The used equation explained 63 % of the regression. These regressions are not described in the present work, because the purpose of the study was to determine the magnitude of the error in calculating the stock of stands using different functions describing age-related changes in height, diameter, number of trunks and trunk volume.

RESULTS AND DISCUSSION

Dahurian larch grows on an area of 19.98 million hectares in Khabarovsk Krai. This is almost 20 % of the forested area of the region. The range of variation in the heights of the model trees measured at the sites within the age class boundaries corresponds to the bonitization scale compiled for Dahurian larch [3–5].

The most common method of determining stand stock is the product of species height and the sum cross-sectional areas. Some researchers apply the 3/2 rule. It relates the number of plants growing per unit area to the size, weight, or volume of the average specimen and, hence with their total (overall) size, weight or stock [7]:

$$V = v \cdot N^{3/2}, \qquad (1)$$

V here is the stock of plantings, m/ha; *N* is the number of trees, pcs./ha; *v* is the volume of an average tree, m^3.

In the formula (1), the number of trees per hectare can be determined on the sites of the SFI or apply the formula [11]:

$$N = C / D^{3/2}, \qquad (2)$$

C here is a permanent value (constant); *D* is the average diameter of the plantation, cm

Equation (2) is based on a certain regularity. In full plantings, the product of the density of the dominant part of the stand by the average diameter of the trunks to the degree of 1.5 is a permanent value; it is determined by the biological characteristics of the species and practically does not depend on the class of plantings, but is caused by the type of tree species.

The numerator of formula (2) is some permanent value (constant) that reflects the intraspecific struggle of trees for food resources. Logically, with all other things being equal, with a small variation, it should remain unchanged (be constant) throughout the entire life cycle of the plant. Its quantitative expression at each age stage is the product of the number of trunks and the average diameter to the degree (*x*):

$$C = N\,(d)^x, \qquad (3)$$

C here is a constant value (with a dimension of pcs. /ha $(cm)^2$); *N* is the optimal number of trunks in the plantation, pcs.; d – the diameter of the tree, cm.

The constant value (C) calculated according to the growth progress tables of normal plantings, with the number of trunks and the average diameter of the plantings can be described by a functional dependence:

$$C = Nd\sqrt{d}. \qquad (4)$$

The constant value (C) varies depending on the forest-forming species and the completeness of the planting. If the constant (C) is known, formula (4) can be used to calculate the number of trunks per hectare.

Changes in the heights and diameters of model for Daurian larch trees in the Far Eastern taiga forest region with age are shown in Pic. 2 and 3.

The correlation between age and height, age and diameter at a height of 1.3 m is shown by the logarithmic equation:

$$H = 6{,}678\ln(A) - 11.444,\ R^2 = 0{,}503,$$

$$D_{1,} = 13{,}753\ln(A) - 38{,}547,\ R^2 = 0{,}703,$$

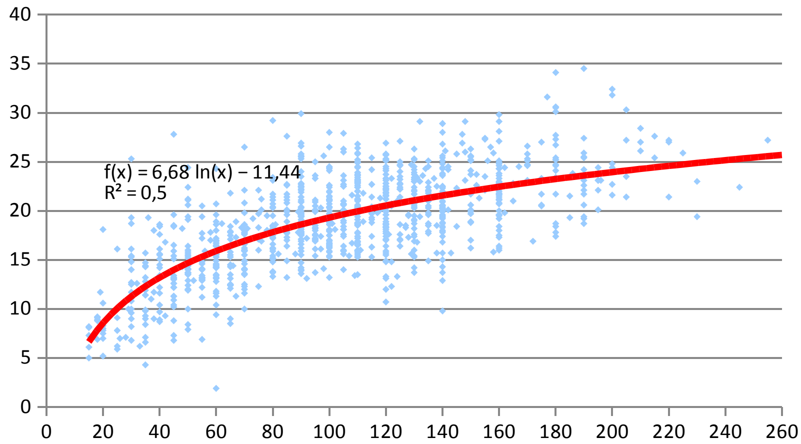
H here is the height of model trees, m; $D_{1,3}$ is the diameter of model trees at a height of 1.3 m, cm; A is the age of model trees, years.

The coefficients of determination of both equations are quite high. In the first case, regression explains 50%, in the second case – 70 % of the variation of the dependent variable, i.e. they can be used to calculate the average values of indicators.

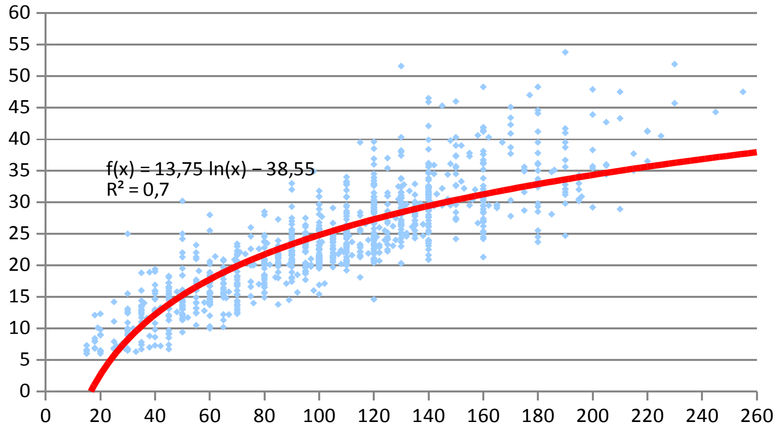
The second type of regression, describing the dependence of the heights and diameters of model trees on age, is represented by a degree equation (Table 1).

Thus, two types of regression differing in the coefficient of determination were selected on the same experimental material. The values of heights and diameters in the growth progress tables were calculated using two types of regression: logarithmic (Table 2) and degree (Table 3). The constant C is taken to be the same for both options (C = 90000). It was calculated according to tables, developed previously for the growth of normal larch plantations of I–III quality classes [1–3].

Other values of forest inventory features (the sum of basal areas, working stock, average and current change in stock) are calculated using formulas well-known in forest inventory.



Pic. 2. Graph of the dependence of the height (H) on the age (A) of the model trees of the Daurian larch



Pic. 3. Dependency graph of diameter per 1.3 m (d1,3) on age (A) of Dahurian larch model tree

Table 1
Regression equations for the connections of forest inventory indicators

N/nn	Regression types	Regression equation of correlation	Coefficient of determination R^2
1	$D_{1,3} = f(A)$	$D = 0{,}6981A^{0{,}671}$	0,81
2	H = f (A)	$H = 1{,}9251A^{0{,}4971}$	0,68
3	S = f (A)	$S = 6E – 05A^{1{,}9102}$	0.82
4	$D_{1,3} = f(H, W)$	D = 12,864H + 13,333W – 44,852	0.63
5	V = f (D, H)	$V = 0{,}000050168241 \cdot D^{1{,}7582894} \cdot H^{1{,}1496653}$	0,84

Note. A – tree age; W – crown width, m; S – square of growth, m^2.

Table 2
Dynamics of forest inventory indicators of Dahurian larch stand
(height and diameter are calculated using logarithmic equations)

Age, years	Height, m	Diameter, cm	Number of trunks, pcs.	Volume of one trunk, m^3	View height	Sum of cross – sectional areas, m^2/ha	Stock, $м^3$/ha	Stock change, m^3/ha	
								average	current
30	11,3	8,2	2138	0,03296	6,2	11,3	77	2,33	–
50	14,7	15,2	1511	0,13203	7,2	27,4	199	3,97	6,45
70	16,9	19,9	1114	0,24891	8,0	34,6	277	3,95	3,90
90	18,6	23,3	800	0,36673	8,6	34,1	293	3,26	0,85
110	19,9	26,1	675	0,48388	9,0	36,1	326	2,96	1,65
130	21,1	28,4	595	0,60044	9,4	37,7	357	2,74	1,55
150	22,0	30,4	537	0,70105	9,6	38.9	376	2,51	0,95
170	22,9	32,1	495	0,81819	10,1	40,0	405	2,38	1,45
190	23,6	33,6	462	0,91783	10,4	40,9	424	2,23	0,95
210	24,3	35,0	434	1,01984	11,4	41,7	476	2,27	2,65

Table 3
Dynamics of taxation indicators of Dahurian larch stand
(height and diameter calculated by degree equations)

Age, years	Height, m	Diameter, cm	Number of trunks, pcs.	Volume of one trunk, m^3	View height	Sum of cross-sectional areas, m^2/ha	Stock, m^3/ha	Stock change, m^3/ha	
								average	current
30	10,3	10,4	2686	0,02296	2,72	22,8	61	1,93	–
50	13,4	13,4	1836	0,05194	3. 66	25,9	95	1,97	1,7
70	15,9	15,9	1419	0,09396	4.73	28,1	133	1,91	1,9
90	18,0	18,3	1245	0,14621	5,53	32.7	181	2,00	2,4
110	19,9	19,9	1021	0,20693	6,65	31,7	211	1,91	1,5
130	21,6	21,6	896	0,27827	7.59	32,8	249	1,91	1,9
150	23,2	23,2	805	0,35513	8,44	34.0	286	1,91	1,8
170	24,7	24,7	733	0,44475	9,30	35,1	326	1,91	2,0
190	26,1	26,1	675	0,53729	10,0	36,1	362	1,91	1,8
210	27,3	27,4	627	0,64339	10,9	36,9	403	1,92	2,0

Note. Fluctuations in taxation characteristics in the growth progress tables were not corrected.

Thus, with the help of several regression equations describing the height, diameter and volume of the trunk, two growth progress tables were developed. The height curves at the age of 110 years have the same values in both tables and correspond to the class III of normal larch plantations [12]. We proceeded from the hypothesis that the forest-forming species in a forest area should be characterized by a statistically average line, which should be a true average, i.e., some base curve for comparison with other lines. To this line, you can attach table of volumes, assortment and commodity tables, and other standards. Practice shows that the presence of such a basis for the forest area will affect the quality of the inventory of larch plantations. Moreover, at the next inventory cycle, it will be possible to explain in detail possible fluctuations of dependent variables with its help. Moreover, it itself will change in one or another way due to the loss of part of the trees and the increase in height. It remains to choose the appropriate curve that would best describe the height regression in the forest area. In our example, the discrepancy between the logarithmic and degree curve does not exceed 5 %. Comparison with GPT of normal plantations [12] showed that larch plantations of the Far Eastern taiga region on an area of 68 million hectares correspond to class III of bonitet. The discrepancy in reserves by age classes in the range of 30–210 years was 12 %.

CONCLUSION

Based on sample trees measured in the state forest inventory, it is possible to develop different types of standards, including growth progress tables. Calculations are simplified by averaging the data of a taxation indicator within the age class and then graphically aligning and only after that describing it with some function. The main part of the growth progress tables in the last century were built according to this scheme. Definitely, it had a local character and was significantly subjective.

The choice of regression equation at describing a non-aggregated sample has an impact on the results of taxation indicators calculations. For example, the divergence of heights in the interval of 30–210 years is equal to 5 %, diameters – 36 %. The value of divergence of the main index – stock, calculated by two variants, is up to 27 %. Therefore, by compiling of the GPT, preference should be given to functions with a higher rate of determination. A comparison with the current growth progress tables of standard larch stands showed that the developed growth progress tables belong to the III class of bonitet, and the differences in stocking over a sufficiently long period (Table 2) did not exceed 12 %.

How to treat the given curves? In our opinion, they are true averages describing the general complex, because they are based on experimental data obtained by method of random sampling with a predetermined accuracy for a certain forest area. It is possible to remove extreme fluctuations of the features. Alternatively, the calculations could be made for stands corresponding to the upper and lower limits of height variation and approach the construction of optimal GPTs for larch stands growing in the Far Eastern taiga forest area.

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МОДУЛЬНАЯ МАШИНА ДЛЯ РАБОТЫ В СЕВЕРНЫХ РАЙОНАХ

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Приведены требования к шасси базовой машины для механизации процесса заготовки и транспортировки растительного сырья в северных районах Красноярского края. Наиболее полно отвечает приведенным требованиям сочлененная гусеничная машина. Обоснованный выбор сочленённой гусеничной машины основан на сравнительном анализе с другими типами транспортных машин по опорным, кинематическим, динамическим показателям, при движении, повороте и действующим нагрузкам в ходовой системе. Предлагаются различные решения при создании сочленённых гусеничным машин путём реализации блочно-модульного принципа, при котором компоновкой унифицированных узлов массового производства может быть создано семейство машин, состоящих из энергетических модулей и технологически активных модулей, с гибкой технологией и с применением новых концепций и технических решений. Энергетический модуль машины может быть создан на базе существующих колёсных тракторов сельскохозяйственного назначения и автомобилей. Тележки для моторно-трансмиссионного блока и технологические тележки могут быть выполнены в виде рамных модулей с различными вариантами ходовой системы, например, на пневматических катках и движитель с резиновыми гусеницами. На тележки возможна установка моторно-трансмиссионных блоков различных колёсных машин различной мощности, в результате чего можно создать спектр унифицированных машин различного технологического назначения и разной мощности, способных работать в любых условиях.

Использование бортовых цепных передач, ведущих мостов автомобильного типа передней тележки, карданной передачи и заднего ведущего моста задней тележки позволяют упростить передачу крутящего момента на ведущие звездочки гусениц тележек. Поворот сочленённой машины может осуществляться за счёт изменения угла между продольными осями энергетической и технологической тележек. Процесс реализуется с помощью дифференциальных и тормозных механизмом установленных на полуосях ведущих мостов.

Ключевые слова: *северные районы, механизация, сочлененных машин, активные модули, новые концепции.*

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MODULAR MACHINE FOR WORK IN THE NORTH AREAS

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The requirements for the chassis of the basic machine for mechanization of the process of harvesting and transportation of plant raw materials in the northern regions of the Krasnoyarsk Territory are given. The articulated caterpillar machine most fully meets the above requirements. The substantiate choice of articulated tracked vehicles based on comparative analysis with other types of vehicles in support, kinematic, dynamic indicators, when moving, turning, and operating loads in the running system. Various solutions are proposed the articulated caterpillar machine vehicles by imple-menting the block-modular principle, in which the layout of unified mass production units can be created a family of machines consisting of energy modules and technologi-cally active modules, with flexible technology and with the use of new concepts and technical solutions. The energy module of the machine can be created on the basis of existing wheeled tractors of agricultural purpose and cars. The trolley for the motor-transmission unit and the technological trolley can be made in the form of frame modules with various variants of the running system, for example, on pneumatic compactors and crawlet drive with rubber tracks. On the trolley can be installation the motor-transmission blocks of various wheeled vehicles of different power, whereby it is possible to create a spectrum of standardized equipment of various technological purposes and in different capacities, capable of working in any conditions. The use of on-board chain drives, driving bridges of the automotive type of the front trolley, cardan gear and the rear driving bridge of the rear makes it possible to simplify the transmission of torque to the on leading asterisks caterpillars trolley. Turning of the articulated machine can be carried out by changing the angle between the *longitudinal axes of the energy and technological trucks. The process is realized by means of differentials and brakes mechanisms installed on the half-axles of leading bridges.*

Keywords: *northern areas, mechanization, articulated vehicles, active modules, new concepts.*

INTRODUCTION

Highly productive forest food resources in the northern regions of the Krasnoyarsk Territory are located in marshy and remote places with long-term vegetation cover.

In terms of transport and operational characteristics of vehicles, the most adapted to northern conditions is an articulated caterpillar vehicle with a block-modular layout scheme.

OBJECTS AND METHODS OF INVESTIGATION

To mechanize the process of harvesting and transporting plant materials under these conditions, base chassis of a vehicle must meet a number of requirements, which, of course, include the following [1–3]:

– ability to work on soils with low bearing capacity, including swamps with a guaranteed exclusion of vehicle flooding, while average specific pressure on supporting surface should not exceed 120–130 g/cm^2;

– ability to work with minimal damage to topsoil;

– movement should not lead to damage to vegetation cover and preservation of stand;

– possibility of quick change of process equipment;

Meeting of these requirements can be ensured by an articulated caterpillar vehicle, which includes an energy and technological bogie connected to each other by a draft gear. These advantages in comparison with vehicles of other design and layout schemes make it possible to realize the following operational advantages:

– when turning, the track width of an articulated caterpillar vehicle is less than that of two tracked vehicles with tracks of equal width;

– in articulated caterpillar vehicle, a kinematic method of rotation is used, in which a change in turning radius occurs due to a change in the angle between longitudinal axes of the trucks, and not due to a change in traction forces on the caterpillars;

– articulated caterpillar vehicle has a reduced pressure on the supporting surface;

– dynamic non-uniformity of loads along the axles and supports of undercarriage system of an articulated caterpillar vehicle is several times lower than that of a two-caterpillar vehicle;

– in articulated caterpillar vehicles, it is possible to implement modular principle of vehicles design, in which, by arranging unified mass production units, a range of vehicles can be created, consisting of energy modules and active technological modules, with flexible technology and using new concepts and technical solutions.

Creation of an articulated caterpillar vehicle and its use is based on a comparative analysis with other types of transport vehicles in terms of reference, layout indicators and the ability to smoothly change radius of movement during a maneuver.

Layout options create a range of unified machines of medium technological purpose and different capacities, capable to work in any conditions.

The energy module of a vehicle for operation in the Northern regions can be created on the basis of existing wheeled machines, which may include both agricultural tractors and cars (Fig. 1). From a base wheeled vehicle, the front axle and rear wheels are used. The motor-transmission unit obtained in this way is installed on a truck made in the form of a module, which is equipped with a rigid frame, a rubber belt track and pneumatic rollers of various design options connected with the frame by suspensions. Rubber tracks are available in a range of design options to reduce machine weight and find applications in various types of linked vehicles.

The connection of the output shafts of the motor-transmission unit with the drive sprockets of the caterpillar truck can be carried out, for example, using onboard chain drives. It is possible to install motor-transmission units of various wheeled vehicles of various capacities on the same truck, as a result of which it is possible to create a range of unified machines for various technological purposes and different capacities, capable of operating in any conditions.

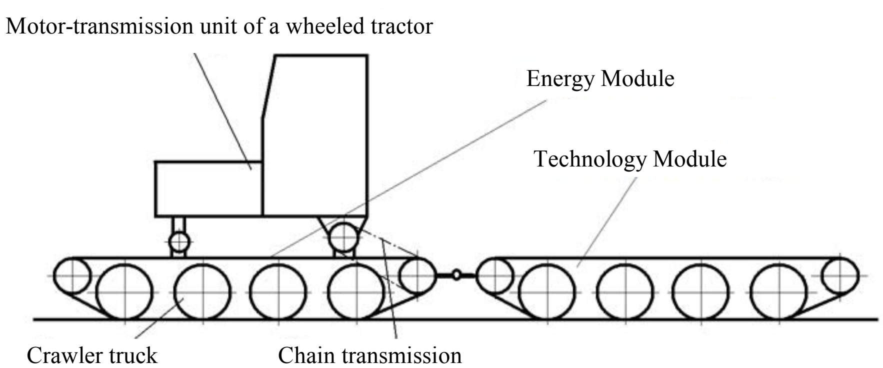

Fig. 1. Scheme of a modular articulated vehicle

The connection of the power caterpillar truck by a draft gear with the second caterpillar truck, intended for mounting technological equipment on it, and transferring part of engine energy of a motor-transmission unit to the second truck to activate its caterpillars forms an articulated caterpillar vehicle with interchangeable technology – trolley. The draft gear of such a machine should provide a quick change of technological trolleys with various technological equipment.

The caterpillars of both trucks must be leading. There are various ways to transfer energy from an energy trolley to a technological trolley. For a small-sized modular vehicle, the device in [4] can be described as the simplest.

Let the energy trolley have a bridge *1* located in the rear part with drive sprockets *2* of caterpillars, and a technological trolley – bridge *4* located in the front part with drive sprockets *3* of caterpillars (Fig. 2). The bridge *1* of the energy trolley and the bridge *4* of the technological trolley are connected by cardan transmission *10*. Thus, torque from the engine is transmitted to all four caterpillars of the machine. When turning the vehicle, thanks to the differentials installed in all axles of the vehicle, different speeds of the right and left caterpillars are provided.

Use of onboard chain drives allows the simplest transfer of torque from the engine-transmission unit to the drive sprockets of the caterpillars. In addition, the chain drive allows to obtain various gear ratios of the drive by installing interchangeable chain sprockets and thereby change traction and speed properties of a vehicle depending on the conditions of its operation. The connection of the bridges of front and rear trucks with a cardan drive makes it possible to simplify the system of power transmission from a front truck to a rear one, reduce the distance between trucks due to elimination of intermediate elements and thereby improve maneuverability of a vehicle, as well as simplify operations for coupling and uncoupling the trucks.

Rotation of an articulated vehicle is carried out by changing the angle between longitudinal axes of the energy and technological trolleys, which can be performed using various devices. For a small-sized articulated vehicle, it is advisable to use the simplest devices, for example, an automobile steering control, or a device according to Russian patent No. 2580599 [5].

Device for controlling an articulated two-cart caterpillar vehicle according to a Russian patent No. 2580599 includes a brake device *1* of a vertical hinge at the connection of the draught bar *2* of a front truck *3* and the draught bar *4* of a rear truck *5*. The brake system *1* is connected by a drive *6* with a control (for example, a lever) located in the driver's cab (not shown in the figure). The caterpillars of a front truck *3* and a rear truck *5* are connected to the power plant through transmission of a vehicle with a branching of energy flows to main gears *7* and *8*, interwheel differentials *9*, *10*, output shafts *11, 12, 13, 14*, kinematically connected with the left and right caterpillars of trucks *3, 5*.

On the output shafts *11, 12, 13, 14* of trucks *3, 5* brake mechanisms *15, 16, 17, 18* are installed. The drive *19* of the left brake mechanism *15* of a front truck *3* is connected to the drive *20* of a right brake mechanism *18* of a rear truck *5* and is connected to the left control (for example, a pedal) in the driver's cab (not shown in the Figure). The drive *21* of a right brake mechanism *16* of a front truck *3* is connected to the drive *22* of a left brake mechanism *17* of a rear truck *5* and is connected to the right control (for example, a pedal) in the driver's cab (not shown in the Figure).

In the described device, complex mechanisms in controlling the rotation of an articulated vehicle are excluded, which leads to a simplification of design of a control device and an increase in its reliability.

Simultaneous rotation of a front truck in required direction, and a rear truck against direction of rotation provides an articulated vehicle with a speedy turn.

Installing a braking device on a vertical hinge allows you to adjust the moment of resistance of changing the angle between longitudinal axes of front and rear trucks, which allows you to reduce dynamic loads when changing a turning radius due to smooth change in relative angular velocity of the trucks and improve control accuracy.

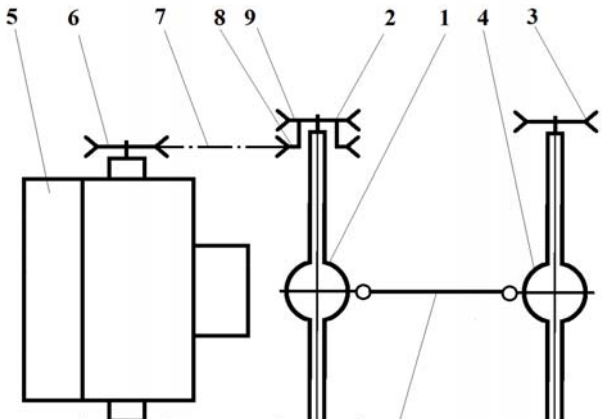

Fig. 2. Scheme of power transmission of a small-sized modular vehicle

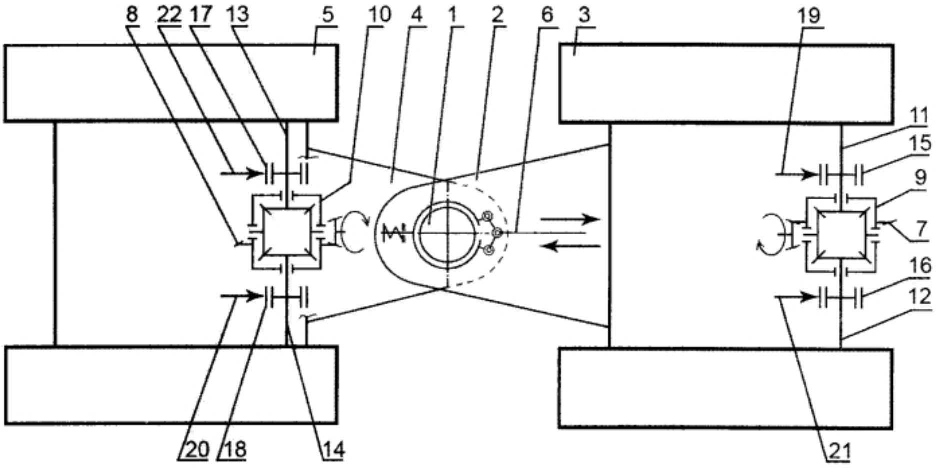

Fig. 3. Control device for an articulated machine according to Russian patent No. 2580599

CONCLUSION

1. The requirements for a base chassis of a vehicle when operating in the northern conditions of the Krasnoyarsk Territory are proposed.
2. The use of an articulated caterpillar vehicle for mechanization of various technological operations in the northern conditions is substantiated.
3. When creating an articulated vehicle, a block-modular layout scheme was proposed, which includes an energy and technological trolley with a draft gear.
4. Possible layout and design schemes of vehicle units were developed using unitized assembly and components of cars, tractors and other machines.
5. Technical solutions and designs of an articulated vehicle make it possible to mechanize technological operations and reduce the cost of highly productive forest food products.

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АВТОРСКАЯ ССЫЛКА

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