Bioecological aspects of plantation nut cultivation of Siberian cedar (*Pinus sibirica* du tour.) in Russia

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**Abstract.** The conditions for obtaining the maximum gross yield of pine nuts on the grafting plantations have been considered. Nut production plantations are created in the most productive vegetative conditions (not lower than II-III quality class). The selection of areas was carried out on the basis of forest vegetation zoning, bioecological properties and climatic conditions. First of all, plantations are laid in the zone of ecological optimum, outside the natural range (zone of coniferous-deciduous forests of the European part of Russia). Valuable clone genotypes of Siberian cedar for seed and pollen productivity have been selected on graft plantations and in the archives of plus tree clones. Mixing of clones is carried out taking into account the reproductive differentiation of genotypes, providing a biologically possible output of full-grain seeds from the cone. Clones of various reproductive types and seed productivity are placed on the plantation in the absence of natural sources of pollination. Dates of flowering and pollen dispersion must be the same. The distance between the trees should ensure the yield increase with full crowns for at least 50-80 years. Maximum distance between high-yielding grafts and pollinating grafts is not more than 15 m.

**Introduction**

The area of natural forests on the Earth is constantly decreasing. About 187 million hectares of forest plantations were created by 2002 to meet the growing demand for wood, sap, nuts and other forest benefits in different countries [1]. They are important for the economy, so their area increases annually. Plantation forest cultivation enables to obtain a large amount of diverse forest products in a regulated mode of density, to create plantations that assimilate atmospheric CO₂, i.e. global environmental value in a short time [2-4]. Approximately 50% of the plantation area is a raw material (wood products for the processing industry). The remaining half of the plantations produces other forest products and weightless forest benefits [4]. The type of target plantation depends on its purpose and the possibility of its profitable production in certain climatic conditions.

Siberian cedar is the main nut-bearing species in Russia. The share of its plantations accounts for more than 80% of the biological yield of all nut-bearing fruits. For 300 years, pine nuts have been an important economic resource of the country. An average of at least 20 thousand tons is harvested in Siberia every year. Cutting of cedar forests was prohibited. The industrial harvesting of cedar wood, which began in the 40s of the 20th century and lasted 50 years, caused enormous economic and
environmental damage to living and future generations. At present, successful pine nut production is possible only in rare high-yielding years. It does not exceed 1-2 (4) thousand tons.

The plantation nut cultivation of Siberian cedar in Russia is a child of need. Its development is caused by a sharp reduction in pine nuts harvesting because high yielding plants were cut over an area of 600 hectares and low seed productivity of the saved natural cedar pines. It continuously decreases in older trees which have reached the apogee of seed production, complexity of nut harvesting in boreal conditions and constantly unsatisfied demand for pine nuts and cedar oil.

Results and discussion

The yield of pine nuts on the plantation is formed as a result of the interaction of genotypes with environmental factors. In many respects, it depends on the technology of creation and agrotechnology of cultivation. Obtaining the maximum gross yield of pine nuts on a plantation is possible under the following conditions: 1) full compliance of the bioecological properties of the species with the proposed growth conditions, 2) use of selected clone genotypes, 3) rational placement and mixing of clones, ensuring the most complete realization of the potential yield of each individual.

Bioecological features of Siberian cedar

Cedar does not have high demands on most environmental factors. It is shade-tolerant, but grows better, earlier, more abundantly and regularly bears fruit in light areas. It is quite winter-hardy and undemanding to heat [5]. It usually reaches the maximum development and longevity in the areas with a high amount of temperatures above 10°C: about 1700-1800°C [6]. It is not demanding to soil in conditions of sufficient moisture content. Trees reach the best development on fertile, deeply drained loamy and sandy soils with a well-defined structure and moisture content. The need for high moisture content and, especially, air humidity, is its only ecological demand. It can not be seen in the areas with an average monthly relative humidity of air for 14 hours below 45°, with its average annual value not less than 60% [7].

The ecological optimum of Siberian cedar, where the most productive plantations (in terms of growth and biological yield of seed) are formed, is located in the southern taiga subzone and in the lowland (taiga) belt of the Altai-Sayan mountain region [8]. Nut production of cedar forests depends on the growing conditions. It decreases in the mountains - with a rise along the high-altitude profile, on a plain - with the distance from the ecological optimum of the species to the borders of the natural range. Cedar forests of the Urals, the Republic of Komi, the Khanty-Mansiysk Autonomous Area, and the Irkutsk Region show low and rare yields.

Division into districts of plantations

The selection of areas and prioritization of nut-producing cedar plantations is carried out on the basis of forest vegetation zoning by S. F. Kurnayev [9]. It is made taking into account the maximum correspondence of the bioecological properties of Siberian cedar to climatic conditions, the optimal heat and moisture regime, and the length of the growing season. Their productivity should not be lower than II-III classes of bonitet.

They are created in the range of Siberian cedar and in the areas of successful introduction of cedar pines. They can be laid in the most productive (for the growth of Siberian cedar forest) conditions on the whole part of the natural range of species, with the exception of the northern taiga districts of the West Siberian and Ural provinces [10].

Firstly, the plantation should be created in the zone of ecological optimum. This is low mountain (taiga) belt of the Altai-Sayan mountain region (up to 800 m above the sea level) in the Salair ridge, Kuznetsk Alatau, Mountain Shoria, North-East Altai, northern part of the Eastern Sayan and on the northern slopes of the Western Sayan. Here there is an optimum heat and moisture regime that ensures regular and abundant seed production on high-fertile soils.

Secondly, it is recommended to plant nut plantations in the middle mountains (800-1200 m above sea level) of the Altai-Sayan mountain region, in the southern taiga district of the West Siberian plain,
in the fir-cedar taiga belt of the high Baikal region and in the cedar taiga belt of the East Sayan. Here, the average nut-productivity of plantations will be approximately 20% lower. Abundant and good yields of seeds will be formed less frequently in the long-term cycle.

Outside the natural range of Siberian cedar, the selection of areas for laying cedar root plantations is carried out by the analog method of the climatic conditions. At the same time, the following indicators limiting seed production and cedar growth are compared: duration and average hydrothermal coefficient of the growing season, amount of precipitation and sum of temperatures over 10 °C.

Climatic conditions are quite acceptable for successful adaptation of Siberian cedar on the European territory of the country. This species can successfully grow on its own roots in the subzones of coniferous, mixed and deciduous forests - from Syktyvkar to Voronezh.

First of all, nut-bearing plantations on cedar rootstocks must be created in the northern and southern subzone of mixed forests of the Russian Plain, in the Central and Bryansk districts of coniferous-deciduous forests. Secondly, they should be created on cedar rootstocks in the northern and southern subzones of the mixed forests of the eastern part of the Russian and Ural plain, in the subzone of the southern taiga area. Here, nut-bearing productivity will be slightly lower.

Thirdly, it is possible to create nut-producing plantations in the subzone of the middle taiga of the Russian Plain and Middle Urals in the most productive forest types (I-II bonitet). It is made by cloning of selected high-yielding individuals of Siberian cedar from the zone of ecological optimum in the third class of bonitet.

**Selection of valuable clone genotypes**

Stable seed-bearing in Siberian cedar occurs as a result of cross-pollination of biologically different tree types. It guarantees species preservation in the process of evolution. Therefore, it is necessary to place various clones (female and mixed reproductive type) to obtain high yields on the plantation. Nut production plantations are created by selected material - grafted seedlings. Cuttings for grafts are harvested on high-producing clone genotypes. These are vegetative offspring of plus trees, which confirmed high values of the species trait (yield, pollen productivity) under clone trials [11]. High-yielding clone genotypes and pollinator clones are selected on graft plantations and in the archives of plus tree clones of Siberian cedar. In fact, these are clone test plantations of initially selected individuals of the nut-bearing species of different yields with different values of other economically valuable traits. They are located in the Altai Republic, the Komi Republic, the Krasnoyarsk Territory, Tomsk, Novosibirsk and other regions.

Phenotypic sign of high yields of Siberian cedar is a well-developed female generative crown layer. Its length and number of fruit-bearing shoots in it are the main integral indicators of the current and potential nut productivity of any tree. There is high direct connection between them: r = 0.84-0.88. Crown width may be auxiliary sign. These phenotypic characteristics of parental productivity are highly inherited in a broad sense during vegetative reproduction. It is H = 0.808-0.901% in the 16-20 year old grafts.

The nature of the research is consistent with the relationship between the phenotypic signs of parental yield and clones (r = 0.76–0.85). This enables their use in the selection of high-yielding genotypes among the clone progeny [12]. High-yielding clone genotypes are selected among the grafts having sprawling, obovoid, cylindrical form of the crown, with a length of the fructiferous line not less than 80% of the entire length of the crown and an abundance of fruiting shoots. The selection of genotypes of high pollen productivity is carried out among the mid-yielding grafts with a pyramidal, conical shape of the crown. The length of the male tier is not less than 50% of the entire crown. There are no male shoots or micro strobos on its branches [11].

**Selection and placement of clones**

The productivity of trees is explained by hereditary genetic properties of organisms and environmental factors that influence the physiological processes occurring in them. The standing density of trees is the most important among them. It largely determines the conditions of growth and seed production: light,
development of crowns, establishment and formation of generative organs, area of nutrition. The density of trees on the plantation should provide the most complete realization of the potential yield of each individual and the maximum gross yield of pine nuts per unit area.

Taking into account the factors affecting photosynthesis, the formation and size of crop, the regularity of fruiting and the energy of growth, the cedars should be placed freely for a long period of its operation for at least 50-80 years. They should have a sufficiently large area of nutrition, well-developed, wide, and extended crown heavily covered with needles. As the crowns close together, the abundance of macro strobes decreases, and the yield decreases. Male generative organs are less sensitive to shading conditions. In sparse village and park cedar forests, the greatest number of them is formed on the shadow side of the crown.

The formation of high yields on the plantations is promoted not only by the preservation in vegetative progeny of the high seed productivity of parent trees and their free placement, but mainly by clone mixing. It should provide effective trans-pollination, which guarantees the maximum biologically possible output of full-grain seeds from a cone. It should be carried out taking into account reproductive differentiation of genotypes, reflecting unequal seed and pollen productivity and different effects of reproductive interaction. High-yielding, female individuals have low pollen capacity. Medium-yielding, mixed reproductive types of cedars are characterized by high pollen productivity and are functional pollinators. The yield of full-grain seeds from the cones largely depends on the fertilizing ability of pollinator genotypes. It is higher in mixed reproductive trees and lower in female cedar trees. When pollinating high-yielding trees with medium-yielding, the number of full-grain seeds in cones (in the years of different yields) is 19-22% higher than in the combinations of partners of the same high seed productivity. The effect is noted, respectively, in 40-73% and in 14-25% of cases [13].

High capacity for hybridization in the interaction of genotypes with sharply differing characters has been established for other plants, which indicates general biological nature of this phenomenon [14]. Therefore, it is necessary to place clones of different reproductive types and yields (high and medium-yielding) to obtain high yields on a nut-producing plantation, in the absence of natural sources of pollination. Duration of flowering of high-yielding clone genotypes should coincide with the time of pollinator cloning.

The formation of reproductive organs on grafts has its own age features. In the first 15–20 years after grafting, the male sphere develops very weakly. Pollination (in the natural range of the species) occurs mainly due to pollen from the adjacent forest walls or individual mature cedar trees. Therefore, cedar nut plantations should be laid primarily near reliable sources of natural pollination in the cedar regions in order to ensure the necessary pollen regime from an early age. In this case, it is possible to clone individuals which are mainly positive for the abundance of high-quality seeds. It is necessary to place different reproductive and seed productivity types of clones to obtain high yields on the plantation. It is necessary in the absence of guaranteed sources of natural pollination, i.e. with significant (more than 1 km on the plain and more than 400 m vertically - in the mountains) removal of the forest walls and mature cedar trees in its range and with their complete absence in the areas of successful introduction of the species. Ratio of high-yielding and mid-yielding clones which looks like -3: 1; -4: 1 is also possible.

Over time, the main pollen background on the plantation is created by medium-yielding clones, which are characterized by the highest pollen productivity. High-yielding plantations show much smaller productivity. Then when they are located next to the medium-yielding, the probability of pollination by the latter will be much greater than between them. Therefore, clones of different yields and pollen productivity, as a rule, should alternate on the plantation: medium-yielding clones are placed in close proximity to high-yielding ones.

The placement of clones is in rows, the mixing of rows is regular. The advantage of this alternation consists not only in the reliable supply of pollen from pollinated clones, but also in the effect of the interaction of different quality genotypes according to the reproductive type.
The neighbor placement of high-yielding clones is allowed. Inter-pollination between them, due to their low pollen productivity, is less likely than pollinating them with the surrounding medium-yielding clones, with higher pollen production (3-4 times).

Medium-yielding clones must be securely isolated from each other by high-yielding. Over-pollination between them does not contribute to the yield increase.

The distance between the trees on the plantation should ensure the formation of crops with full crown lightning. It depends on the intensity of its growth, and varies in different climatic conditions. Inoculation are placed according to the scheme 8×8 -10×10 m in a row and between rows (120-150 pieces / ha) in the zone of the Siberian cedar ecological optimum. It is made according to the scheme 7×7 (200 pieces/ha) or 7×6 (250 pieces/ha) in the areas of successful introduction of Siberian and European cedar.

Plants in the adjacent rows are arranged in a chessboard order: the even rows are displaced for ½ of the distance with respect to plants in the odd rows. This improves luminance and increases power supply area (figure 1).

The maximum distance of pollinated high-yielding grafts from pollinator clones on the plantation is determined by the range of pollen spreading. It ensures normal pollination and the number of pollinators by their total pollen productivity. The dispersion of the main pollen mass is very limited. The greatest pollen amount settles within the projection of tree crown. It decreases twice in a radius of 5–15 m. It decreases four times at a distance of 20–25 m [15]. At the cedar plantation, the range of dispersion of the main mass of pollen will be reduced even more. Here, wind power plays a big role. Densely coniferous crowns of cedars, more saturated with the branches, than Scots pine tree, have 1.6-1.8 times increase of the above-ground phytomass weight. It reduces the wind speed almost by 5 times [16]. With this in mind, the maximum distance of high-yielding grafts from pollinating scions should not exceed 15 m, with a distance between trees in rows and between rows from 7 to 10 m.

The ratio of clones on the plantation depends on the distance between the trees and the number of grafts of each clone. With the 7×7 m scheme, the ratio of high-yielding clones to medium-yielding pollinator clones is 3: 1. Every fourth inoculation on 1 ha in a row is a pollinator. There are 3 of them in odd rows, and 4 - in even rows (in total - 50 pieces). High-yield grafts - 150 pieces. 4 high-grade genotypes are cloned, with 36-37 grafts each, and 2 medium-yielding (21 and 28 each). Pollinating clones alternate in rows: one - in odd rows, another - in even rows.

When the scheme is 8×8 m, the ratio of high and medium-yielding clones is 4: 1. 3 grafts-pollinators on 1 hectare are in odd rows, 2 - in even ones (in total - 30 pieces). High-yield grafts - 115 pieces. 4 high-yielding clones are used, 28-29 grafts of every clone, and 2 medium-yielding clones (12 and 18 pieces). The alternation of the last ones is inter-row (table 1).

On the plantation, located near reliable sources of natural pollination, only high-yielding plants are planted, followed by adjoining. Their number depends on the number of harvested cuttings5 or 4 clones are placed in the presence of 30-40 pieces from each one.

Biodiversity and, possibly, plant resistance is reduced with a limited number of clones on the plantation [17, 18]. The likelihood of closely related crosses increases. However, this maintains high seed and pollen productivity of clone genotypes, the inter-pollination between which does not have a large effect on the quantity and nutritional properties of the commodity (food) nut.
Clones planted from a single geographical area or a high-altitude ecological sub-belt can be seen on the plantation. With the concentration of clones of various origins, due to non-simultaneous, asynchronous development of male and female generative organs, ecological isolation arises during over-pollination: macro strobes do not realize their potential reproductive abilities. This leads to a sharp yield decrease.

Clones with synchronous development of generative organs, the same dynamics of fruiting, ripening and litter of cones should be combined into separate blocks with a minimum area of 1 hectare to improve the efficiency of nut harvesting and reduce the loss of seeds and cones.

Table 1. Layout of clone placement on the nut-bearing plantations of cedar pines with ordinary placement and regular mixing with placement of 7×7 m; when mixing 3:1; for 6 clones.

|    | 1  | 1  | 1  | 2  | 2  | 2  | 3  | 3  | 3  | 4  | 4  | 4  | 4  |
|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 1  | 1  | 1  | 1  | 2  | 2  | 2  | 3  | 3  | 3  | 4  | 4  | 4  | 4  |
| ■  | 1  | ■  | 2  | ■  | 2  | ■  | 3  | ■  | 3  | ■  | 4  | ■  | 4  |
| 1  | 1  | 1  | 2  | 2  | 2  | 3  | 3  | 3  | 4  | 4  | 4  | 4  |
| ■  | 1  | ■  | 2  | ■  | 2  | ■  | 3  | ■  | 3  | ■  | 4  | ■  | 4  |
| 1  | 1  | 1  | 2  | 2  | 2  | 3  | 3  | 3  | 4  | 4  | 4  | 4  |
| ■  | 1  | ■  | 2  | ■  | 2  | ■  | 3  | ■  | 3  | ■  | 4  | ■  | 4  |
| 1  | 1  | 1  | 2  | 2  | 2  | 3  | 3  | 3  | 3  | 4  | 4  | 4  |
| 1  | 1  | 1  | 2  | 2  | 2  | 3  | 3  | 3  | 3  | 4  | 4  | 4  |
| ■  | 1  | ■  | 1  | ■  | 2  | ■  | 3  | ■  | 3  | ■  | 4  | ■  | 4  |
| 1  | 1  | 1  | 2  | 2  | 2  | 3  | 3  | 3  | 3  | 4  | 4  | 4  |
| ■  | 1  | ■  | 1  | ■  | 2  | ■  | 3  | ■  | 3  | ■  | 4  | ■  | 4  |
| 1  | 1  | 1  | 1  | 2  | 2  | 2  | 3  | 3  | 3  | 3  | 4  | 4  | 4  |
| 1  | 1  | 1  | 1  | 2  | 2  | 2  | 3  | 3  | 3  | 3  | 4  | 4  | 4  |

1-4 – high-yielding clones; ■, · - medium yielding pollinator clones
Table 1a. With placement of 8×8 m; at mixture 4:1; for 6 clones.

| 1 | 1 | 1 | 2 | 2 | 3 | 3 | 3 | 4 | 4 | 4 | 4 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ■ | 1 | ■ | 2 | ■ | 2 | ■ | 3 | ■ | 4 | ■ | 4 |
| 1 | 1 | 1 | 2 | 2 | 3 | 3 | 3 | 4 | 4 | 4 | 4 |
| 1 | • | 1 | • | 2 | • | 3 | • | 3 | • | 4 | • |
| 1 | 1 | 1 | 2 | 2 | 3 | 3 | 3 | 4 | 4 | 4 | 4 |
| ■ | 1 | ■ | 2 | ■ | 2 | ■ | 3 | ■ | 4 | ■ | 4 |
| 1 | 1 | 1 | 2 | 2 | 3 | 3 | 3 | 4 | 4 | 4 | 4 |
| 1 | • | 1 | • | 2 | • | 3 | • | 3 | • | 4 | • |
| 1 | 1 | 1 | 2 | 2 | 3 | 3 | 3 | 4 | 4 | 4 | 4 |
| ■ | 1 | ■ | 2 | ■ | 2 | ■ | 3 | ■ | 4 | ■ | 4 |
| 1 | 1 | 1 | 2 | 2 | 3 | 3 | 3 | 4 | 4 | 4 | 4 |

1-4 – high-yielding clones; ■, • - medium yielding pollinator clones

Conclusion
Using placement patterns that ensure efficient pollination or with reliable sources of natural pollination, the first industrial yield of pine nuts (60-100 kg/ha) is formed by the age of 12-13 years of grafting on nut-producing plantations created by selected clones in highly productive soil and climatic conditions, primarily in the zone of ecological optimum of the species and in the areas of efficient introduction. It reaches 150–200 kg by the age of 20, 300-400 - by 25, 500-600 kg/ha - by 30, and it further increases. The harvest on the plantation from the age of 25 significantly exceeds seed productivity of the best 200-240-year-old taiga pine forests. It exceeds the near-plantings after 30 years old.

The advantages of plantation nut cultivation are territorial proximity of plantations, mechanization of labor-intensive processes of nut procurement, living conditions of workers, high labor productivity and low cost of production, relatively fast payback - 15-26 years, depending on the type of cedar products (nut, refined grains, or oils).

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