The effect of a single inbreeding on the growth and development of fast-growing tree species, *Betula pendula* and *Betula pubescens*

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Abstract. The aim of the research is to study parameters of seed reproduction systems in *Betula pendula* and *B. pubescens*, find possibilities for producing viable inbred plants, and analyze their growth and development and hybrid heterosis at crossing the selected forms in generations F₁ and I₁. Differentiation in deciduous trees by self-fertility level was established. By this feature the progeny of different tree groups have different genetic and selection value depending on pollination method of parent trees: at open pollination the progeny of self-sterile and transitional forms (cross-pollinating) are the most fast-growing and resistant to unfavorable environmental factors, whereas at self-pollination – the progeny of self-fertile forms. Accordingly parent trees were classified into three groups: self-fertile, self-sterile and transitional forms. Frequency of self-fertile forms and preservation of inbred plants in downy birch are higher than the similar indicators in silver birch. Thus an ambiguous effect of closely related crossing in tree species on the growth and development of their seed progeny was revealed. The effect of inbreeding on some trees is positive, on other negative, and there is the third group, in which the growth deflections caused by inbreeding are inessential. Such trees are suggested for use in various selection programs.

1. Introduction

Inbreeding, or closely related crossing, refers to general biological phenomena. Currently, the scientific community has already established a negative opinion about this biological phenomenon, which is practically expressed in inbreeding depression. Inbreeding causes a decrease in the average phenotypic values of all quantitative traits in the animal and plant world, especially affecting productivity and yield [1]. This provision was derived and tested on annual crops (soybeans, beans, tomatoes, corn). The minimum values of quantitative traits were revealed in the seed progeny after 5-7 tests (depending on the culture) self-pollination. It is believed that such selective traits as productivity and productivity pass into a homozygous state and are fixed hereditarily. In the course of further crossing of such homozygotes with each other, the effect of heterosis is observed, which consists in exceeding the average phenotypic values of such traits as height growth, diametric growth in the original parent forms [2].

As to woody plants, many problems in this respect remain insufficiently studied; thus, the Birch genus (*Betula*) is a complicated one, as regards its systematization. There are contradicting data about the possibility of natural hybridization and attitude to inbreeding for this genus. Some species (forms), the Karelian birch (*Betula pendula* Roth var. *carelica* (Mercklin) Hämet-Ahti), for example, have
several life forms. Other reproductive and selection features of this genus, in particular, their differentiation by reproduction systems, require clarification [3].

At present, it is acknowledged that one of the major factors in planning and carrying out of genetic selection programs are peculiarities of reproductive system of a species, however, many of its peculiarities in arboreal species have been studied rather insufficiently. Among them is the genetic system of seed reproduction. Thus, *B. pendula* and *B. pubescens*, as well as many other forest-forming species are considered allogamous species. There are also no experimental data about the structure of its native populations by the types of seed reproduction systems. For the solution of practical questions of selection, such characteristic is also necessary for each selected form. However, selection and seed growing in forestry are mainly directed at the utilization of woody plants only as cross-breeds.

Recently, many works and generalizations have appeared concerning the effect of inbreeding on the manifestation of qualitative and quantitative traits in plants and animals. E. Joly [4] highlights the following advantages of inbreeding. Firstly, a reduction in cost compared to sexual reproduction, since in sexual reproduction, each of the parent individuals contributes half of the inheritance of the offspring, while in asexual reproduction, the offspring inherits the full parental genome. Secondly, inbreeding is necessary for the manifestation of predominantly recessive phenotypes, since useful mutations are sometimes in a recessive state. Finally, Mueller's ratchet principle: The third advantage of inbreeding is that it is the only effective way for diploid organisms to combat the accumulation of recessive harmful mutations in their genomes. The fact that mutations accumulate steadily in genomes with a large number of generations is usually called the Muller ratchet.

The systematic provision of the (*Betula pendula* Roth var. *carelica* (Mercklin) Hämet-Ahti) isn't established. One researchers consider it as a form of a silver birch, others - downy birch, the third find at it signs and the first and the second. There is an opinion and on the specific status of this tree. From hypotheses of an origin distinguish infectious and genetic. Different opinions exist and about nature of inheritance of this sign - dominant and recessive. The fact also is interesting that at the Karelian birch by open-pollination the feature is inherited from 50% of progeny [5].

The main aim of growing downy birch is to produce pulp wood and fuel wood with low costs. The size or quality of the stems is often too poor for veneer and saw logs, especially when growing on peatlands and other wet sites [6]. A birch has a valuable non-wood product - birch sap. A birch sap has a high nutritional value, it is necessary to combine batches of raw materials obtained from as many trees as possible [7].

Modern hypotheses of tree death are based on our understanding of the circulation of water in plants. Failures of the conducting system in plants appear to occur when the loss of water from evaporation becomes greater than the absorption through the roots, which creates a high water tension in the xylem, and as a result, there is a progressive formation of voids and loss of xylem conductivity, resulting in the death of the tree [8, 9].

The death rate of downy birch trees up to 40-50 years on peaty soils in Western and Northern Finland is estimated as not very high [10]; it is also noted that the rotation of birch crops in less than 40 years is unpromising.

Birch is also used as an object for genetic engineering in fast-growing tree species. Thus, transgenic plants of silver birch were obtained by introducing the sugar beet chitinase gene (chiIV) in order to improve resistance to fungal diseases of birch leaves: birch rust (causes *Melampsporium betulinum*) and birch leaf spot (*Pyrenopeziza betulicola*) [11]. It is believed that the introduction of a renal meristem into a culture in vitro is more stable for micro-propagation than a culture isolated from more differentiated tissues, for example, from leaves [12]. The use of DNA markers in applied fields, in particular in breeding, proved to be expedient and economically justified, and their use in basic research allowed us to reach a new level of understanding of the organization and evolution of the genomes of the studied objects [13]. In the crop, inbred species such as maize and Arabidopsis are highly homozygotic, but many outcrossing species and clonally propagated crops are highly heterozygotic, with numerous repetitive elements, single nucleotide polymorphisms, and structural variants distinguishing haplotypes [14].
Birch is highly resistant in urban plantings, which, in addition to decorative properties, have high phytoncidal qualities. A downy birch is widely used to preserve the unique natural communities of northern and low-mountain East Kazakhstan in newly created botanical expositions [15]. Birch species are widely used as models for omix technologies [16-18], morphological features of trees [19].

The aim of the research is to study parameters of seed reproduction systems in *Betula pendula* and *B. pubescens*, find possibilities for producing viable inbred plants, and analyze their growth and development and hybrid heterosis at crossing the selected forms in generations F₁ and I₁.

2. Materials and methods

Birch is one of the main forest-forming tree species. The biological features that favor the use of birch as a model object for the production of varieties-lines include: 1) Frequent, almost annual, fruiting; 2) Early (at the 5th – 7th year) entry into the reproductive stage of ontogenesis and, consequently, a short time period between adjacent generations (in our experiments, male flowering was observed already at the 3rd year); 3) Potential capacity for different pollination methods: out-, cross- and inbreeding; cross-breeding during interspecific and intraspecific hybridization; 4) Birch is a monoecious plant; 5) Differentiation of native birch populations into self-sterile and self-fertile forms; 6) The possibility of vegetative reproduction of valuable breeding forms (in vitro cloning); and 7) The presence of trees in natural populations of different levels of self-fertilization, which allows you to limit the number of generations of self-pollination.

These features allow us to justify the practical application of methods of both analytical selection (selection of valuable forms based on the analysis of the nature of inheritance of their traits during seed reproduction) and synthetic (crossbreeding, backcrossing). The trees from autochthonous populations of silver birch and downy birch have been used as initial objects. Hybridization and self-pollination were carried out in 1981. Trees from autochthonous populations of silver birch (growing on dry land, designated - C) and downy birch (growing on moist, swampy terrain, designated - B). A sample of silver birch trees was randomly selected on the territory of the (the Voronezh State Nature Biosphere Reserve named after V. Peskov) (northern part of the Usmansky Bor) – 61 trees. The number of selected downy birch trees is 36 trees. The method of hybridization and self-pollination is that parchment insulators (handmade) were placed on branches with male catkins and female flowers one week before flowering. To prevent the ingress of foreign pollen, cotton wool was placed in the neck of the insulator. Control over the flow of flowering was carried out on the surrounding birch trees. Two weeks after flowering, the insulators were removed, and the branches were labeled. After maturing, the seeds were collected and dried. As a control, seeds from open pollination of the same trees were used. At the age of two years, the seedlings were transplanted to the forest-cultivated area in the 298 block of the Reserve according to the 3 x 1 m scheme. For each family, the following parameters were measured: trunk height (m), standard deviation (σ, m) and coefficient of variation (Cᵥ, %).

The conducted studies on the performance of birch seeds do not give unambiguous results and do not allow testing for self-fertility in relation to empty seeds to completed ones (when conducting self-pollination). Therefore, the level of self-fertility was determined by the index of self-fertility of growth in families obtained by different methods of pollination, assuming that the offspring of self-fertile trees with self-pollination, their growth and development will exceed that of the offspring obtained by open pollination.

Also experimentally obtained: i) hybrids between local birch species, direct and reverse crosses; ii) hybrids between native and introduced birch species, direct crosses; iii) families obtained by forced self-pollination and open pollination of local birch species; iv) families of birch trees selected by phenotype (non-standard sexualization, cap forms of *B. pubescens*, decorative leaf, dark bark, fast-growing forms) – from open and self-pollination. Figure 1 shows a general scheme of the selection process for obtaining inbred and outbred plant material.
3. Data analysis

The choice of a woody plant breeding program depends on their reproduction system. Birch show both vegetative and seed propagation, and in this respect, it is a convenient object for research.

The following ecological, morphological and cytological features were used in the identification of species: 1. Ecological: growing conditions; 2. Morphological: i) the shape of the leaf blade, ii) the presence of pubescence in young 1-2 year old shoots; 3. Cytological: ploidy level according to literary sources.

The growth of trees in height is one of the main signs of productivity that have practical significance. In this regard, we studied and compared the variability of growth, and determined the nature of the relationship in the inheritance of this trait in two-year-old and ten-year-old plants of the offspring of the downy birch and the hanging birch, whose mother trees belong to different systems of seed reproduction. Consider the height and diameter of the trunk of ten-year-old families of the downy birch. A total of 36 families were involved in the analysis.

One of important "tools" for revealing genetic diversity is inbreeding. Self-pollination separates both types of birch trees by their reaction to this method into two groups. More demonstratively, the two-group structure of sample trees by seed efficiency under self-pollination manifests itself when using the self-fertility index (Isf). Self-fertility index is the ratio (1):

\[ Isf = \frac{P_s}{P_o}, \]

where \( P \) is the value of the quantitative feature, \( s \) is a self-pollination, \( o \) is an open-pollination.

For a more complete genotypic characterization of the studied mother birch trees and their attribution to a particular breeding system, a new indicator was introduced – the self-fertility index (Isf) of the quantitative trait (6). It is defined as the ratio of the values obtained by self-pollination for the studied trait (for example, by height) to the values of the trait in trees obtained by open-pollination, the latter were used as a control. The obtained data make it possible to classify the mother birch trees into several ranks according to the self-fertility index by height:

1. High \( Isf \geq 1.5 \);
2. Average \( 1.0 \leq Isf \leq 1.49 \);
3. Lowered \( 0.75 \leq Isf \leq 0.99 \);
4. Low \( Isf \leq 0.74 \).

In a rough classification, trees with \( Isf > 1 \) are self-fertile, and those with \( Isf < 1 \) are self-sterile. Conventionally, the total variability range of the trees by \( Isf \) was broken down into 5 classes of trees: highly self-sterile (hss), self-sterile (ss), partially self-fertile (psf), self-fertile (sf), and highly self-fertile (hsf).
4. Results

The seed progeny of the nine mother plants of the downy birch (table 1) has a large variability in height. With self-pollination, it ranged from 3.7 m in the form B-18 to 6.63 m in the form B-12; with open pollination, it ranged from 3.78 m in the form B-14 to 5.87 m in the form B-18. The seed progeny of two trees (B-11 and B-12) had an Isf > 1.5 (1.52 and 1.72, respectively), so they are classified as highly self-fertile. Tree families B-10, B-14, and B-15 are classified as fertile with Isf = 1.04; 1.31, and 1.00. The next group belongs to the category of partial-sterile trees: B-17, B-22, and B-34 with self-fertility indices of 0.98, 0.95, and 0.91, respectively. The seed progeny of one tree from the sample - B-18, experienced a depression in growth after a single inbreeding and had an Isf = 0.63. Measurements of the trunk diameter carried out on the same sample, in general, correspond to the data on growth with minor individual differences.

Table 1. A growth in height of the seed progeny of downy birch' families under different pollination methods (age 10 years).

| N moth. trees | n  | Method of pollination | Trunk height, m | Standard deviation, σ, m | Coefficient of variation, Cv, % | Self-fertility index, Isf (height) |
|---------------|----|-----------------------|-----------------|--------------------------|-------------------------------|----------------------------------|
| B-10          | 13 | sp                    | 5.05 ± 0.35     | 1.3                      | 26                           | 1.04                             |
|                | 13 | op                    | 4.86 ± 0.41     | 1.5                      | 32                           |                                  |
| B-11          | 5  | sp                    | 6.56 ± 0.10     | 0.2                      | 13                           | 1.52                             |
|                | 5  | op                    | 4.33 ± 0.24     | 0.5                      | 11                           |                                  |
| B-12          | 8  | sp                    | 6.63 ± 0.12     | 0.2                      | 3                            | 1.72                             |
|                | 11 | sp                    | 4.95 ± 0.48     | 1.5                      | 31                           | 1.31                             |
|                | 12 | op                    | 3.78 ± 0.35     | 1.2                      | 52                           |                                  |
| B-14          | 4  | sp                    | 4.50 ± 0.50     | 0.9                      | 19                           | 1.00                             |
|                | 9  | sp                    | 4.77 ± 0.30     | 0.9                      | 18                           |                                  |
| B-15          | 5  | op                    | 4.48 ± 0.46     | 1.0                      | 23                           |                                  |
|                | 9  | op                    | 4.87 ± 0.21     | 0.8                      | 16                           | 0.98                             |
| B-17          | 14 | sp                    | 3.70 ± 0.59     | 1.5                      | 42                           | 0.63                             |
|                | 10 | sp                    | 5.87 ± 0.51     | 0.9                      | 16                           |                                  |
| B-22          | 6  | sp                    | 5.25 ± 0.47     | 1.1                      | 22                           | 0.95                             |
|                | 11 | op                    | 5.53 ± 0.30     | 0.9                      | 16                           |                                  |
| B-34          | 10 | sp                    | 4.42 ± 0.47     | 1.5                      | 34                           | 0.91                             |
|                | 16 | op                    | 4.85 ± 0.21     | 0.8                      | 17                           |                                  |

asp – self-pollination; op – open-pollination.

Thus, on the example of a sample of the offspring of nine mother birch trees obtained with different pollination methods, a wide polymorphism of the mother trees in response to self – pollination was revealed – from self-sterile to highly self-fertile, as well as transitional forms – partial-sterile and partial-fertile. In quantitative terms, transitional forms predominate – 67% of the sample. The extreme classes – self-fertile and self-sterile - are represented by 22 and 11% of trees, respectively.

The seed progeny of the nine mother plants of the silver birch (table 2) has a large variability in height. In the self-pollinated forms of silver birch, the growth in height varied from 5.02 m (the same as the average family indicator) in C-31 to 7.95 m in C-36. The offspring of the self-sterile form C-26 is characterized by a depressed growth at the age of thirteen with this method of reproduction – 5.20 m. The offspring of the self-fertile form C-54 is distinguished by a good growth – 7.44 meters, which allows it to be included in the leading group (together with C-30 and C-36). With open pollination, the offspring of the mother plants of the same name have the best growth of C-26 (8.63 m), C-36 (8.10 m) and C-31 (7.93 m).
Table 2. A growth in height of the seed progeny of silver birch families under different pollination methods (age 10 years).

| N moth. trees | n | Method of pollination | Trunk height, m | Standard deviation σ, m | Coefficient of variation Cv, % | Self-fertility index, Isf (height) |
|---------------|---|-----------------------|----------------|-------------------------|-------------------------------|-------------------------------|
| C-26          | 6 | sp                    | 4.05 ± 0.85    | 1.9                     | 49                            | 0.83                          |
|               | 7 | op                    | 4.88 ± 1.10    | 2.4                     | 50                            |                               |
| C-30          | 19| sp                    | 4.68 ± 0.35    | 1.4                     | 51                            | 1.09                          |
|               | 26| op                    | 4.29 ± 0.51    | 1.7                     | 39                            |                               |
| C-31          | 8 | sp                    | 5.50 ± 0.59    | 1.6                     | 28                            | 1.10                          |
|               | 12| op                    | 5.02 ± 0.54    | 2.0                     | 39                            |                               |
| C-36          | 6 | sp                    | 5.12 ± 0.43    | 1.0                     | 20                            | 1.31                          |
|               | 9 | op                    | 3.90 ± 1.53    | 2.7                     | 68                            |                               |
| C-51          | 8 | sp                    | 3.63 ± 0.73    | 1.6                     | 49                            | 0.82                          |
|               | 12| op                    | 4.41 ± 0.61    | 1.7                     | 39                            |                               |
| C-54          | 11| sp                    | 5.79 ± 0.65    | 2.1                     | 54                            | 2.56                          |
|               | 15| op                    | 2.18 ± 0.47    | 1.2                     | 53                            |                               |
| C-59          | 3 | sp                    | 4.13 ± 0.80    | 1.4                     | 33                            | 1.16                          |
|               | 4 | op                    | 3.53 ± 0.92    | 1.6                     | 45                            |                               |
| C-62          | 14| sp                    | 3.76 ± 0.41    | 1.6                     | 39                            | 1.00                          |
|               | 14| op                    | 3.76 ± 0.53    | 1.7                     | 44                            |                               |

The seed progeny of the self-sterile form C-26 with age significantly differentiated in height (data at the age of ten. In the offspring of the C-31 form, the average family parameters shifted from 5.5 to 5.20 m due to the elimination of tall individuals (from n = 8 to 4). Poor growth in open pollination both at the age of ten and at the age of thirteen was observed in the offspring of the self-fertile mother tree C-54 – 2.18 and 5.44 m, respectively.

The coefficient of variability of $C_v$ in self-pollination varies from 13(C-30) to 46% (C-26). The highest $C_v$ is the self-sterile form of C-26. The lowest indicator of $C_v$ is in the self-fertile form C-30. The average selection value of the coefficient is 23%.

In families obtained by self-pollination, this indicator varied from 4 (C-26) to31% (C-59), i.e., the variability of the trait with this method of pollination was significantly less than with a single self-pollination. The average sample value of $C_v$ was 18%. The offspring of the self-sterile form of C-26 had the lowest index. The offspring of the self-fertile form C-30 had a value of 15%, close to the average selection indicator.

5. Discussion

Self-pollination is a method differentiating the trees of different genotypes. Open-pollination reveals a phenotypical variability of seed efficiency features, whereas self-pollination reveals a phenotypical variability of these features.

This phenomenon constantly attracts the attention of researchers, because it allows you to get a certain economic effect. Thus, Straus [20], who studied the relationship between inbreeding and heterozygous loci in Pinus attenuata, concludes: “Thus, unless the relationship between heterozygosity and growth is drastically greater in other taxa or environments, it should be very difficult to detect overdominance under the background variability that characterizes natural populations, even when many loci are studied”.

A study conducted on 9-year-old birch hybrids of the 3rd generation obtained under greenhouse conditions and under forced flowering showed the following [21]. Genetic yield improvement in silver birch is most likely to succeed with selection and the breeding of local well-adapted material within well-defined breeding zones. These conclusions are also confirmed for our hybrid birches growing in the Central Black-Soil region.
Within the specified groups of the trees, differing by the level of self-fertility (except hsf trees), and for sample trees in general the statistically valid distinctions in mean values of a feature are also revealed under different methods of pollination. Only in the group of hsf trees the change of pollination method (from open to self-pollination) does not have a reliable influence on the yield of full-grain seeds. The study of germinating capacity – survival (seeds – seedling trees) in families of the birch families with different level of self-fertility under open pollination revealed a higher percent of germinating capacity – survival in the group of hsf trees, 65%, whereas in other groups – 51-53 %.

In a sample of 61 silver birch trees and 36 downy birch trees, it can be seen that there is a certain species specificity in response to adverse environmental conditions, which consists in a greater number of surviving downy birch trees compared to the silver birch. However, taking into account that the trees were selected both on the basis of preservation (drought resistance) and on the basis of productivity, more productive genotypes were preserved in the downy birch.

The seed offspring of both the silver birch and the downy birch react differently to inbreeding. The families of the self-pollinated offspring of the self-pollinated trees of both the silver and the downy birch significantly exceed the families of the same trees that were open-pollinated in height and trunk diameter at chest level (this is also confirmed by statistical methods). In the seed progeny of self-sterile trees, on the contrary, the families obtained by open pollination have the best growth, and the worst - by self-pollination. This pattern can be traced in all periods of the ontogenesis of the studied birch species. The most indicative (informative) segment of ontogenesis (among the four tested) is ten years of age. This applies to both the family growth indicators and the growth self-fertility index. In both types of birch, the coefficient of variation of $C_v$ growth in plants obtained by self-pollination varied much more (4–39% in $B. pubescens$ and 13-46% in $B. pendula$) than in open pollination (8-25% and 4-31%, respectively).

**6. Conclusion**

Thus, the corresponding classification of mother trees into 3 groups is carried out: self-fertile, self-sterile and transitional forms. Families of self-pollinated offspring of self-pollinated trees of both birch species statistically significantly exceed in height the families of the same trees that were pollinated freely. In self-sterile trees, on the contrary, families have the best growth with open pollination, and the worst - with self-pollination. According to the relative productivity, defined as the product of the height and diameter ranks, families with good productivity only with self-pollination, only with free pollination, as well as fast-growing families with different pollination methods were identified;

When carrying out genetic and selection manipulation in order to obtain highly productive birch stands through selection and hybridization, it is desirable to pre-test the mother and father trees for the level of self-fertility.

Since self-fertile and self-sterile forms have been identified in natural birch populations, and self-pollinated offspring have been obtained, it is proposed to use them in different breeding programs: i) On the basis of self-fertile (by analogy with agricultural plants), it is possible to obtain selfing lines and interlinear heterosis hybrids; ii) On the basis of self-sterile forms, it is possible to obtain population varieties.

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