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Application of growth traits and qualitative indices for selection of Scots pine (*Pinus sylvestris* L.) elite trees. A case study from Volyn region, western Ukraine

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Abstract

Since the plus trees are selected based on phenotype, it is necessary to evaluate them in progeny test. The aim of this study is an indication of selecting elite mother trees based on the results from half-sib progeny test trials. As study sites, two Scots pine half-sib progeny tests were selected. During evaluation, the progenies had reached the age of 38 and 40 years, respectively. In both progeny trials, quantitative parameters and qualitative traits of Scots pine half-sib progenies were investigated. Based on these data, complex evaluation of half-sib families was carried out. We concluded that, Scots pine progenies at the age of 38 and 40 years in fresh and moist mixed forests are characterised by acceptable quality, with the survival being 25%–33% per progeny test trial. Based on a complex evaluation of 38- and 40-year-old half-sib progenies of plus trees, we proposed to select 31% of tested plus/mother trees as candidates for elite trees. Further, the list of candidates for elite trees was created with five plus trees from the Volyn region (26% of the total tested from the region) and four plus trees from the Lviv region (40% of the total tested from the region). With age, the share of the best and undesirable trees decreases, while the proportion of intermediate trees increases in both control trees and half-sib progenies. At the age of 38 and 40 years, the proportion of fast-growing offspring was from 0% to 36%, while the declining trend that was observed in previous years was being continued. Thus, due to the declining trend in the proportion of fast-growing offspring observed at the age of 38 and 40 years, we propose to select candidate trees for an elite group not early than after 40 years of test their progenies.

Key words

tree breeding, half-sib families, progeny tests, DBH, height growth

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Introduction

Plus trees are selected by their phenotype, which reflects the interaction of both the gene pool of trees and environmental conditions. To determine the effects of these factors on the phenotype, the plus trees' progenies are tested in progeny test trails. In turn, these trials serve forest breeders a better understanding of heritability processes for both quantitative and qualitative traits. However, the conducting of such experiments is a time- and labour-intensive process.

The main objective of the Scots pine breeding programme in the Volyn region (since the early 1970s) has been production of improved seed material (Hayda et al. 2019). The primary focus was on reproductive material from seed orchards, both clonal and seedling. However, for the establishment of seed orchards, the plus trees which can produce high-quality offspring are necessary. Therefore, in Volyn administrative region, during the period of 1975–1998, 23 progeny test trials of Scots pine with a total area of 21.8 ha were created. In total, progenies of 148 plus trees from Volyn (115 families), Lviv (20 families) and Zhytomyr (13 families) administrative regions are currently tested in all progeny tests. But a survey of progeny test trials revealed that only 61% of them were suitable for further studies (Andreieva et al. 2004).

The most important aspect behind carrying out progeny test trials is to obtain results, do their analysis and arrive at an interpretation. Ukrainian forest tree breeding programme classifies the trees in tree stands considering their social status, quality and vitality. This classification entails distinguishing three groups of best, intermediate and undesirable trees (Molotkov et al. 1972; Debryniuk et al. 1998). Best trees are the trees that are outstanding in size and quality of the trunks. The main indicators for the best trees are superior growth in height and diameter, straight stem and no signs of disease. Intermediate trees are the trees of average productivity and quality. The group of intermediate trees predominates in the stand. Undesirable trees are the trees with the weakest growth, with a very knotty or crooked trunk, multi-stem trees, as well as dwarfish or dying trees. However, to select elite mother trees, it is necessary to apply the complex multitrait evaluation of the tested families. Among the many evaluation methods, one of the easiest is the method of coordinates proposed by Bulygin (1985). For each studied trait, standardisation is performed (mean values of families are divided by the maximum value of the trait, and the obtained values are raised to a square). Then for each family, the standardised values of the each trait are summed and the value of the complex evaluation of the family is obtained. Based on the results of the complex evaluation, a family ranking is created to select families according to the chosen strategy.

According to Maslakov (1980), the biosocial status of trees is stabilised since the age of 8–15 years; as a result, the leader trees retain their position in tree stand throughout life. Other authors (Osipova 2002; Efimov 2000) state that the first estimation is possible not earlier than 20 years of age of the tree, when the growth rate of the tree is stabilised. However, Galdina (2003) recommends conducting the preliminary estimation of the productivity of Scots pine progenies at the age of 35–40 years or one-third of the maturity age. According to the 'Guidelines on forest-seed production', the evaluation of plus trees in Ukraine is based on the results from progeny test trails (Molotkov et al. 1993). There are three main periods of the evaluation of plus trees related to the age of their offspring: short-term evaluation (at the age of 5 years), medium-term evaluation (at the age of 10–20 years) and long-term evaluation (at a mature age). The studies of Mazhula (2000) and Krynytskyy et al. (2006) demonstrated that only 30%–40% of plus trees can confirm their superiority based on the results achieved by their offspring. Given the general combining ability, only such trees can be considered as elite trees and are necessary when establishing seed orchards.

The main aim of this study is to propose the Scots pine elite mother trees based on the results from the test trials of 38- and 40-year-old half-sib progenies. For this purpose, we focused on two progeny trials in the Volyn administrative region. To achieve such a goal, we applied complex evaluation of the quantitative and qualitative traits for the tested families.

Material and methods

Study sites

Two Scots pine half-sib progeny tests (Fig. 1) established in Kivertsi Forest District were used to evaluate the performance of plus trees progenies.

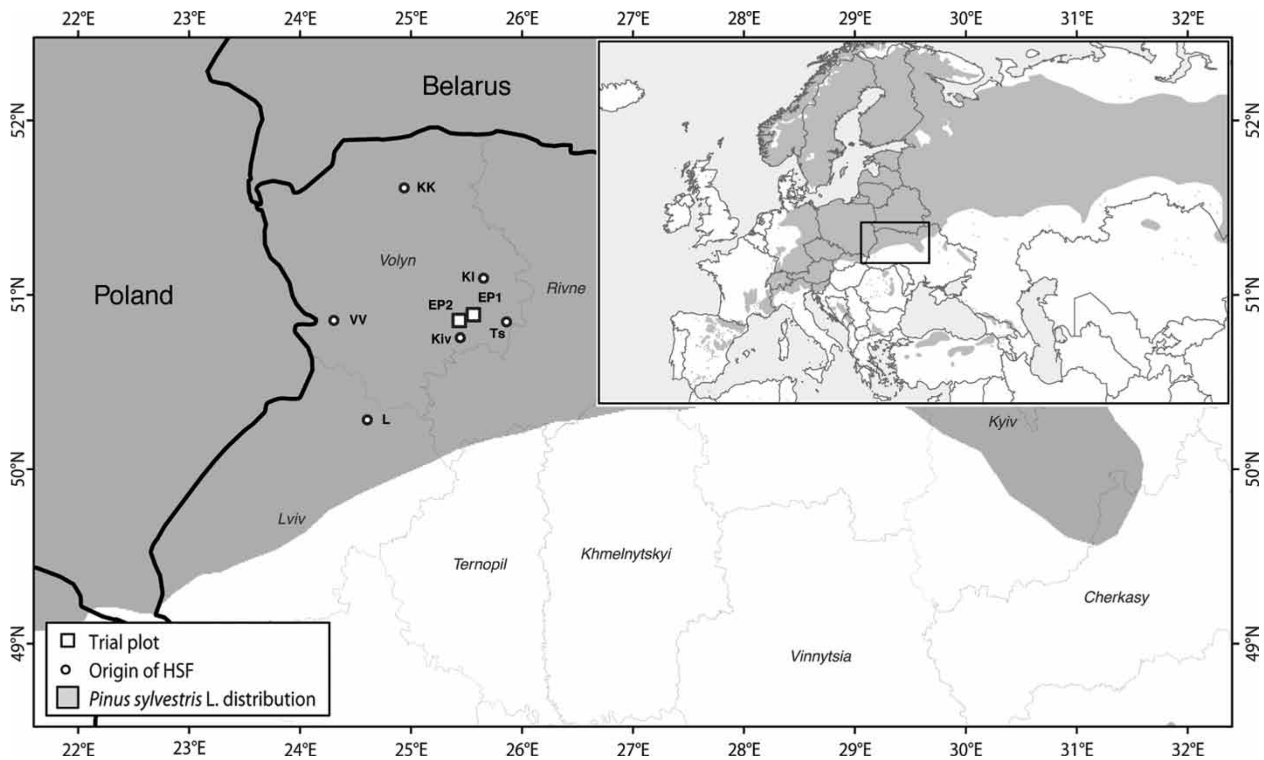

Figure 1. Location of progeny test plots and origin of Scots pine half-sib families. Upper right map in grey – Scots pine distribution range in Europe according to http://www.euforgen.org

Table 1. Characteristics of progeny test trials (Voitiuk and Korytan 1999; adapted)

Site ID	Forestry	Year of establish-ment	Number of HSF	Spacing (m)	Forest type*	Soil type	CT origin (Forest District)
EP1	Sokyrychi	1975	18	3.0 × 0.75	C_{2-3}	Sod-podzolic gleyic sandy loam soil	Volodymyr-Volynskyi, Kivertsi, Tsiuman, Radekhiv
EP2	Kivertsi	1977	11	3.0 × 1.0	C_3	Medium podzolic sandy loam soil	Kivertsi

* According to Pohrebniak (1955), C_{2-3} is fresh–moist mixed deciduous forest and C_3 is moist mixed deciduous forest. CT – control trees.

Experimental plot 1 (EP1) was established in 1975 (Tab. 1), in which 18 half-sib families (HSF; open pollinated progenies of a tested plus tree) from Volyn and Lviv administrative regions were included in the experiment (Tab. 2). In this experiment also (as in other experiments of this time), control trees (CT) were planted. To produce CT seedlings, a mixture of seeds from four forest districts were used. The progeny test plot was established at a plain site with the sod-podzolic gleyic sandy loam soil after clear-cutting of the naturally regenerated mixed deciduous stand. Accordingly, the forest site type was a fresh–moist mixed deciduous forest. EP1 was established without soil preparation. Seedlings were planted in a single repetition. On average, 104 seedlings for each HSF were planted per repetition (two or three rows with spacing of 3.0 × 0.75 m). After planting, the first tending cut at the progeny trial was done after 25 years of growth.

Experimental plot 2 (EP2) was established in 1977 (Tab. 1), in which 11 HSFs from Volyn and Lviv administrative regions were included in the experiment (Tab. 2). To produce the CT seedlings, seeds harvested in Kivertsi Forest District were used. The progeny test plot was established at a plain site with medium podzolic sandy loam soil type after the clear-cut, without removing stumps. The forest site type was a moist mixed deciduous forest. The test was designed with three replications per HSF (similar to complete randomised blocks design, but the test was not divided into blocks). On average, 22 seedlings with spacing 3.0 × 1.0 m were planted for each family per replication.

Table 2. Characteristics of tested HSFs (Voitiuk and Korytan 1999; adapted)

HSF origin ID	Forest District	Administrative region	Number of tested HSFs	
			EP1	EP2
Kiv	Kivertsi	Volyn	7	–
KK	Kamin-Kashyrskyi	Volyn	1	–
Kol	Kolki	Volyn	–	5
L	Radekhiv	Lviv	4	6
Ts	Tsiuman	Volyn	2	–
VV	Volodymyr-Volynskyi	Volyn	4	–

HSFs – half-sib families

Quantitative and qualitative traits

Height growth and diameter at breast height (DBH) were measured at the age of 38 (EP1) or 40 (EP2) years. Biometric parameters were used to calculate the average trunk volume using Nikitin's (1979) formula:

$$V = d^2 \cdot \left(\frac{h}{3} + 0.5\right) \cdot 10^{-4}$$

where:
V – the trunk volume in m^3,
d – the diameter at breast height in cm,
h – the height of the trunk in m.

The assessment of individual qualitative traits was not performed, while the percentage of the best trees per HSF was used as a qualitative index.

Data from previous years for the tested sites were taken from recently published studies (Voitiuk and Korytan 1999; Voitiuk 2000; Andreieva and Voitiuk 2008).

Evaluation of the plus trees by their half-sib progenies

The complex evaluation of the results was performed according to the above-described Bulygin's (1985) method. The assessment was based on the following traits: height, DBH, trunk volume, survival, productivity (volume of wood per ha) and proportion of the best trees. The final decisions were made according to the next breeding strategy: if the complex evaluation index of HSF was higher than the index CT, the mother tree of HSF was considered as the elite tree.

Statistical analysis

Statistical analysis was performed with the STATGRAPHICS Centurion and R (R Core Team 2020) software. Analysis of variance was calculated using Fisher's criterion according to Dospiehov (1985) method. Age–age correlations for height growth were calculated as Pearson's correlation coefficients. Additionally, correlations were calculated between juvenile height and studied mature traits (diameter, survival and productivity). All correlations were computed for HSFs' means.

Results and discussion

Analysis of quantitative traits in EP1 at age 38 years (average of HSFs: height – $20.3^{\pm 0.1}$ m, DBH – $22.8^{\pm 0.3}$ cm, trunk volume – $0.409^{\pm 0.01}$ m^3) revealed that any HSF was significantly higher than CT (Fig. 2). While 33% of HSFs (Kiv-1, Kiv-4, Kiv-6, KK-1, L-3, L-5) were not significantly different from CT, all other (67%) HSFs were significantly lower than CT. A similar result was obtained for DBH, i.e. any HSF was significantly higher than CT. While 39% of HSFs (VV-7, Kiv-2, Kiv-6, Kiv-7, Kiv-8, L-5, Ts-4) grew at the same level as CT, 61% of HSFs were significantly lower than CT. However, the trunk volume of 72% of HSFs was similar to CT and the rest (28%) of HSFs (Kiv-3, Kiv-8, L-2, L-4, Ts-8, VV-1) had significantly lower trunk volume than CT. In turn, survival of 44 HSFs (Kiv-1, Kiv-8, Kiv-7, Kiv-8, L-2, L-3, L-4, L-5, VV-3) was better than CT.

Similar analysis performed on EP2 at age 40 years (average of HSFs: height – $19.5^{\pm 0.2}$ m, DBH – $27.3^{\pm 0.4}$ cm, trunk volume – $0.528^{\pm 0.01}$ m^3) revealed that 36% of HSFs (Kl-2, Kl-9, Kl-12, L-19) were significantly higher than CT (Fig. 2). All others were not significantly different from CT in terms of height. However, with regard to

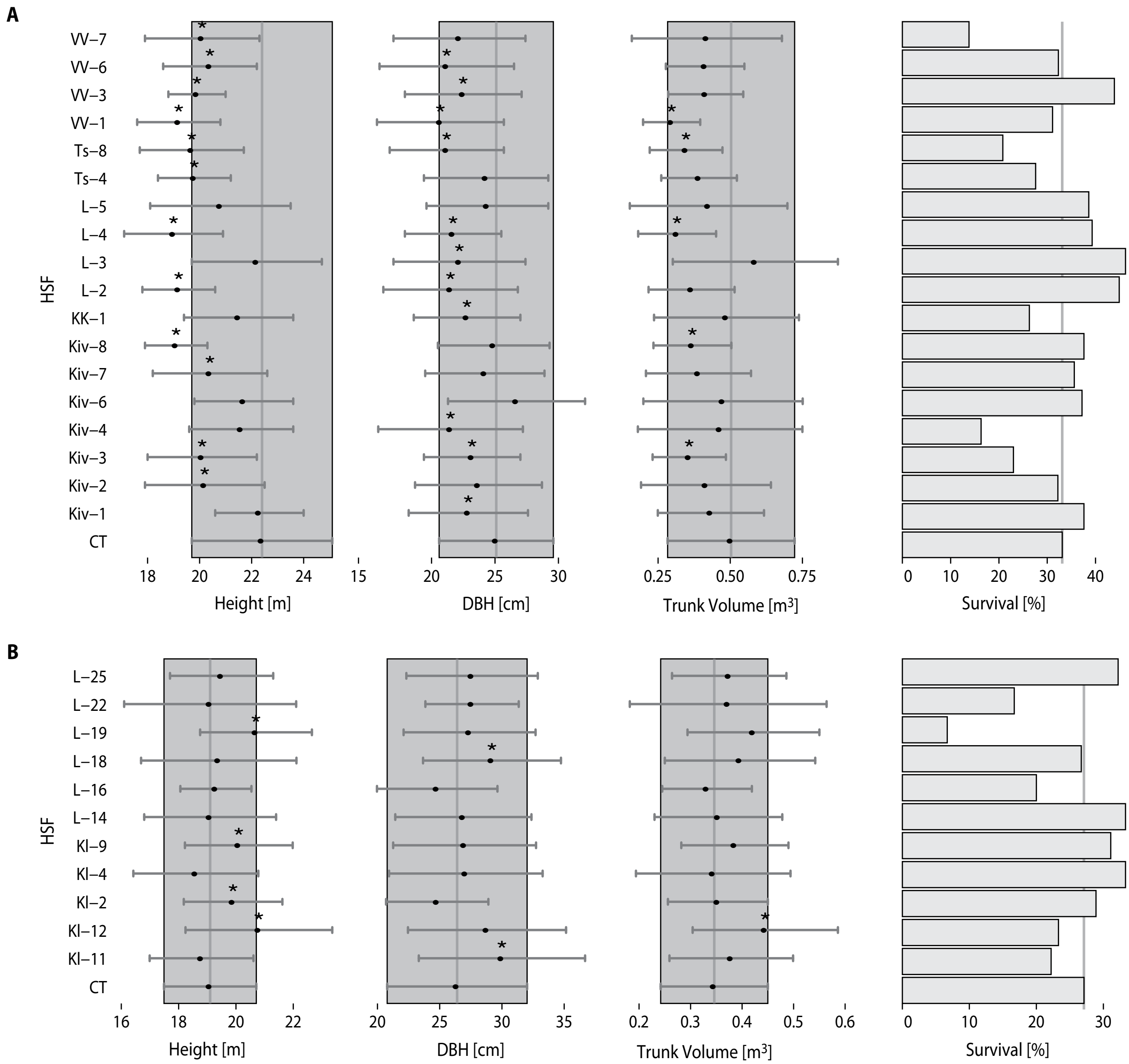

Figure 2. Biometric parameters of Scots pine HSF and CT in EP1 (A) and EP2 (B). Asterisks denote significant difference with CT ($t_f \geq t_{0.05}$); dots – HSF/CT means; whiskers – standard deviations; vertical grey line – mean for CT; light grey zone – standard deviation for CT. HSF – half-sib families, CT – control trees

DBH, 18% of HSFs (Kl-11 and L-18) significantly exceeded CT and 82% of HSFs grew as CT. Only one HSF (Kl-12) significantly exceeded CT in trunk volume, while the rest (91%) of HSFs were not significantly different. In turn, survival of 45% HSFs (Kl-2, KL-4, Kl-9, L-14 and L-25) was better than CT.

Comparison of HSFs and CT by the quality of trees in EP1 at age 38 years (Fig. 3) showed that 28% of HSFs (Kiv-4, VV-7, L-3, KK-1, L-5) had 1.5–3 times higher proportion of best trees than CT, while 72% of HSFs had a lower proportion of best trees than CT. The same comparison for EP2 at age 40 years (Fig. 3) showed similar patterns as in EP1. However, the proportion of best trees in 64% of HSFs was higher than in CT.

According to the results of the complex evaluation of HSFs in EP1 (Tab. 3), only Kiv-6 and L-3 progeny

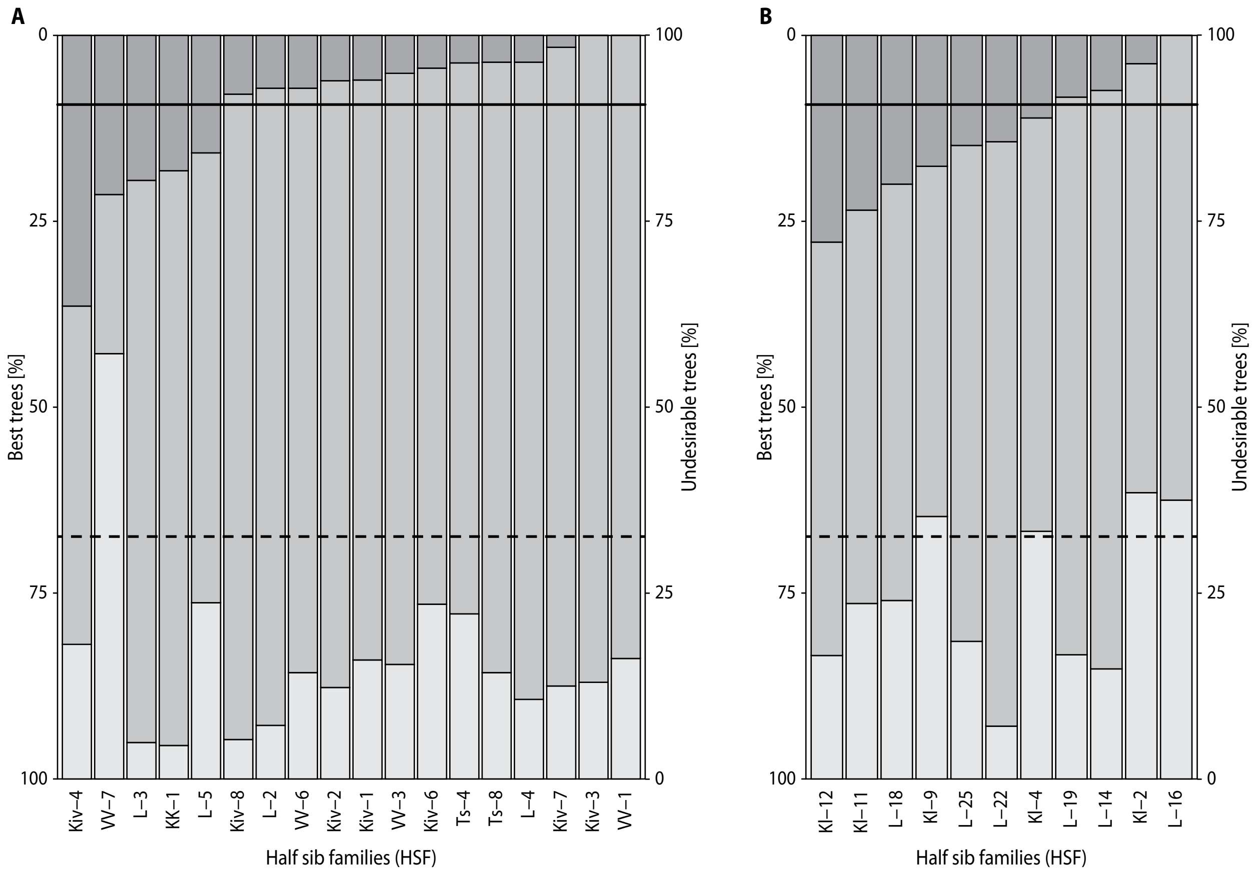

Figure 3. Distribution of Scots pine offspring according to the breeding structure of trees in EP1 (A) and EP2 (B). Dark grey – best trees, medium grey – intermediate trees, light grey – undesirable trees, solid line – best trees in CT, dashed line – undesirable trees in CT

(11% of tested HSFs) trees had higher rank than CT. It means that mother trees of this HSF can be recommended as elite trees. The progeny of 89% of mother trees had lower ranking than CT. Complex evaluation applied for EP2 (Tab. 3) revealed that Kl-12, L-18, L-25, Kl-9, Kl-11, Kl-4 and L-14 (64% of tested HSFs) had higher rank than CT, and thus, their mother trees can be recommended as 'elite trees'. The progeny of 36% of plus/mother trees had lower ranking than CT.

Analysis of the dynamics of the quality of the progenies in EP1 revealed that the proportion of best trees and undesirable trees decreased with age (Fig. 4); at the same time, the proportion of intermediate trees increased with age. The average proportion of best trees at age 38 years was 9.3% and 10.3% for HSFs and CT, respectively, although the proportion of intermediate-quality trees was 74.5% and 66.2%, respectively. The proportion of undesirable trees was 16.2% and 23.5% for HSFs and CT, respectively. A similar result was obtained in EP2 (Fig. 4). Here, the average proportion of best trees at age 40 years was 13.5% for HSF and 9.3% for CT, while the proportion of intermediate trees was 62.3% and 58.1% for HSF and CT, respectively. In turn, the proportion of undesirable trees was 24.2% and 32.6% for HSF and CT, respectively.

The results of previous short-term evaluation showed that the proportion of fast-growing families in experimental plots were from 36% to 89% (Voitiuk and Korytan 1999), while mid-term estimation demonstrated changes in proportion of fast-growing families to be from 44% to 55% (Voitiuk 2000; Andreieva and Voitiuk 2008). However, our results at 38 and 40 years of age revealed that the proportion of fast-growing HSF decreased, reaching no more than 36%.

Table 3. Ranking of HSFs on EP1 and EP2 based on the results of the complex evaluation

HSF	Height	DBH	Trunk volume	Survival	Volume of wood	Proportion of best trees	Complex evaluation	Rank
EP1								
Kiv-6	0.94	1.00	1.00	0.65	1.00	0.01	4.60	1
L-3	0.98	0.69	0.50	1.00	0.77	0.29	4.23	2
Control	1.00	0.88	0.83	0.51	0.66	0.08	3.96	3
L-5	0.86	0.84	0.65	0.70	0.69	0.19	3.92	4
Kiv-1	0.99	0.74	0.57	0.66	0.58	0.03	3.57	5
Kiv-8	0.73	0.87	0.60	0.66	0.61	0.05	3.51	6
VV-3	0.79	0.71	0.43	0.90	0.60	0.02	3.45	7
Kiv-7	0.83	0.82	0.60	0.59	0.55	0.00	3.40	8
Kiv-4	0.93	0.65	0.42	0.12	0.08	1.00	3.20	9
L-2	0.73	0.65	0.34	0.94	0.49	0.04	3.19	10
Kiv-2	0.81	0.79	0.54	0.49	0.41	0.03	3.06	11
KK-1	0.92	0.73	0.52	0.32	0.26	0.25	3.01	12
Ts-4	0.78	0.83	0.58	0.36	0.32	0.01	2.87	13
L-4	0.72	0.66	0.34	0.72	0.38	0.01	2.84	14
VV-6	0.83	0.63	0.35	0.49	0.27	0.04	2.61	15
Kiv-3	0.81	0.76	0.50	0.25	0.19	0.00	2.49	16
VV-7	0.81	0.69	0.42	0.09	0.06	0.35	2.40	17
VV-1	0.73	0.60	0.29	0.45	0.20	0.00	2.28	18
Ts-8	0.77	0.63	0.33	0.20	0.10	0.01	2.05	19
EP2								
Kl-12	1.00	0.92	1.00	0.49	0.70	1.00	5.11	1
L-18	0.87	0.95	0.93	0.64	0.86	0.52	4.76	2
L-25	0.88	0.85	0.75	0.94	1.00	0.28	4.69	3
Kl-9	0.93	0.81	0.72	0.87	0.90	0.40	4.65	4
Kl-11	0.82	1.00	0.97	0.44	0.62	0.71	4.57	5
Kl-4	0.80	0.82	0.64	1.00	0.91	0.16	4.32	6
L-14	0.84	0.80	0.65	1.00	0.93	0.07	4.29	7
Control	0.84	0.77	0.60	0.66	0.57	0.11	3.56	8
Kl-2	0.92	0.68	0.51	0.75	0.55	0.02	3.42	9
L-22	0.84	0.85	0.72	0.25	0.26	0.26	3.18	10
L-19	0.99	0.83	0.81	0.04	0.05	0.09	2.81	11
L-16	0.86	0.68	0.48	0.36	0.25	0.00	2.63	12

Age–age correlation for height is most relevant at a juvenile age (Fig. 5) when observations are made for each year. In the next years, due to the fact that the measurement is usually done less frequently, it is not possible to detect inter-annual trends in correlation coefficients between quantitative traits. In the case

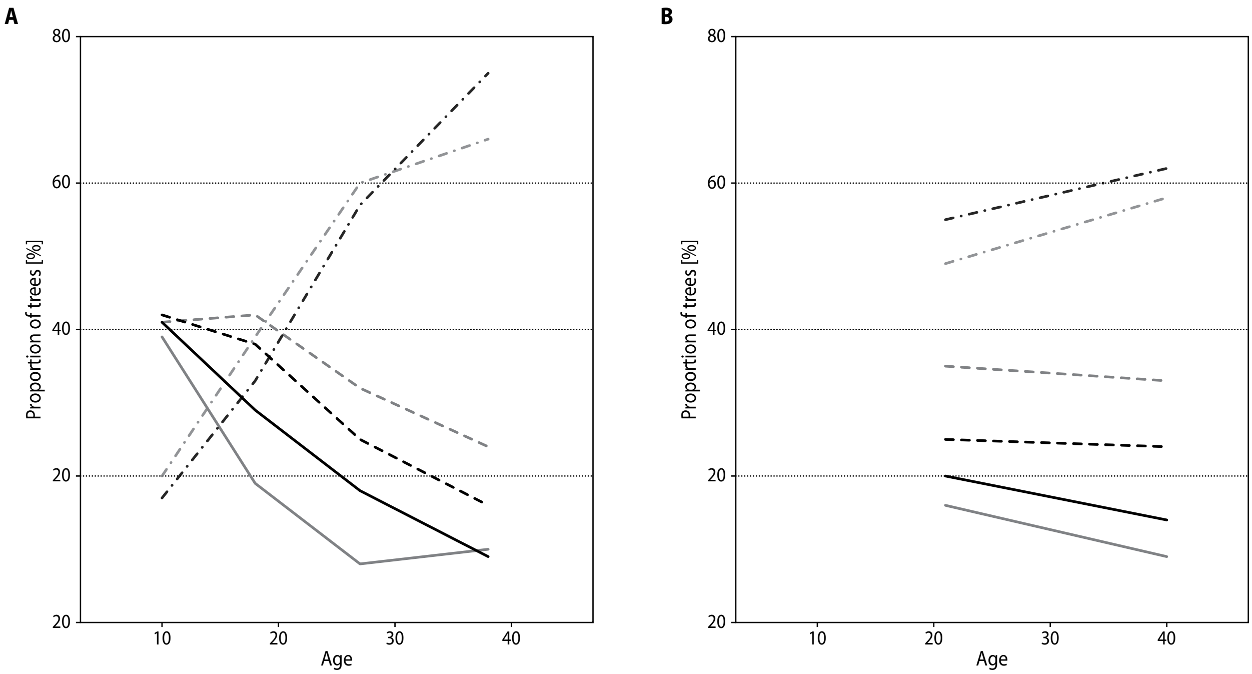

Figure 4. Dynamics of mean breeding structure of Scots pine half-sib families (HSFs) and control trees (CT) in EP1 (A) and EP2 (B). Grey line – CT, black line – HSF, solid line – best trees, dotted dashed line – intermediate trees, dashed line – undesirable trees

of EP1, height at the age of 18 years significantly correlated with heights between the ages 3 and 10 years, while the correlation for mean height at the age of 27 years was significant only for age 5 and 18 years. At the age of 38 years, correlations for height with earlier measurements became irrelevant and its value ranged from −0.26 to 0.12 (for the ages of 2 and 27 years, respectively). The same situation was observed in EP2. After the age of 8 years, significant correlation was observed between 8 and 20 years. While at the age of 40 years, the correlations for heights with all the previous years were weak. Moreover, the height at these ages (38 and 40 years) for both sites correlated neither with DBH nor with survival. However, in both experimental plots, many significant correlations were observed for survival at the age of 38 and 40 years and the heights in younger ages. Is it possible to predict survival at these ages (38 and 40 years) based on the height growth rates data at the juvenile age? Indeed, it is difficult to answer this question in the absence of an early test-based survival study. However, according to the studies conducted by Persson and Andersson (2003), at the within-population level, estimates of genetic correlation between height and survival were mostly large and positive. In this study, where measurements were performed on 9- to 13-year-old progenies (polycross and open-pollinated progenies), the arithmetic mean and standard error across trials were 0.479 ± 0.39. According to the authors, the most notable result was the contrasting correlation patterns observed across environments between tree height and field survival in the material sampled. The above results demonstrated that tree heights achieved from young trees planted in harsh conditions, may reflect tree health and survival ability to a greater extent than growth capacity. In turn, Gil (2014) showed that the average DBH at the age of 38 years was greater in variants with lower number of trees per hectare, while no effect of survival was observed on the mean height. It can explain lack of any significant correlations between these tree traits at the ages of 38 and 40 years. According to collected data, after 20 years of growth, there is an overall decrease in the average annual growth rate (Fig. 6). It can explain the changes in the ranks of mean heights at the age of 38 and 40 years, while wider studies on the age–age correlations between height and survival are needed.

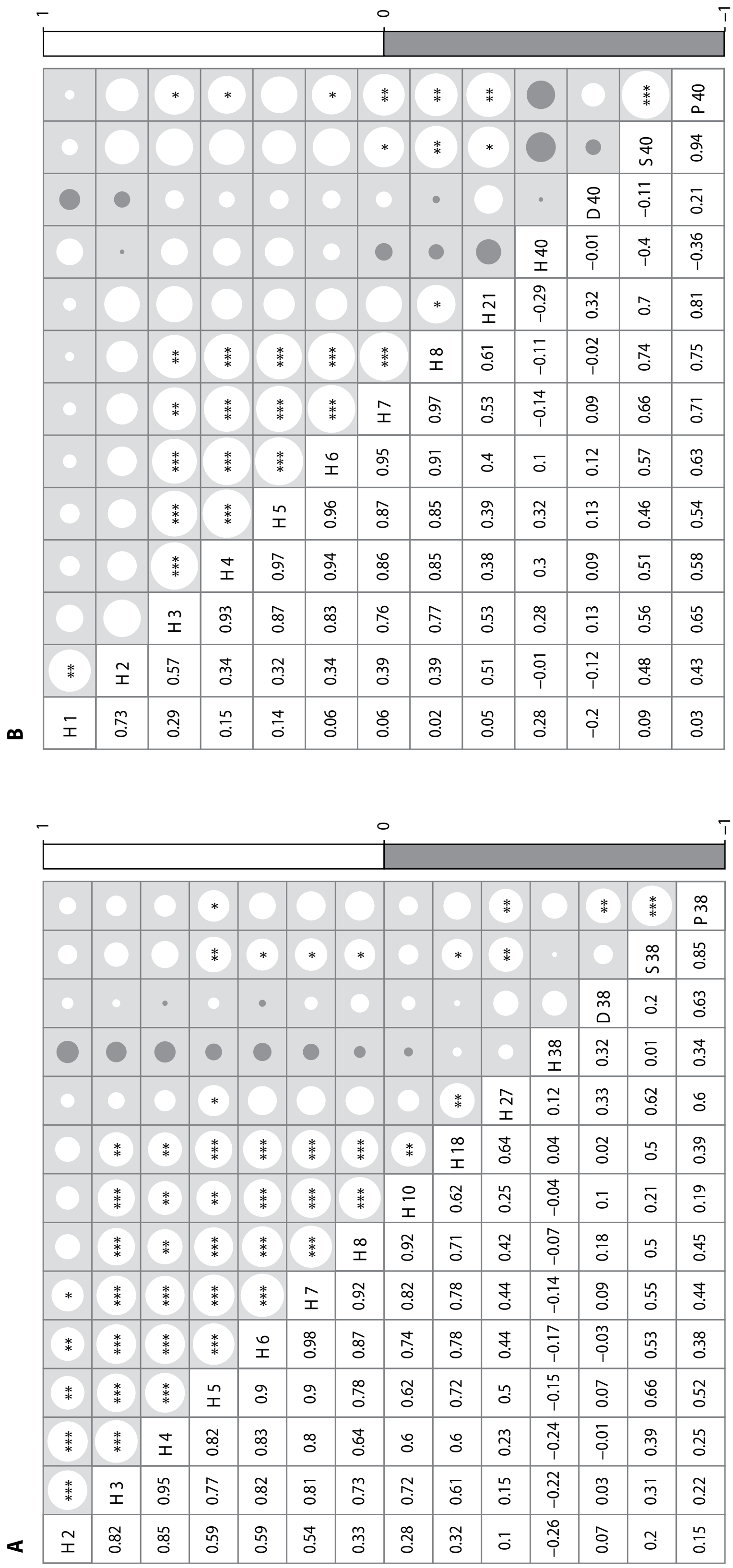

Figure 5. Age–age correlations for height growth (H) and correlations between height in all studied ages and other traits (D – diameter of breast height, S – survival, P – volume of wood) in mature age. Panel A – EP1 study site, panel B – EP2 study site. Correlation significance: $*p < 0.05$, $**p < 0.01$, $***p < 0.001$

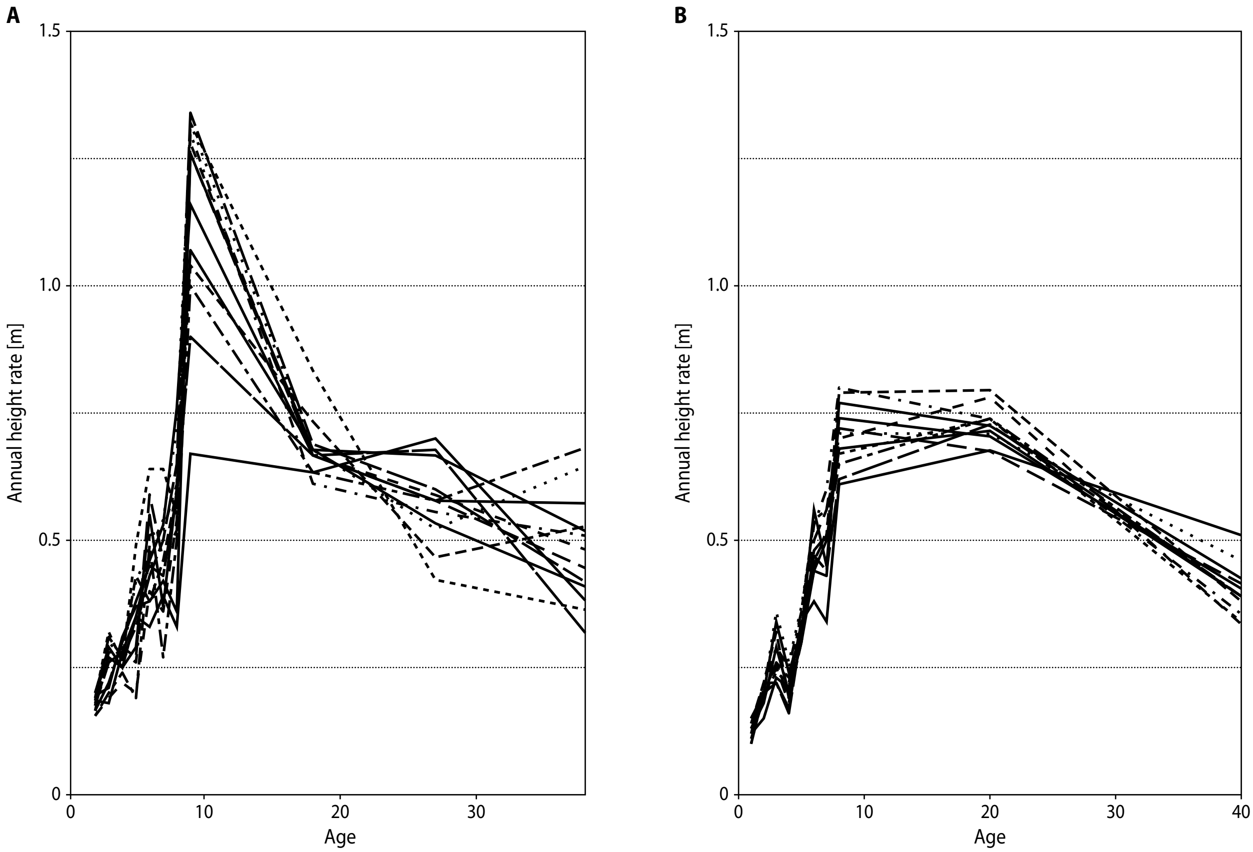

Figure 6. Annual growth rate trends in EP1 (A) and EP2 (B). Each line represents a different half-sib family

Conclusions

In fresh and humid mixed forests, the Scots pine HSFs grew according to I[B] and I[a] site index and were characterised by good vitality, with a mean survival of 25%–33% (EP2 and EP1, respectively). Thus, according to the complex evaluation of 38- and 40-year-old half-sib progenies, we propose to select 31% of the studied plus/mother trees as candidates to 'elite' trees. In particular, five from Volyn region (Kiv-6, Kl-12, Kl-9, Kl-11, Kl-4 – 26% of the total tested from the region) and four plus trees from Lviv region (L-3, L-18, L-25, L-14 – 40% of the total tested from the region) were selected.

With age, the proportion of best trees as well as undesirable trees, decreases, while the number of intermediate trees increases in both HSFs and CT.

The results of previous short-term evaluation showed that the proportion of fast-growing families in experimental plots was from 36% to 89%, while mid-term estimation demonstrated changes in proportion of fast-growing families to be from 44% to 55%. However, our results, at the ages 38 and 40 years, revealed that the proportion of fast-growing HSFs decreased, reaching no more than 36%.

Our study demonstrated a decreasing trend in the annual height growth rate in 20-year-old Scots pine trees. It can explain the weak age–age correlations for height growth. However, wider studies of correlations between juvenile height and mature survival are also needed.

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