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Reconstructing the origin of silver fir (*Abies alba* Mill.) stands in the Białowieża Forest

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Abstract

The Białowieża Forest, one of the largest and best-preserved forest complexes in Europe, is located outside the continuous distribution range of silver fir (*Abies alba*). The area hosts several artificial stands of this species, including old stands that are in good condition. The aim of this study was to reconstruct their origin and establishment conditions. In the Polish part of the Białowieża Forest, 13 sites with the presence of silver fir were identified and described, including 9 old stands. These sites share three key features: anthropogenic origin, generally minimal human intervention in their growth and development after establishment, and location outside the continuous distribution range of the species. Analyses of dendrometric traits showed that many trees reach parameters comparable to those observed under optimal conditions within the natural distribution range of silver fir. Historical reconstruction suggests that the stands most likely originated from direct seeding on clear-cuts created during intensive logging by The Century European Timber Corporation Ltd. in the interwar period (1924–1929). Based on silvicultural, historical and ecological arguments, it appears highly unlikely that silver fir planting stock was produced and used at that time in the Białowieża Forest. The hypothesis proposed here assumes that silver fir seeds were sown under the developing canopy of secondary-succession pioneer species. The surviving old trees and their progeny show a high degree of adaptation to the continental climate of north-eastern Poland. The origin of these stands should be further verified by comparative genetic studies of silver fir populations in Europe and Poland.

Key words

Białowieża Forest, *A. alba*, outside natural range, climate adaptation, regeneration history, direct seeding

Introduction

Knowledge of the history of silver fir in the Białowieża Forest is crucial for two main reasons. First, it enables an objective assessment of the species' performance outside its natural range, under a more continental climate. Second, it helps to evaluate the potential of the species for climate-smart forest management beyond its historical distribution zone.

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Forest composition models predicting potential ranges of tree species distribution under ongoing climate change indicate favourable prospects for silver fir (*Abies alba* Mill.) in Poland and Central Europe (Dyderski et al. 2018; Vitasse et al. 2019). In simulations for the period 2061–2080, silver fir is classified as a 'winner' species among late-successional trees expected to benefit from future climatic conditions (Dyderski et al. 2018).

Several artificial stands of *A. alba* exist within the Polish part of the Białowieża Forest, including old stands approaching 100 years of age that are in good condition. In the context of climate change, increasing tree mortality and declining resistance to biotic and abiotic factors, these stands provide a unique opportunity to analyse the adaptive potential of silver fir beyond its historical range. Improving our understanding of the history, establishment and performance of *A. alba* in the Białowieża Forest may prove valuable for developing climate-smart management strategies for forest ecosystems in north-eastern Poland and Central Europe.

No archival materials concerning the introduction of silver fir to the Białowieża Forest in the second half of the interwar period (1918–1939) have been found (Kosel et al. 2022). For example, the Białowieża Forest District archives contain forest management plans only from the period after the Second World War. This is not surprising, given the difficult socio-political conditions and war-related disturbances at that time, as well as the then widespread practice of very limited documentation of silvicultural activities (Pilat 1929). It is therefore possible that official written records simply do not exist. The first reports on the presence of silver fir in the Białowieża Forest appeared only in the second half of the 20th century and contain divergent information on the time of origin of these stands (Korczyk 1995, 2008).

The origin of the old *A. alba* trees in the Białowieża Forest remains unknown (Gunia and Kowalski 1968; Korczyk 2008; Bardzajn 2010), although, according to Mejnartowicz (1996), their genesis is not associated with the Tisovik autochthonous silver fir reserve (the Belarusian part of the Białowieża Forest). In the first half of the 20th century, forest seed zoning was still in its infancy. German companies were the main producers and suppliers of forest tree seeds in Europe (Pilat 1929), which is one of the reasons why Norway spruce populations in the Białowieża Forest are dominated by genotypes from the southern rather than north-eastern part of the species' natural distribution range (Lewandowski 2014; Nowakowska et al. 2017). It cannot be ruled out that the silver fir seeds used in the Białowieża Forest also originated from German sources.

The aim of this first comprehensive study was therefore to reconstruct the conditions and methods of appearance of silver fir outside its natural distribution range in the Białowieża Forest, in particular: 1. whether it was by planting or direct seeding; 2. whether the site was an open, not overgrown clear-cutting or it was shaded by secondary succession of pioneer species. To this end, field surveys, historical analyses and silvicultural reasoning were combined in order to formulate a coherent hypothesis about the genesis of the existing old stands of *A. alba* in the Białowieża Forest.

Material and methods

The Białowieża Forest is located in north-eastern Poland and western Belarus. In 2014, it was inscribed on the UNESCO World Heritage List as one of the best-preserved lowland forests of the temperate zone in Europe. It is also a biosphere reserve, an Important Bird Area and an integrated Natura 2000 site (Kujawa et al. 2016). Approximately 75% of its area is currently excluded from active forest management, which contributes to the preservation of high naturalness and structural diversity (Jaroszewicz et al. 2019; Paluch 2022).

The Białowieża Forest occupies a slightly elevated, gently undulating plain within the Central European Lowland (Więcko 1984). The prevalence of sandy parent material has resulted in the dominance of rusty soils, which account for approximately 39% of the area (Kabała et al. 2021). In recent decades, distinct climatic changes have been documented: between 1951 and 2019 the number of frost days decreased by 29, while the number of hot days increased by 19 (Boczoń and Sałachewicz 2022). At the same time, the groundwater level dropped by 0.5–1.5 m, with consequences for soil moisture and hydrological regimes (Grygoruk et al. 2022).

Historically, the Białowieża Forest was used with varying intensity for approximately four thousand years. Timber harvesting, charcoal production, resin tapping, beekeeping and livestock grazing were practiced. It served as a source of mushrooms, berries and medicinal plants. In the last centuries, the Białowieża Forest also served as a royal and later state hunting ground, which limited large-scale deforestation and helped preserve its forest character. The most dramatic periods of exploitation occurred during the First World War (about 4 million m³ of timber), the interwar period (2.4 million m³ between 1924 and 1929) and the Second World War (1.5 million m³) (Więcko 1980; Mysiak 2020; Paluch 2022; Kosel et al. 2022).

When determining the location of silver fir plots, scientific literature (Gunia and Kowalski 1968; Korczyk 1995, 1999, 2008; Mejnartowicz 1996), information from forestry workers and forest management materials, and the results of our own route surveys were used. *A. alba* was found in three Forest Enterprises: Hajnówka, Białowieża and Browsk, in 13 plots, including 9 with old-growth silver fir; the Białowieża National Park was not included in this study. The list of silver fir habitats in the Białowieża Forest that we have established is broader than that available in the literature (Faliński et al. 1992).

The measurements of the main dendrometric parameters (diameter at breast height, DBH and the height, H) of old silver fir trees were carried out using callipers and a Vertex 5 hypsometer (Haglöf, Sweden), which was also used to determine distances between trees. The volume of individual trees was calculated using volume tables of Czuraj (1991). To increase calculation accuracy, double interpolation of the tabular data was performed, accounting for both DBH and H (Bruchwald 1999). Statistical analyses were conducted in Excel and using the Statistica software package.

In this study, we present detailed measurement data only for subcompartment 498 Ci (Tab. 1), which we consider representative of the remaining eight old silver fir plots discovered in the Polish part of the Białowieża Forest. All of these plots are characterized by a visually similar vertical structure, typical of silver fir stands. Their distinctive feature is the presence of several clearly dominant trees and a significant representation of a height group with varying degrees of suppressed growth.

Moreover, just on the 498 Ci subcompartment based on increment cores collected as close to the root collar as possible (8–52 cm) from 29 mature sample trees, the age at the sampling height was determined. The number of years required to reach the sampling height was calculated using data on the growth rate of natural regeneration at this plot. According to the obtained dendrochronological data (unpublished), the age of old silver firs at the plot 498 Ci was approximately 98 years in 2026. It should be noted that even the not so tall trees were of this age. Judging by visual assessment and selective dendrometric measurements (453 Al, 526 Bd, Tab. 1), the age is approximately the same in the remaining plots.

The cornerstone of the methodological approach was comprehensive data acquisition, based on a systematic analysis and interpretation of all the circumstances surrounding the emergence of the silver fir stands investigated in this study.

Results

In the Polish part of the Białowieża Forest, 13 sites containing silver fir were identified, consisting of small stands, stand fragments, groups and single trees aged approximately 30–100 years (Tab. 1). 9 of these sites represent old silver fir stands or groups. These sites share three common features:

1) anthropogenic origin;
2) generally minimal human intervention in their growth and development after establishment;
3) location outside the continuous range of the species.

Many old silver firs have reached large dimensions and well-developed crowns, comparable to trees growing under optimal conditions within the natural distribution range of the species (Szymkiewicz 2001). For example, the volume of individual trees in Białowieża Forest ranged from 2.5 to 7.1 m³ (Tables 1 and 2), whereas habitats typical for silver fir (the Carpathians) stem volumes of 2.5–3.3 m³ are reported (Dobrowolska et al. 2015).

Particularly illustrative is the comparison of one of the best-performing trees (in terms of dendrometric parameters) in plot 11 (Tab. 1) with silver firs from the Tisovik reserve (the Belarusian part of the Białowieża Forest) and from within the species' natural distribution range. The oldest fir in the Tisovik reserve (at least 250 years old), windthrown in 1922, was 33.5 m tall; however, it was more than twice as old as the trees in our

Table 1. Localization and brief description of silver fir habitats in the Polish part of the Białowieża Forest

Plot serial number	Forest Enterprise, Forest District	Subcompartment codes and its geographic coordinates	Description
1	Hajnówka, Wilczy Jar	416Ad, 416Cf; N 52°70', E 23°65'	Progeny of autochthonous silver fir from the Tisovik reserve (the Belarusian part of the Białowieża Forest) growing in a half-sibs plantation in the amount of 1,918 trees and aged 31–34 years (in 2026). The plantation is fenced and consists of three plots of 0.22 ha each. Trees in all plots are in excellent condition. The second and third plots showed an increased mortality in the first years after planting, which was due to the influence of late spring frosts. The stand is registered in the European database of important genetic conservation sites.
2	Białowieża, Podcerkiew	520Ac N 52°67', E 23°70'	The forest cultures from seedlings of autochthonous silver fir from the Tisovik reserve, age 30 years (in 2026). Four unfenced plots with a total area of 0.83 ha were heavily damaged by animals. Planting material for these cultures was produced in the former nursery of the Białowieża Forest Enterprise.
3	Browsk, Jelonka	121Dh N 52°80', E 23°69'	Progeny trial established in 1997 from seeds collected in the Białowieża Forest Enterprise, Stoczek Forest District, subcompartment 453Al (see stand 6 below). It is not fenced and, therefore, heavily damaged by animals.
4	Białowieża, Batorówka	469Ad N 52°69', E 23°72'	A forest plantation, 19 years old (in 2026). Planting material – 3-year-old seedlings from the Goldap Forest Enterprise. Seeds collected from trees in Makówka Forest District, subcompartment 177c; origin – probably Germany. Planted on the fenced territory of the former forest nursery; area 1.4 ha; initial planting density 5,700 seedlings/ha. Needs to be cleaned up.
5	Białowieża, Stoczek	500Cd N 52°67', E 23°84'	A group of 11 old trees at the age about 100 years heavily damaged in their youth by animals. The undergrowth is also badly damaged by animals.
6	Białowieża, Stoczek	453Al N 52°70', E 23°89'	A group of 93 old trees at the age about 100 years covering area of 0.38 ha. The fenced stand is in excellent condition as is the undergrowth.
7	Browsk, Jelonka	156Aa, 156Ba N 52°79', E 23°77'	Two old trees in good condition, approximately 100 years old, the potential seed dispersal area has recently been fenced off.
8	Browsk, Jelonka	156Ba N 52°79', E 23°77'	One old tree at the age about 100 years, in average condition, the seeding area is not fenced, and there is no natural regeneration.
9	Browsk, Krynica	769Ac N 52°88', E 23°63'	An unfenced group of five old trees at the age about 100 years. Animal-damaged trees are significantly stunted, and there is no natural regeneration observed.
10	Białowieża, Grudki	499Ch N 52°67', E 23°83'	An unfenced two old trees at the age about 100 years. One of them was significantly stunted due to animal damage. The second one is still in excellent condition, but it is tilted by the wind and apparently has a torn root system. There is no natural regeneration.
11	Białowieża, Grudki	526 Bd N 52°67', E 23°82'	A group of 40 old trees at the age about 100 years, scattered over an area of 6.39 ha, not enclosed by a fence. Trees undamaged in youth by animals now show excellent growth rates. Natural regeneration is represented by single specimens, which are severely damaged by animals. One tree in this group showed the best growth performance in Białowieża Forest: H = 33m, DBH = 71 cm, V = 7,11m^3.
12	Białowieża, Grudki	498 Ci N 52°67', E 23°81'	A fenced group of 30 old trees at the age about 100 years spread over an area of 1.4 ha. Natural regeneration due to damage to the fence was injured earlier by animals, but it is now in good condition and its population reaches 13.85 pcs/ha.
13	Białowieża, Stoczek	452 Bh N 52°70', E 23°89'	Seven old trees at the age about 100 years in a **quite good condition,** arranged in a compact group. Natural regeneration is represented by single specimens, which are severely damaged by animals.

study. A silver fir from the Świętokrzyskie Mountains (Poland), also destroyed by a hurricane, reached 44.5 m at 220 years of age (Środoń 1983). The oldest fir from the Jata Nature Reserve (Poland) – the closest natural island habitat to the Białowieża Forest – was 34 m tall at 205 years of age (Korczyk 1999).

Table 2. Silvicultural characteristics of old silver fir trees at the age about 100 years in Białowieża Forest, subcompartment 498 Ci

Tree ID	Diameter at breast height (cm)	Height (m)	Crown		The volume
			length (m)	% in relation to the tree height	of the trunk (m^3)
1	2	3	4	5	6
A	47.7	25.1	19.3	76.9	2.09
B	18.7	20.6	14.1	68.4	0.34
C	14.8	14.0	10.1	72.1	0.14
D	19.8	16.0	13.8	86.3	0.26
J	19.6	12.6	9.9	78.6	0.21
K	9.8	7.0	4.1	70.7	0.02
E	32.4	18.8	14.8	78.7	0.78
1	68.9	34.6	26.0	75.1	5.74
2	25.4	25.4	18.1	71.3	0.69
3	48.8	29.4	22.7	77.2	2.61
4	33.5	25.2	17.9	71.0	1.13
5	35.8	22.4	16.4	73.2	1.17
6	62.4	28.7	20.8	72.5	3.99
8	39.7	29.0	22.8	78.6	1.57
9	31.7	24.0	15.7	65.4	0.98
H	18.0	9.4	7.2	76.6	0.13
G	15.5	12.4	7.2	58.1	0.12
F	49.0	29.1	20.8	71.5	2.59
10	27.0	25.2	16.3	64.7	0.77
20	15.2	10.7	7.5	70.1	0.10
11	59.7	29.3	19.2	65.5	3.84
12	46.7	30.7	17.6	57.3	2.53
13	40.2	30.7	23.6	76.9	1.92
14	49.1	27.7	18.2	65.7	2.55
15	38.4	27.5	18.1	65.8	1.57
I	16.1	10.6	7.0	66.0	0.13
1	2	3	4	5	6
16	51.5	30.5	19.1	62.6	3.00
19	57.7	31.6	24.3	76.9	3.82
17	30.0	18.5	14.0	75.7	0.67
18	35.0	26.4	19.5	73.9	1.28
Mean value	35.27	22.77	16.20	71.44	1.56
Standard deviation	16.2	7.93	5.76	6.56	1.46
Coefficient of variation	45.93	34.83	35.55	9.18	93.71
Median	34.3	25.2	17.8	71.8	1.15
Minimum	9.8	5.75	4.1	57.3	0.02
Maximum	68.9	34.6	26	86.3	5.74

As noted above, many trees have large dimensions. It should also be noted that they possess pointed crowns and exhibit intensive fruiting (Fig. 1), indicating that, despite their advanced age, they have not yet entered a degenerative senescence phase. In some stems, frost cracks originating from extremely cold winters (e.g., 1928–1929, 1939–1940, 1955–1956) (Dziubałtowski 1930; Zeliński 1952; Tumiłowicz 1966; Marsz and Styszyńska 2018) are visible, but these injuries are now completely overgrown (Fig. 2).

Figure 1. Intense fruiting of about 100 years old silver fir in Białowieża Forest (Tab. 1, subcompartment 498 Ci; Tab. 2, tree ID – 1), which retains the pointed shape of its crown (photo by K. Gabrysiak)

An irregular arrangement of trees was recorded (Fig. 3). The reduction in their number over the course of a century has resulted in old trees being positioned in small groups, pairs or even singly. The irregular spacing of the trees (Fig. 3), with distances ranging from 1.34 to 8.03 m (average 3.74 m) and no indication of a planting pattern, further suggests direct seeding rather than row planting. This growth pattern is entirely consistent with the species' biology (Bendkovsky 2021).

Figure 2. Numerous overgrown frost cracks on the tree of silver fir in Białowieża Forest (Tab. 1, subcompartment 498 Ci) (photo by A. Marozau)

Discussion

The current state of the studied populations of *A. alba*, which have passed through a double sieve of natural selection (nearly a century of growth of the parent trees and several decades of natural regeneration development) (Aitken et al. 2008), reflects both their norm of reaction and the potential for genotypic expression under local environmental conditions (Dyderski et al. 2018; Graudal et al. 2020), which is confirmed by provenance studies (Bardzajn 2010).

Trees that survived episodes of abiotic stress continued to grow and reproduce, achieving substantial dendrometric parameters (see section Results). It is likely, however, that some individuals did not survive these harsh events and that the present stands represent a set of trees that successfully passed through a strong climatic selection filter (Szmyt 2020). This suggests that the existing old silver firs and their progeny are genetically and phenotypically adapted to the continental climate of north-eastern Poland.

A key question concerns the method by which silver fir was introduced into the Białowieża Forest: by planting or by direct seeding. From a silvicultural perspective, the production of silver fir planting stock in the temporary nurseries operating in the Białowieża Forest during the interwar period appears highly unlikely. In spring sowing, seeds require prolonged cold and subsequent wet stratification; in autumn sowing, stratification takes place under natural conditions. Seedling production lasts three to five years and usually involves at least one transplant in the nursery and root pruning. Seedlings require mulching, weeding, soil loosening, watering, shading during hot periods and protection against late spring frosts and severe winters (Szymański 2000; Wesoły and Hauke 2009). At that time, nursery technology in the Białowieża Forest was primitive and focused mainly on undemanding species such as Scots pine, Norway spruce and common broadleaves (Kosel et al. 2022).

Moreover, the clear-cuts created by The Century European Timber Corporation Ltd. were very large (approximately 100 m wide and 1,000 m long, i.e., roughly 10 ha each), and by 1929, their total area had reached 7–8 thousand ha (Kosel et al. 2022). Even for the main tree species, the available planting stock was insufficient, and vast clear-cut areas were left to regenerate naturally. Under these circumstances, producing planting stock of a demanding species such as silver fir – in the absence of a local seed base and appropriate infrastructure – seems unrealistic. Transporting seedlings from southern Poland or from abroad (e.g., Germany or

Figure 3. Placement of a group of old silver fir trees at the age about 100 years in Białowieża Forest (Tab. 1, subcompartment 498 Ci; Table 2, trees ID – 1, 2, 3, 4, 5) (photo by A. Marozau)

the Czech Republic) would have been logistically difficult and economically unjustified during the interwar period.

By contrast, direct seeding of silver fir appears more realistic. Seed propagation is well-suited to *A. alba* owing to its relatively large seed size, successful early adaptation of seedlings to shade and rapid development of the root system (Dobrowolska et al. 2017). In Europe, increasing attention has been paid to the artificial regeneration of silver fir from seed, particularly in the context of transforming spruce stands (Huth et al. 2017). Although direct seeding is not always effective and may be limited by seed quality and site conditions (Suszka 1983, 2008), it requires much less infrastructure than seedling production. Considering these arguments, the use of planting stock can largely be ruled out, while the hypothesis of direct seeding becomes the most likely scenario – especially in view of the constraints of long-distance seedling transport. Soil preparation was probably simple and superficial, involving manual removal of ground vegetation and, at most, light loosening of the upper soil layer to improve seed–substrate contact. In some places, seeds may have been sown directly onto litter where living ground cover was absent.

The timing and conditions of sowing are also important. Intensive clear-cutting by The Century European Timber Corporation Ltd. took place between 1924 and 1929, with the contracted annual timber harvest of approximately 400,000 m³ (Mysiak 2020). Under the agreement with the Polish government, the company was responsible for logging, while reforestation remained the obligation of the Polish side. Due to the vast area of clear-cuts and limited nursery resources (their total area was only about 60 ha), the predominant regeneration method, as noted above, was natural succession.

For a short period immediately after clear-cutting, the lower vegetation layers were suppressed. In subsequent years, however, herbaceous vegetation, shrubs and natural tree regeneration developed rapidly (Więcko 1980), leading to a secondary succession sequence from *Rubus idaeus* L. communities towards *Tilio-Carpinetum* type associations (Falińska 2012). Under such conditions, a natural canopy of pioneer species formed, providing gradually increasing shade.

Silver fir and Norway spruce share similar shade requirements during their juvenile stages, which supports the idea that silver fir seeds were sown under the developing secondary canopy of species such as *Carpinus betulus* L., *Betula pendula* Roth, *Populus tremula* L. and *Salix* spp. (Paczoski 1930; Brzeziecki 2018), where shade-tolerant spruce also naturally regenerated, rather than on open clear-cuts. In this context, it should be noted that according to forest management data (Decyzja... 2012), both silver fir and spruce, as well as birch, in subcompartment 498 Ci were of the same age – namely, 98 years in 2022, which aligns closely with our unpublished data (Materials and Methods section).

The radial growth of nearly 100-year-old silver firs was very weak in the first years of ontogenesis (Fig. 4), which supports the hypothesis of their establishment under a canopy of pioneer species. Had sowing taken place immediately after felling on an open site where secondary succession was delayed (e.g., due to the intensive development of *Calamagrostis arundinacea* (L.) Roth), one would expect an initial phase of vigorous early growth followed by an earlier growth slowdown and senescence (Bernadzki 2008). No such pattern was observed. Instead, the growth dynamics correspond to the typical life cycle of a late-successional species established under partial shade. Despite their considerable age, the old silver firs do not show specific morphological modifications, such as the so-called 'stork's nest' (Marozau et al. 2021), which would indicate a cessation of height growth (Jaworski and Paluch 2007). On the contrary, their crowns remain pointed and, as noted, fruiting is abundant (Fig. 1).

Genetic variation in silver fir is a key determinant of its adaptive potential along environmental gradients, particularly altitudinal and latitudinal clines. Studies of European lowland *A. alba* stands, located within or beyond the continuous natural range, indicate that standing genetic variation supports local adaptation to summer drought and late spring frost typical of north-eastern Europe (Bergmann et al. 1990; Coşgun et al. 2025). These patterns underscore the critical role of preserving high-diversity sources for assisted migration and restoration programmes under ongoing climate change (Kremer et al. 2025). Based on earlier analyses of 17 loci from 11 isoenzyme systems, the level of genetic variability in silver firs from subcompartment 498 Cg (the previous designation of subcompartment 498 Ci investigated in the present study) was relatively high compared to the relic Belarusian Tisovik population, and similar to other stands and populations from the species' continuous range, including Skarżysko and Tomaszów Lubelski (Mejnartowicz 1996). Specific parameters for subcompartment 498 Cg – mean number of alleles per locus (1.588), mean number of alleles per polymorphic locus (2.429), percentage of polymorphic loci (99% criterion) = 41.176%, observed heterozygosity (H_o) = 0.140 and expected heterozygosity (H_e) = 0.138 – indicated a moderate level of intrapopulation variability, with H_o close to H_e, suggesting no significant excess or deficit of heterozygotes (Mejnartowicz 1996).

It is reasonable to assume that the silver firs from subcompartment 498Ci, studied here, may have similar genetic-variability parameters to those revealed by Mejnartowicz (1996) and thus may also be characterized by relatively high genetic diversity. This, in turn, suggests the introduction of genetic material from areas with greater diversity (e.g., German populations), potentially supporting hybridization and genetic enrichment of the studied stands. In this context, it would be worthwhile to examine whether gene flow between neighbouring populations affects the adaptive potential of silver firs from subcompartment 498Ci to the local environmental conditions of the Białowieża Forest, similar to what has been demonstrated for the monumental spruces there in the face of recent bark beetle outbreaks (Nowakowska et al. 2020; Kamińska et al. 2021).

However, another plausible scenario is that the seeds were obtained from nearby island populations of silver fir located at the northern margin of the species'

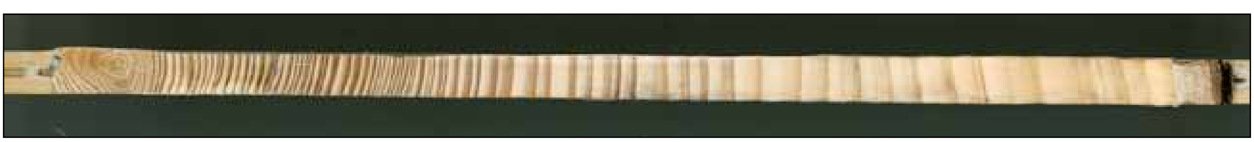

Figure 4. Core sample one of the studied silver fir trees in Białowieża Forest (Tab. 2, tree ID 9) (photo by K. Pilch)

natural distribution range (e.g., Jata, Jedlina, Topór and Rudka) (Abramowicz 1952). The Tisovik reserve in the Belarusian part of the Białowieża Forest, situated only about 8 km from plot 6 (Tab. 1), hosts an autochthonous silver fir population, but genetic studies, as mentioned above, suggest a different origin for the analysed stands (Mejnartowicz 1996).

The most probable explanation for the establishment of these silver fir stands is that a local forester, interested in experimenting with the species, obtained seeds from available sources and sowed them on clear-cuts created during interwar logging. This activity may have been carried out on a relatively small scale, possibly without formal documentation, as a personal initiative. The resulting stands, although limited in area, have survived to the present day and now represent unique objects from both scientific and practical perspectives.

The final answer regarding the origin of silver fir in the Białowieża Forest could be obtained through comparative genetic studies of different *A. alba* populations in Europe and Poland. Such studies, currently underway at the Institute of Forest Sciences of the Białystok University of Technology, will help identify potential source populations and clarify whether the Białowieża stands are more closely related to German, southern Polish or local island populations at the north-eastern edge of the species' range.

Conclusions

Outside its natural range, mature silver fir grows in nine plots in the Polish part of the Białowieża Forest. It emerged in the first half of the 20th century, probably as a result of seeding in clear-cuts under the canopy of naturally regenerated pioneer species. Now about 100 years old, the late-successional, shade-tolerant *A. alba* retains pointed crowns and bears fruit almost annually. Reproductive generations of varying ages are forming (subject to fencing), indicating that the environment meets the requirements of the species. In light of ongoing changes in forest ecosystems, these stands have significant scientific and practical importance.

Previous analyses of the genetic structure of isolated *A. alba* populations, such as those in the Białowieża Forest, underscore the critical importance of monitoring gene flow between relict and introduced stands. This process may significantly influence the long-term stability of forest ecosystems under climate change and biotic pressures. These dynamics should be assessed in further genomic research using DNA markers to obtain a more precise picture of the genetic processes involved. Further comparative genetic studies of silver fir populations in Europe and Poland are essential to confirm the provenance of the seeds used in the Białowieża Forest and to better characterize the adaptive potential of these stands.

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