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Reintroduction of the European silver fir (*Abies alba* Mill.) in Białowieża Forest

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Abstract

In 1996 and 1998, Professor A. Korczyk created a half-sib plantation of the European silver fir (*Abies alba* Mill.) in the Polish part of the Białowieża Forest (Hajnówka Forest District, sub-district Wilczy Jar, subcompartments 416Ag and 416Cf). The planting was carried out in furrows at a spacing of 1.3 × 1 m in three plots of 0.22 ha each in an area of fresh broadleaved forest. To grow the seedlings, seeds from the "Tisovik" tract (in the Belarusian part of the Białowieża Forest) were used. According to some researchers, the *Abies alba* in this tract has a natural origin and is a relic of the Białowieża Forest. Given this circumstance, and in connection with the mass drying-out of the Norway spruce, *Picea abies* (L.) Karst., there is a practical interest in studying the growth of fir establishment in this territory. The results of our studies (2018) indicated the very intensive growth of this species in 22-year-old cultures (sub-compartment 416Ag, plot 1, 10 half-sib families). The trees showed no signs of disease or insect damage, their crowns were conical in shape and the shoots were densely covered with needles. The good state of the forest planting can be considered as evidence of soil and hydrological conditions suitable for growth and meeting the ecological and biological requirements of *A. alba*, as well as confirmation of its autochthonous nature.

Keywords: *Abies alba*, reintroduction, half-sib plantation, Białowieża Forest

Introduction

As noted by Szafer (1920), one of the most significant and interesting natural features in the Białowieża Forest is the growth of silver fir on its territory, in only one place (the Cisówka, now Tisovik, tract). He believed strongly that this native species to the Białowieża Forest has been growing there for a considerable time. This plot is separated from the northern border of the area of silver fir in Europe by about 500 km. It was discovered by Górski in 1829 and he was the first to study the silver fir growing there. In his opinion, the appearance of this species in the Białowieża Forest coincided with the formation of its original space (reviewed in Szafer 1920). According to Paczoski (1930), the silver fir stand in the Tisovik tract is an example of the virgin forest of the Białowieża Forest. For the sake of objectivity, it should be noted that some researchers have pointed to the artificial origin of the silver fir in the Białowieża Forest (Trauwetter 1850, Graubner 1918, reviewed in Szafer 1920, Karpiński 1933). However, the dominant idea is that this plot of fir is natural in character (Škutko and Martinovič 1967, Gunia and Kowalski 1968, Parfenov and Kozlovskaja 1971), which is supported in more contemporary works (Strelkov et al. 1996, Korczyk et al. 1997, Korczyk 2015a). According to Korczyk et al. (1997), silver fir acted in the past as an admixture in other places of the Białowieża Forest. This may indicate paleobotanical data confirming the presence of its traces in the form of pollen (from 0.5 to 2% of the pollen from all tree species) in the early Holocene and Atlantic periods (Paszewski and Poznański 1935, Paszewski 1937, Dąbrowski 1959). It is interesting to note that in the past, silver fir acted as an admixture, not only in different parts of the Białowieza Forest, apparently, but also outside the continuous area, in different parts of Poland. For example, in 1854, the rich soils of the Rogowskie forests (Jasienia tract) were dominated by straight-grown Scots pine (*Pinus sylvestris* L.), mixed with Norway spruce (*Picea abies* (L.) Karst.), and in some places also with silver fir and oak (*Quercus robur* L.) (Kowalski 1994).

The problem of the origin of the silver fir in Białowieża Forest – whether it is artificial or natural – is of interest, and not only from a theoretical point of view. In view of the ongoing significant changes in vegetation, it also has immediate practical significance. The need to conserve forest genetic resources is discussed in Article 7.1 of the Forest Act of 1991 (Ustawa... 1991). According to Order No. 23 of the Minister of Environmental Protection, Natural Resources and Forestry dated January 8, 1994, the tasks are to protect biological diversity in the Białowieża Forest and, which is especially important in our case, to restore the damaged and degraded fragments of natural communities by active forestry methods (Decyzja... 1994).

In this regard, we would note that even if there were approximately 200 silver fir trees in the Tisovik tract in 1888 (Ermochin et al. 2016), now there are only about 24 of them left. The main reasons for such a significant decrease in the already small population of mature trees include unauthorised felling (especially in the first half of the 20th century) and windfall. At present, a reliable double fence is in place: an outer one, surrounding all the plants in the population and covering an area of about 14 hectares, and an inner one, retaining about 85% of the plant population in an area of about 1.5 hectares. As a result, natural regeneration is protected against damage from wild animals (bison, deer (90%), roe deer), and there are now more than 10 plants with a diameter of over 6 cm which are already going to the next tree layer.

Since the prevailing opinion is that the silver fir in the Białowieża Forest has a natural origin, urgent and consistent actions to preserve the remaining gene pool are required. Professor A.F. Korczyk has taken on this task. Under his leadership, and with the direct participation of the Belarusian part of the Białowieża Forest, the collecting of seeds (with climbing trees), and the planting material from them, was organised in the Tisovik tract in 1992 and 1995 (Korczyk et al. 1997). In 1996 and 1998, a half-sib plantation of silver fir was created in the Hajnówka Forest District, Wilczy Jar forestry (in the Polish part of the Białowieża Forest).

It is of interest not only as an object that serves to preserve the gene pool of presumably autochthonous silver fir, but also because its study will provide a preliminary answer to the question about the possibility of successfully setting up artificial stands of this species in the Białowieża Forest region in the future. This stand is especially important in the context of the drying-out of Norway spruce stands, which has become very intense in recent decades due to global climate change. The mass breeding of the eight-toothed bark beetle (*Ips typographus* L.) and the subsequent recent outbreak (which started in 2012) has led to the death of Norway spruce stands in the Białowieża Forest with a standing volume of 1.4 million m^3 (Brzeziecki et al. 2018). Studies conducted since 1936 in the five most important types of forest habitat in the Białowieża Forest have shown that the hornbeam (*Carpinus betulus* L.) is the most expansive species gradually occupying the Norway spruce econiche (Brzeziecki 2017).

A reasonable response to a change in the forest stand species composition postulates, among other things, the need to study the possibility of establishing forest cultures of autochthonous species similar in ecological requirements to the Norway spruce.

Of course, they should be resistant to the ongoing climate change as far as possible. It seems to us that silver fir is one such species. It should be emphasised that it is also very similar in appearance to the Norway spruce, which is important to maintain the habitual types of the Białowieża Forest ecosystems, which have changed significantly in appearance in recent years. In connection with the above, particularly noteworthy is the assertion by a group of authors that the silver fir has great potential to thrive under warmer conditions in western and central Europe provided there is sufficient rainfall, as forecast by climate models for most regions by 2100 (Vitasse et al. 2019). This study is not about Eastern Europe, but since the trend of climate change is the same as in other European regions (Loginov 2015), it is advisable to check the possibility to artificially cultivate silver fir in this region too.

In the context of our research, it is positive that even though the area of Scots pine and Norway spruce forests in Poland decreased from 75.6% to 69.3% and from 8.8% to 6.9%, respectively, during the period from 1948 to 1985, the silver fir area, albeit at a minimum level, remained unchanged – at 2.7% and 2.9% (Kowalski 1994). However, according to Korczyk et al. (1997), the area of silver fir forests has reduced throughout the species area. For example, according to Bernadzki (2008), the silver fir population in Germany decreased by 60–70% during the 20th century. The author gives examples of the good growth of silver fir stands outside its natural area (Sweden, Denmark), and in this regard he recommends paying attention to the introduction of silver fir in forest stands as an admixture outside its natural area in Poland. This is also a very strong motivation for us to carry out our research. Namely, even if we admit the artificial origin of the silver fir in the Tisovik tract, it is still advisable to study the possibility and features of its artificial renewal in the Białowieża Forest, and not only in its Polish part.

The aim of the study was to assess the 22-year-old silver fir artificial stand (Figure 1) in the context of its possible reintroduction in the Białowieża Forest. The study of the state of the young stand of silver fir and its prospects in the Białowieża Forest is being carried out for the first time and is very relevant in connection with the significant changes in its species composition currently taking place.

Figure 1. General view of the half-sib plantation of silver fir (photo by A. Marozau)

Material and methods

Study plot: *location, history and current condition*

The plot of the half-sib plantation of silver fir No. 1 had a flat surface and was on a flat-undulating plain, characteristic of the Białowieża Forest. The geographic coordinates were E 23°39′16″, N 52°42′30″ (Korczyk 2015b). It was established by A.F. Korczyk in the Polish part of the Białowieża Forest (Hajnówka Forest District, sub-district Wilczy Jar, sub-compartment 416Ag) in fresh broadleaved forest (*Lśw*) in October 1996 by planting in furrows (7,692 specimens/ha) over an area of 0.22 ha. According to the data in Korczyk (2015b), the soils on the plot are characterised as rich "Eutric Cambisols and Epdystric Cambisols on loamy sands" (*Op. cit.,* p. 153). The plot was fenced off. It was rectangular in shape and oriented by the short side (as well as the furrows) facing north-south. The length of the furrows was 27 m; they were prepared in the summer of 1995 on a newly clearcut site. Due to the presence of a significant number of stumps, the furrows were not placed perfectly parallel to each other.

The cut-down tree stand had a natural origin and arose on one of the numerous clearcuttings carried out in 1924–1929 by the English company, the Century European Timber Corporation. The uncut stand part consisted mainly of birch (*Betula pendula* Roth) and hornbeam (*C. betulus* L.), though single oaks (*Q. robur* L.) were also found. The broadleaved stand was directly adjacent to the experimental plot, creating lateral shading for the silver fir saplings (Figure 2).

The planting material consisted of 4-year-old seedlings. A total of 1,551 specimens representing 11 half-sib families (Korczyk 2015b) were planted in 65 rows, which were numbered in ascending order from west to east. The individual half-sib family was seed offspring from a separately numbered tree in the Tisovik tract in the Belarusian part of the Białowieża Forest (Kartel et al. 1999), of which only one of the parents (the mother) was certainly common. The volume of one of the half-sib families (No. 1) was very small – only three specimens – and as a result it was excluded from the study. The half-sib families No. 9 and No. 18, which were present on the plot but not indicated in the work (Korczyk 2015b), were also not considered.

Figure 2. The broadleaved stand was adjacent to the experimental plot (photo by A. Marozau)

In 2013, thinning was carried out in the already closed stand, during which approximately 400 trees were cut down. It had a negative selection character with elements of positive selection (Haze 2012).

Therefore, the object of the study, the majority of which was carried out in 2018, was the closed, single-layered, clean, even-aged silver fir sapling stand. It was established in the Polish part of the Białowieża Forest by the dense planting of 4-year-old seedlings, which were half-sibling offspring of *A. alba* from the Tisovik tract. This object is registered in the EUFORGEN-EUFGIS portal (the European database of important genetic conservation objects) (EUFGIS 2018). In 2018, the stand was at the beginning of the second age class (the stand age was 22 years, the tree biological age was 26 years). The shrub layer was absent; the forest vegetation cover was practically absent. Observations were also carried out in the next two years, in 2019 and 2020.

Methods and equipment used in the study

The data on the average diameter of the stand were obtained through a complete DBH (diameter at breast height) calipering of the trees. Measurements were carried out using tree callipers with an accuracy of 0.1 cm. The set of measured trees (701 specimens) was divided into twelve 2-cm diameter steps. Trees that were significantly stunted (0.5–1.0 m high), dried out or damaged were not considered. For each diameter step, at least three tree heights were measured using a SUUNTO PM-5/1520 altimeter with an accuracy of 1 m. The average stand height was determined based on its calculated average diameter on the height curve (Mirošnikov 1980).

In 100 trees selected by random sampling in proportion to the representation of diameter steps, the placement height of the first live branch was measured. The difference between the average height of the trees of each diameter step and the average distance from the root neck to the first live branch is the length of the crown. The estimation of the length of the crown was made in accordance with the IUFRO classification (Jaworski 2013).

To determine the changes in the tree spatial distribution, we measured the distances in the four cardinal directions to the nearest neighbouring trees of 126 randomly selected specimens. The average distance to the neighbouring trees was calculated as the arithmetic mean of these values (Kotscan 2014).

To determine the effect of the silver fir stand on soil acidity in the upper 5-cm soil layer, measurements were taken at 30 points located evenly throughout the entire plot of the *A. alba* establishment and at 30 points located in the broadleaved stand evenly along the perimeter around the establishment at a distance of 10 metres from the borders. A Takemura-DM-15 soil pH and moisture tester was used.

The calculation of indicators of the various tree distributions, average, minimum and maximum values, standard deviation and the coefficient of variation was carried out using the Statistica 10.0 software package (StatSoft 2010) according to the generally accepted methods for forestry (Atroščenko and Maškovskij 2010).

The general view of the half-sib plantation No. 1 from the air was done with a DJI Mavic 2 Pro drone.

Results

The placement of trees, their growth and development

Owing to the enclosure of the plantation, the influence of a negative biotic factor (ungulates) was eliminated (Vitasse et al. 2019). Subsequently, after the canopy closed, a natural thinning of the stand, which had a rather high initial density degree, occurred. By 2010, about 75% of the plants from the original number planted had been preserved (Table 1).

In 2018, their number decreased to 701 (45.2%). This was mainly due to the late cleaning carried out in 2013 (see the *Material and methods*). In addition, the influence of intraspecific competition continued to have an effect. As a result, the initial tree layout of 1.3 × 1 m was modified, and it formally acquired the form of 1.9–2.1 × 1.8–1.9 m (Table 2).

The most significant transformation was the arrangement of trees in rows: the distance between them increased on average by 90–110%. The average distance between the trees in adjacent rows increased by 80–90%. The maximum distance between the trees in a row reached 6.1–6.3 m because of the late cleaning and natural thinning. The minimum recorded values of the distances both in a row (0.69– 0.77 m) and between rows (0.58–0.59 m) indicated that the planting step within rows and the parallel arrangement of the rows were not always maintained. The latter was explained by the difficult conditions for the preparation of the furrows in the cutting area. However, the average distance to neighbouring trees (Lav) was only 1.9 m and had a relatively low coefficient of variation (25.9%), veiling the unevenness of their distribution. With the actual presence of 701 trees in a plot of 0.22 ha (Table 1), this was equivalent to 3,186 specimens in one hectare.

Analysis of the tree distribution by diameter was the most objective and, in this regard, the most frequently used method for assessing the prevailing forestry structure of the stand. Based on an initial eye assessment of the average diameter, the trunk distribution data for this indicator were grouped by steps of 2 cm thickness, as noted above (Figure 3).

As can be seen, the distribution has comparatively large thickness step amplitude for an even-aged young

Table 2. Description of the main statistical indicators

Indicator	Average value	Minimum value	Maximum value	Coefficient of variation, %
D[a]	10.01 ± 4.13	0.50	23.70	41.25
H[b]	9.43 ± 3.18	3.50	15.00	33.70
Ln[c]	2.13 ± 1.09	0.77	6.15	51.63
Ls[d]	1.94 ± 0.88	0.69	6.30	45.87
Le[e]	1.89 ± 0.72	0.58	3.75	38.10
Lw[f]	1.81 ± 0.73	0.59	4.26	41.29
Lav[g]	1.93 ± 0.49	1.10	3.42	25.91

Note: [a] – average diameter of the trunks (diameter at breast height), cm; [b] – average height, m; [c] – distance to the nearest tree in a northerly direction (distance in a row), m; [d] – distance to the nearest tree in a southerly direction (distance in a row), m; [e] – distance to the nearest tree in an easterly direction (distance between rows), m; [f] – distance to the nearest tree in a westerly direction (distance between rows), m; [g] – average distance to the nearest trees, m.

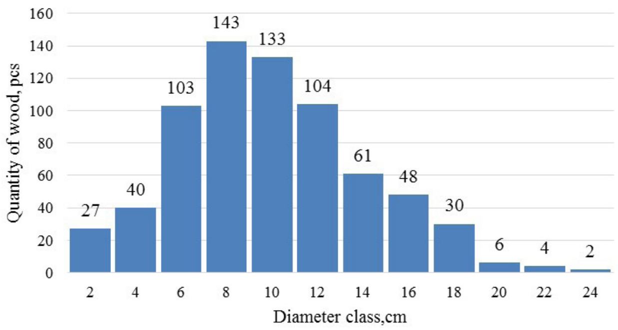

Figure 3. Distribution of trunks by 2 cm thickness steps

Table 1. Dynamics of changes in the number of trees from 1996 to 2018

Half-sib family	The number of plants by year of observation (specimens)					
	1996[a]	2000[a]	2004[a]	2006[a]	2010[a]	2018[b]
2	336	325	251	247	238	157
3	75	74	54	51	49	31
4	70	70	59	59	59	24
5	258	233	166	167	154	73
11	66	66	61	58	52	34
12	38	37	30	27	20	13
15	333	333	291	286	286	180
16	18	18	17	17	17	11
17	327	327	266	265	265	167
21	27	27	22	20	20	11
Total	1551	1513	1220	1200	1163	701

Note: [a] – research from Korczyk (2015b); [b] – own research.

stand. This is also evidenced by the trunk diameter coefficient of variation, 41.3% (Table 2). This sufficiently significant value indicates a high level of variability of this feature. It should be noted that with such a coefficient of variation, and a given accuracy level of 95%, a sample size of 296 trees would be sufficient (Bondarenko and Žigunov 2016). In our case, the number of specimens was much larger (701 trees), which indicates that the high level of data obtained representativeness. The trees were distributed in 12 steps, starting from 2 cm steps. The maximum thickness step was 24 cm. However, the number of clearly dominant trees representing the upper thickness steps (from 20 to 24 cm) was insignificant. Most of them were concentrated in the thickness steps from 6 to 12 cm (69.4%).

The distribution of trees by thickness was characterised by an asymmetric, single-peak curve, usual for even-aged clean stands created by planting and having the same care (Figure 3). The asymmetry coefficient for this distribution was calculated as the ratio of the third central moment to the cube of the standard deviation. It is equal to 0.432, which indicates a shift in the distribution to the right of normal. That is, the right branch of the distribution curve, where more developed trees with larger diameters are concentrated, is much longer than the left branch, represented by trees lagging in growth.

The average diameter of our 22-year-old stand was 10.0 cm and its height was 9.4 m (Table 2). The visual estimate of the maximum annual linear growth of the main axis, not only in recent years (Figure 4) but also at the beginning of the existence of the forest culture (Figure 5), was about 50 cm, which also corresponded to the parameters of photophilous pine (*P. sylvestris* L.).

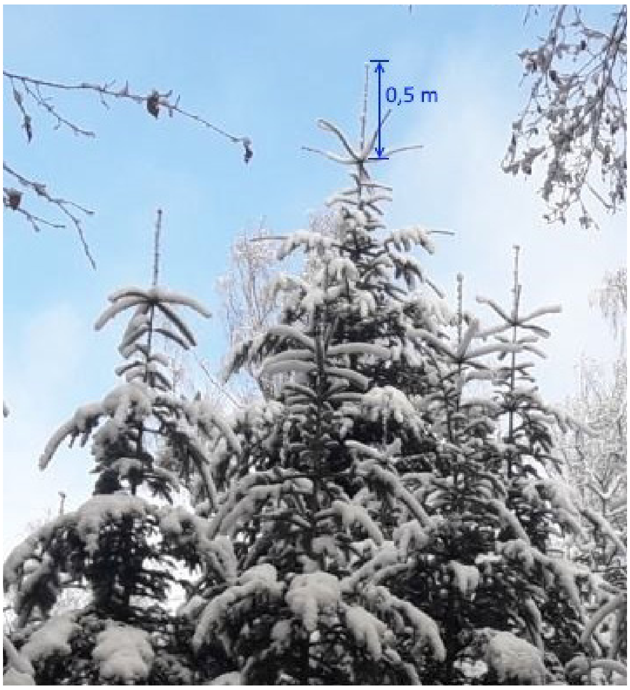

Figure 4. *A. alba* linear growth in 2018 (photo by A. Kaliszuk)

Figure 5. *A. alba* linear growth in the early years (photo by A. Marozau)

Table 3. Height of the reintroduced silver fir in the Białowieża Forest in different years

Height (in centimetres – 2000–2010; in metres – 2018) / % in relation to the previous period				
Year of observation				
2000[a]	2004[a]	2006[a]	2010[a]	2018[b]
54.46± 24.82	120.2 6 ± 47.76 / 220.8	201.13 ± 70.98 / 167.2	394.86 ± 145.74 / 196.3	10.01 ± 4.13 / 253.5

Note: [a] – research from Korczyk (2015b); [b] – own research.

The above data on diameter and height are static; they reflect only a single time point and do not show the actual course of the stand growth from the very beginning of its creation. The addition of the height data from its earlier stages (Korczyk 2015b) to the data obtained by us would allow the creation of a more complete picture of the height growth dynamics (Table 3).

As can be seen, the four-year period from the beginning of the establishment of the crop to 2000 was characterised by relatively weak growth. Then there was very intensive growth, starting in 2000 and continuing up to 2018 onwards.

Figure 6 shows a graph illustrating the dependence of tree height on diameter. The determination coefficient is 0.917, which indicates a strong relationship between these indicators and is consistent with the stand characteristics (clean, even-aged and single-layered). The calculated significance level of the *t*-criterion (*p*-value) for coefficient ***a*** was 0.001090, while for ***b*** it was 0.000004. Both levels were less than 0.05, and therefore the coefficients ***a*** and ***b*** are reliable at a 5% significance level. The significance of

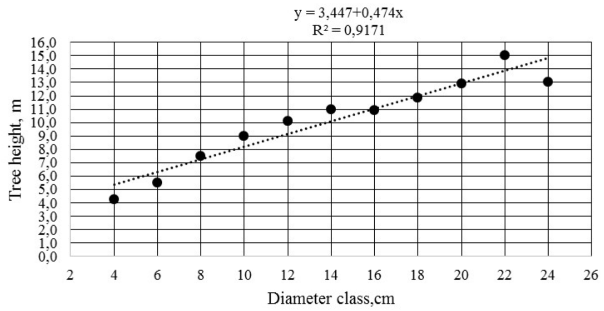

Figure 6. Dependence of tree height on trunk diameter

the F-criterion of less than 0.000001 indicates the resulting equation has a high degree of reliability. It is noteworthy that the coefficient of variation for the height of the trees was very high – at 33.7% (Table 2).

The formation of crowns

Successful growth is the derivative of the tree increments in height and diameter. In turn, the increase depends on the degree of development of the photosynthetic apparatus, which is largely determined by the state of the crowns. In the first five thickness steps (steps 2–10 cm), the length of the average crown varied from 53.2% to 68.7% (½ to ⅔) of the height of the tree (Table 4). With the increase in the thickness of the trees (steps 12–20 cm), the length of the crown also increased proportionally, making up from 72.6% to 77.0% (> ⅔) of the height of the tree. In trees with the most significant diameters (steps 22 and 24 cm) and height, the crowns had a maximum size of 81.4–82.1% (> ⅘ of the height).

The tree crowns have a conical shape (Figure 4) with shoots densely covered with needles. In general, the plants do not show visible signs of disease or insect damage. On trees in most thickness steps (except for 2 and 4), the average height of the crown placement starting point differs slightly from 2.2 to 2.9 m.

Table 4. Crown length depending on the diameter and height of the tree

Thickness step, cm	Tree average height, m	Average height of the crown placement start, m	Crown's average length, m	Average crown length in % relative to height
2	3.3	1.3	2.0	60.6
4	4.0	1.3	2.7	67.5
6	4.7	2.2	2.5	53.2
8	7.0	2.8	4.2	60.0
10	8.3	2.6	5.7	68.7
12	10.0	2.3	7.7	77.0
14	10.6	2.9	7.7	72.6
16	11.0	2.8	8.2	74.5
18	11.8	2.9	8.9	75.4
20	12.1	2.8	9.3	76.8
22	12.3	2.2	10.1	82.1
24	14.0	2.6	11.4	81.4

Figure 7. Natural cleansing of the boughs (photo by A. Marozau)

The stand has entered the stage of the natural cleansing off the boughs. The smallest dead boughs, densely located on the lower part of the trunks, are beginning to fall away, while the stronger dead boughs, located at about 1.5 metres and above, are still held firmly (Figures 5 and 7).

In the second half of the summer of 2020, a massive yellowing and falling of needles from the branches of the lowest part of the crowns was noted. This was the first time that this phenomenon had been recorded in our three years of observation of the state of the plantation that started in 2018. It is important to emphasise, however, that the tops of the crowns continue to look as good as before (Figure 8). A visual assessment indicated that the length of the annual shoot during this period was more than half a metre.

Figure 8. General view of the half-sib plantation from the air in August 2020 (photo by Ł. Prokopiuk)

The beginning of fruitage

More than 10 specimens became fertile for the first time in 2019 (Figures 9 and 10). These are the tallest trees of Kraft's crown classes I and II, representing half-sib families Nos. 2, 4, 5, 15 and 17. As is well known, the female cones of the silver fir are in the uppermost part of the crowns (Suszka 1983). Due to the raising of the crowns upwards, as mentioned above, the light content of the most developed trees improved so much that fruiting was stimulated. The formation of cones was also noted in 2020 (Figure 11 a, b). Obviously, it is too early to talk about the beginning of sustainable fruiting. However, the fact that seed production has begun indicates that the plantation is moving into a new qualitative state. While remaining a scientifically important forest cultural object, it is becoming an element of the seed farming system. Moreover, it is a genetically structured element (different half-sib families) and unique of its kind, since for some reason the gene pool in the Tisovik tract in some cases has already been irretrievably lost.

Figure 9. Cone scales from fruitage 2019 (photo by A. Marozau)

Figure 10. Seeds from fruitage 2019 (photo by A. Marozau)

Figure 11 a, b. Fruiting 28-year-old trees in August 2020 (photo by K. Onikijuk)

The floor covering, the ground litter and the soil reaction

Due to severe shading, ground vegetation cover was practically absent. In the gaps in the canopy which are beginning to form, one can find single specimens of *Galeobdolon luteum* Huds. and *Oxalis acetosella* L. The presence of these indicator species is evidence of a high level of soil fertility.

It should be noted that the ground litter was also not characterised by significant development. Its thickness was about 1 cm. The litter was comprised of various components: leaves of hazel (*Corylus avellana* L.), hornbeam, birch and oak, brought by the wind from the adjacent stand, and dead small boughs. The main component of the litter was fir needles (Figure 8).

The comparison of the reliability of the difference in the average soil pH value on the fir plantation (6.63 ± 0.10) and in the adjoining broadleaved stand (6.57 ± 0.20), according to the Student's *t*-test (Dospechov 1985), showed no statistically significant difference. The significance level of the Student's *t*-test is greater than 0.05 (0.26665 > 0.05) (Figure 12).

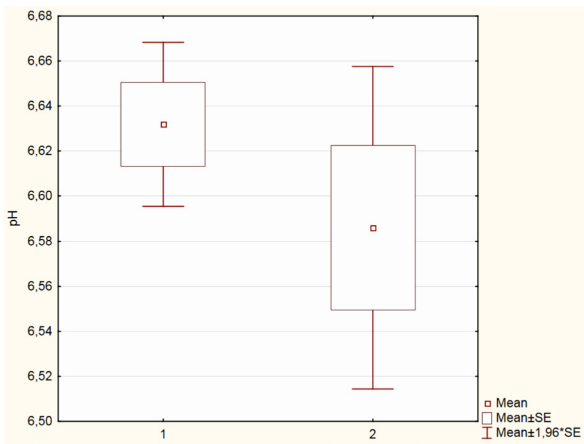

Figure 12. Soil reaction in the upper 5-cm soil layer in the broadleaved stand (1) and in a half-sib plantation of the silver fir (2)

This established fact is rather unexpected, and it allows us to tentatively assume that the studied coniferous tree does not have the same modifying effect on soil pH as other coniferous species (pine, spruce), which reduces the value of this indicator.

Discussion

Almost all the seedlings were damaged to some extent by late spring frosts, which were especially severe in the first 4 years after planting. The nature and degree of the damage varied: from freezing of the main shoot or lateral shoots to death of the whole plant. According to the results of a tree count held in 2000, the percentage of plants damaged by frost was more than 30% (Korczyk 2015b). These facts indicate that the presence of only lateral shading from the forest wall is not enough to create a comfortable thermal regime and appropriate light conditions for young silver fir plants. Obviously, the cause of death of the seedlings in the early years was not only late spring frosts. The plants are also likely to have died because of excessive solar insolation, but we could find no information about this in the literature (Korczyk 2015b). In connection with this, we would focus attention on the accepted direction of the rows – north-south. In our opinion, this was the right organisational and technical decision as arranging the rows in that way meant that the tree crowns shaded each other as much as possible in the afternoon (Kruzhilin 2015). However, this effect can only be expected at the beginning of the tree canopy closing phase, and not in the first years after planting.

In 2013, thinning was carried out, the main principle of which, as has been noted, was the negative selection method (Haze 2012, Labocha and Šiman 2015). Certain trees from the middle thickness steps were also cut down, which made a competitive influence on their neighbours. The increased tree concentration in the middle thickness steps, as well as the significant representation of the left branch (Figure 3), indicates further thinning would be feasible. In this case, it is probably necessary to apply a positive selection, that is to say, the cutting should be carried out according to the grassroots method (Haze 2012). In this case, in our opinion, it is necessary to focus on the very weak degree of intensity. This is due to the following considerations. The density of crops was initially very high (7,692 specimens/ha) and almost corresponded to the upper recommended limit of 8,000 specimens/ha (Jaworski 2011, Haze 2012). Silver fir, especially at a young age, is one of the most tolerant of light-deficient species (Jaworski and Zarzycki 1983, Bernadzki 2008, Jaworski 2011). And since the most important principle in the management of silver fir stands is the formation of a vertical structure, those plants that are lagging in growth should not be forgotten about. Due to their specific features, they are far from as hopeless as they seem, and they have “not yet said their last word” (Bronisz and Bijak 2012). During following thinning, therefore, the removal of not only obviously supressed trees but also implicitly (that is, it is not clear whether they will live or not) supressed ones can lead to potentially undesirable consequences.

The current state of the studied stand could indicate (Tables 2–4, Figure 3) that the prevailing influence of positive factors is more conducive to the good growth of trees rather than inhibiting it. For example, the average diameter of the trees and their height (Table 2) approximately corresponded to the indices for natural stands: 35–37-year-old silver fir and 23–25-year-old pine (Szymkiewicz 2001). And that means, firstly, that the correct cutting method was chosen and, secondly, that the growing conditions suit the *A. alba* requirements.

In the studied stand, only recently there has been a change from the thicket stage to the pole wood stage. For the latter, three features are most characteristic: 1) increased self-thinning; 2) the intensive growth of the best trees in terms of height; and 3) the beginning of the division into dominating classes. The size of the coefficient of variation of the height of the trees (Table 2) is very significant and clearly does not correspond to the variability of this feature in stands that have a silvicultural characterisation like the object under study (Atroščenko 2009). At the same time, only this fact alone convincingly confirms the reality of the above features of the pole stage of our stand.

The above should be considered when conducting the next thinning, which in essence: 1) must not contradict the species biology; and 2) must correspond to the forest stand morphogenesis at this age stage.

The relatively weak growth from the beginning of the establishment of the crop to 2000 (Table 3) is explained by the adaptation of plants after planting, the stressful effects of abiotic factors and, obviously, the lack of crown density in young trees. The studied stand is currently characterised by a very high growth rate. This was pointed out after 2000 and up to 2018 onwards and it is completely non-typical for the natural seed renewal that is most common for silver fir. It is logical to assume that one of the reasons for this phenomenon is the intensification of intraspecific competition in a closed, single-layered, clean, even-aged, young stand with artificially-increased density.

However, in our opinion, the interpretation of good plant growth as being a response modification reaction to a cardinal change in the light factor is more consistent with reality. This modification, induced by environmental conditions, is quite obviously not adequate to the genetically fixed constitution of *A. alba*. In particular, it does not correspond to the rhythm of its development formed during evolution. And this contradiction of the species biology is one of the main anthropogenic factors in the acceleration of the ageing process, leading ultimately to the white fir trees dying out faster (Bernadzki 2008). Therefore, artificial renewal in completely deforested areas, and the formation of subsequently closed, single-layered, single-species, even-aged stands promote very rapid tree growth at a young age.

It is possible that this situation is taking place in our case. In this regard, we note that the behaviour of stands quality in different age periods can be both stable and unstable. In the latter case, changes in the trajectory of taxation indicators lead to the stand quality either increasing or decreasing with age (Rogozin and Razin 2015). The stand quality of the studied stand can be currently estimated as I (Szymkiewicz 2001).

However, it must also be remembered about the old silvicultural rule, formulated by H. Mayr, which states that "...each tree species, possessing in the optimum of its growth a certain shade tolerance... becomes more photophilous in the colder part of its area". Therefore, for example, "...such shade-tolerant species as fir and beech in a colder climate become also more photophilous" (Morozov 1949, p. 115). And this fundamental circumstance should also not be overlooked during the reintroduction of the silver fir in the Białowieża Forest with material from the Tisovik tract located about 500 km northeast of the border of its area, i.e., in relatively harsher climates. It can be assumed that the response to the light factor in the studied silver fir is somewhat different from plants from the central part of the area. It is probably more photophilous, but still not to the extent that its ability to live in overshading at a young age would be radically changed.

Silver fir cultures are still so tightly closed that they retain their original monodominant composition (Figures 1, 5, 7 and 8). This is despite the direct adjoining to them of a hornbeam birch stand – a potential source of lateral seeding (Figures 2 and 8). In this respect, we note that according to the IUFRO classification, even the least developed trees in the studied stand can be assigned to the fourth (highest) class according to the length of the crown (> ½ of the tree height) (Jaworski 2013). Note also that two oppositely directed processes are currently taking place on the plantation, proceeding with unequal activity. There is intensive annual growth of the upper part of the crowns, as well as periodic (not yearly) needle drop, entailing the death of branches in the lower part. These facts indicate a gradual transformation of the crowns manifested in two ways: 1) their length increases; and 2) they "raise themselves" higher above the ground surface.

The situation with the closure of the silver fir culture canopy, as mentioned above, is hardly possible even in a spruce forest culture of the same age, not to mention a pine culture. This feature of the development of the silver fir artificial forest stand can be evaluated in two ways. On the one hand, this is evidence of its phytocoenotic resistance and stability now. On the other hand, it is a prerequisite for a number of problems in the future. As is well known, the mixed stands formation is one of the main conditions for their high quantitative and qualitative parameters to the age of maturity. In the studied forest stand, created on rich soil, this condition is currently not being met. However, for naturally growing silver fir, which prefers just such soils, participation in mixed stands as an admixture is very characteristic (Jaworski and Zarzycki 1983, Wojterski 1983, Ilmurzyński and Włoczewski 2003, Bernadzki 2008, Jaworski 2011, Vitasse et al. 2019).

Thus, two features of the silver fir forest culture can be distinguished which are likely to negatively affect their condition in the future: intensive growth at a young age, and a monodominant composition.

The flow of organic fall into the soil was negligible; in particular, there were no plant residues of vegetation cover. The fall of needles began entering the soil at least 15 years ago (silver fir needles have been falling to the soil surface in this forest stand for approximately that length of time) but they have not accumulated into the form of a dense, thick layer, as spruce needles do (Dymov et al. 2012). Instead, they have decomposed intensively, improving soil fertility, refining the structure of the soil upper horizon, and thus setting good conditions for natural seed renewal in the future. According to our visual assessment, the dynamic of fir needle mineralisation is comparable to the rate of leaf destruction. And this is the main reason for the insignificant thickness of the litter layer.

The absence of the effect of silver fir on soil acidity can be explained by the fact that 15 years is still not a term long enough for the influence of a new tree species to manifest itself. The intra-group variation of the studied parameter in the white fir plantation is two times less than in the hornbeam-birch stand. However, even the most extreme pH values in both cases do not go beyond a very narrow interval located at the border of weakly acidic and neutral soil.

Individual trees at the biological age of 27 years, growing in a closed stand, have entered the generative stage. This is several years earlier than the beginning of fruiting of silver fir in stands of natural origin, which start at the age of 30 years (Suszka 1983, Bernadzki 2008). In closed stands, they usually bear fruit at the age of 60–70 years (Jaworski 2011). We interpret this earlier onset of the generative phase as further proof of the good condition of the trees, which is due to the correspondence of the local conditions to their biological and ecological needs.

Conclusions

The establishment of silver fir monocultures in clearcut plots is evidently not consistent with the biology of the species, which suffers, especially at a young age, from late spring frosts as well as excessive solar radiation. The introduction of the silver fir into a culture in an open place without a canopy covering should be recognised as risky at the very least.

When the practical work on the reintroduction of the silver fir is carried out later, it will be advisable to focus on traditional previous establishments, for example birch, or sub-canopy cultures. This will protect the plants from the negative effects of late spring frosts and excessive sun exposure.

After the problems associated with the mismatch between the thermal and light conditions at the earliest stage of growth of the half-sib plantation, its good condition now can also be regarded as evidence of the suitability of the soil and hydrological conditions for growth and for meeting the ecological and biological requirements of silver fir. In addition, this fact also confirms the autochthonous nature of this tree species in the Białowieża Forest.

In the future, it will be necessary to focus on studying the dynamics of the natural process of tree differentiation and mortality, as well as fixing a comparative analysis of the growth and development phases of both individual plants and the stand.

The extremely early entry of the half-sib plantation into the fruiting stage is further proof of the good state of the trees due to the compliance of the local conditions with the constitution of *A. alba*. The ascertained fact of seed production has multiplied the value of this object for forestry as a seed reserve base. The close placement of different half-sib families on the plantation makes favourable conditions for the exchange of genetic information, an important prerequisite for the effective reproduction of the autochthonous *A. alba* population from the Tisovik tract, which is most adapted to lowland conditions. The new qualitative state of the half-sib plantation assumes maximum use of the seed yield to produce planting material to reintroduce this tree species.

The progressive degradation of Norway spruce forests and the deterioration of the state of pine stands require new approaches and solutions in the field of forest resources reproduction. Our studies have shown the high degree of adaptability of a young silver fir stand to the edapho-climatic conditions of the Białowieża Forest. The results give grounds for this tree species to be considered as a possible element in the system of optimisation of the species structure in this region under modern conditions.

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