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Silver fir restitution: The role of seedling stock type in adapting to various environmental conditions

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Abstract: Due to past human activities, *Abies alba* Mill. (European silver fir) now covers only 0.7% of the forest area in the Sudety Mountains. A large-scale restitution program has been launched to produce, plant, and effectively protect over 200 million seedlings. This study aims to validate commonly used seedling stock types and provide critical insights into identifying the most effective one. Three-year-old bareroot seedlings were produced in the open-canopy nursery (3/0) or under-canopy nurseries in Scots pine (*Pinus sylvestris* L.) (3/0 Sp) or Norway spruce [*Picea abies* (L.) H. Karst] (3/0 Ns) stands. Two stocks were produced in a greenhouse and transplanted to an open-canopy nursery (2/1) after the second year or into containers designed by Kosterkiewicz (2/1 K). Seedlings have been planted in four regions in the Sudety Mountains. Two performance characteristics have been measured: height and survival rate. Our findings demonstrate a clear gradient in sapling performance among seedling stock types (survival rate): 2/1 K (81%), 3/0 (73%), 3/0 Sp (73%), 2/1 (70%), 3/0 Ns (62%). This paper has shown that under favourable environmental conditions, bareroot seedlings can sufficiently achieve stable regeneration. Containerised seedlings perform better in harsher and more challenging microclimatic or trophic conditions. Kosterkiewicz's method presents a relatively low-cost and environmentally friendly alternative for silver fir restitution.

Keywords: bareroot stock; container stock; Kosterkiewicz containers; nursery operations; transplanting

Silver fir (*Abies alba* Mill.) is a widely distributed species from Southern to Central Europe, primarily occupying mountain areas at sites ranging from rocky to deep and moist soil characterised by pH from acid to neutral (Boratyński 1983; Mauri et al. 2016; Ruosch et al. 2016; Dobrowolska et al. 2017). However, the areas inhabited by the original populations of silver fir were heavily limited. Human-induced intensive deforestation, overlapping with the threats arising from industrial pollution, makes silver fir very susceptible to pathogens and insects, and replacement by fast-growing Norway spruce [*Picea abies* (L.) H. Karst] converted forest to a monospecific system, further contributing to the reduction of the past distribution (Boratyński, Filipiak 1997). In recent times, however, there is a growing need to replace Norway spruce monocultures – characterised by a high risk of excessive mortality – with stands with diversified species composition and age structure. This shift in focus necessitates re-evaluating species-specific growth features and silviculture

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practices (Hlásny et al. 2017; Reventlow et al. 2023; Ambs et al. 2024). Currently, the past limiting factors, such as air pollution load and unsustainable forest management, are supposed to be minimised (Mikulenka et al. 2020). Still, other factors increased their importance: pressure from wild game (Carpio et al. 2021; Konôpka, Šebeň 2024; Brabec et al. 2024) and changes in climatic conditions (Bledý et al. 2024). The former is generally regarded as the primary cause of problems with the regeneration of silver fir (Šuleková, Kodrík 2011).

To achieve the desired contribution of 20% to the silver fir composition characteristic of high-biodiversity forests, stock type selection must include practices that optimise seedlings' morphological and physiological characteristics for growth after planting in different fields (Barzdajn 2000, 2012). Indeed, increasing the resilience of silver fir on degraded lands and designing reintroduction strategies for natural species requires consideration of both biological and morphological characteristics of the species, as well as site-specific edaphic factors (Cairns et al. 1997; Chirino et al. 2008). Practices that promote root and shoot development patterns similar to those of naturally originated seedlings are critical for successful forest establishment beyond the young forest stage. Notably, the potential for water absorption is determined shortly after seedlings are planted in the field (Devine et al. 2007). Any alterations or disturbances in proper horizontal and vertical root distribution can make seedlings susceptible to asymmetrical root distribution or spiralling (Grossnickle, El-Kassaby 2016). Therefore, ecological requirements are limited to two types of planting stock – bareroot and container-grown – used to produce silver fir seedlings in nurseries. When choosing seedling stock type, many aspects should be considered, i.e. species ecological requirements, the species' growth dynamics and ontogenetic development, production and transportation costs, and the seedlings' ability to compete with weeds. Firstly, silver fir is sensitive to open-growth conditions and requires additional protection against temperature extremes and drought. In natural conditions, moderate canopy openness (up to 20%) creates suitable conditions for optimal fir sapling growth and survival, as overstory protects them (Boratyński 1983; Kučeravá et al. 2013). Secondly, the long development during the first ontogenetic phase necessitates producing at least three-year-old seedlings before establishing plantations (Huth et al. 2017). In the past, silver fir seedlings were produced in temporary nurseries established under the overstory of a stand localised near the planting sites. Such practice has two main advantages: low transportation costs, acclimation to local site conditions, and the ability to meet the ecological requirements of young silver firs. In other words, it mimics the conditions of natural regeneration but concentrates production like in a conventional nursery. However, these seedlings are not well acclimated to open-growth conditions and may suffer from root system alterations that disrupt the natural strategy for acquiring water in deeper soil layers. Seedling production without canopy cover helps them acclimate better to open-growth conditions. However, the lack of protection makes them more vulnerable to late frosts and high-temperature amplitudes. Seedlings produced in a containerised system increase seed utilisation effectiveness and have less impact on root system architecture. This reduces planting stress and extends the time for successful plantation establishment (Wilson et al. 2007). Jan Kosterkiewicz (1991) developed a unique, primarily low-scale seedling stock type designed explicitly for silver fir. This system aims to prevent root deformation and promote well-developed taproots and bunches of fibrous roots.

This investigation was carried out to solve the problem of choosing the universal seedling stock type, which can be adopted in any restitution program of silver fir or other species with similar ecological requirements. Here, we put forward three hypotheses:

H_1: Transplantation during production increases seedlings' performance in the field.

H_2: Containerised stock performs better than bareroot stock.

H_3: Containerised stock overperforms other stocks regardless of site conditions.

Our first hypothesis is based on the findings of Robakowski et al. (2021), who predicted that seedlings grown under the shade and then transplanted to open-light conditions would be suitable for planting in differentiated forest environmental conditions. Secondly, containerisation makes roots less sensitive to planting shock – the root structure is not affected by extraction from nursery and sudden change of soil environment. The planting process of containerised seedlings is easier, contributes to fewer errors and is cheaper. Moreover,

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better root attributes and higher biomass allocation to roots explain higher seedling survival of containerised stock. The third hypothesis is likely the most crucial for the silver fir restitution program, as foresters seek a universal method that proves effective regardless of site conditions.

Given the distinct environmental characteristics of each site, our results may offer insights into technologies that could support reintroduction efforts, especially in regions with comparable conditions in parts of Europe. We have compared five seedling stock types to determine the most efficient one based on growth dynamics and survival rate during the critical phase of stand development after transferring from the nursery to natural conditions.

MATERIAL AND METHODS

Seedling production. Silver fir seeds were collected from the seed orchard located in the Międzylesie Forest District (Figure 1B). The seed orchard was established in 1968 with 1 103 grafts (309 grafts left; Barzdajn 2012), representing 43 clones (Barzdajn, Kowalkowski 2007). In accordance with meteorological conditions, seeds were sown by hand using broadcast seeding in the spring of 2014 in the open-canopy nursery (treatment 3/0) or greenhouses covered by polyethylene foil (treatments 2/1) in the Międzylesie Forest District nursery located in Międzygórze. For the two remaining treatments, seed were sown under a canopy of Scots pine stand (8 km from the nursery, in Idzików) with stocking index 0.4 (3/0 Sp) or in a shelter with a side cover of surrounding Norway spruce stand (3 km from nursery and 11 km from Idzików) – 3/0 Ns. Seedlings under all treatments were grown in brown soil and fertilised with Hydrocomplex (200 kg·ha^{-1}, N: 12%, P: 11%, K: 2.7%, Mg and microelements). Fungicides Topsin (thiophanate methyl) and Granuflo (thiram) were applied in doses recommended by producers. Weeding was done in spring and in summer, up to 4 times per year. The five tested technologies (experimental treatment) are briefly described in Table 1.

Seedlings grown in greenhouses have been transplanted into the open-canopy nursery (2/1) or Kosterkiewicz containers (2/1 K) into substrate based mainly on high moor peat and compost (forest soil and sawdust) in a 1 : 1 ratio, with an admixture of perlite. Containers designed by Kosterkiewicz are built from a rectangular sheet of hard plastic of 0.5 mm thickness with dimensions of 35 × 18 cm. After the sheet is bent along four edges 7 cm apart, a cuboid is constructed without a bottom and lid.

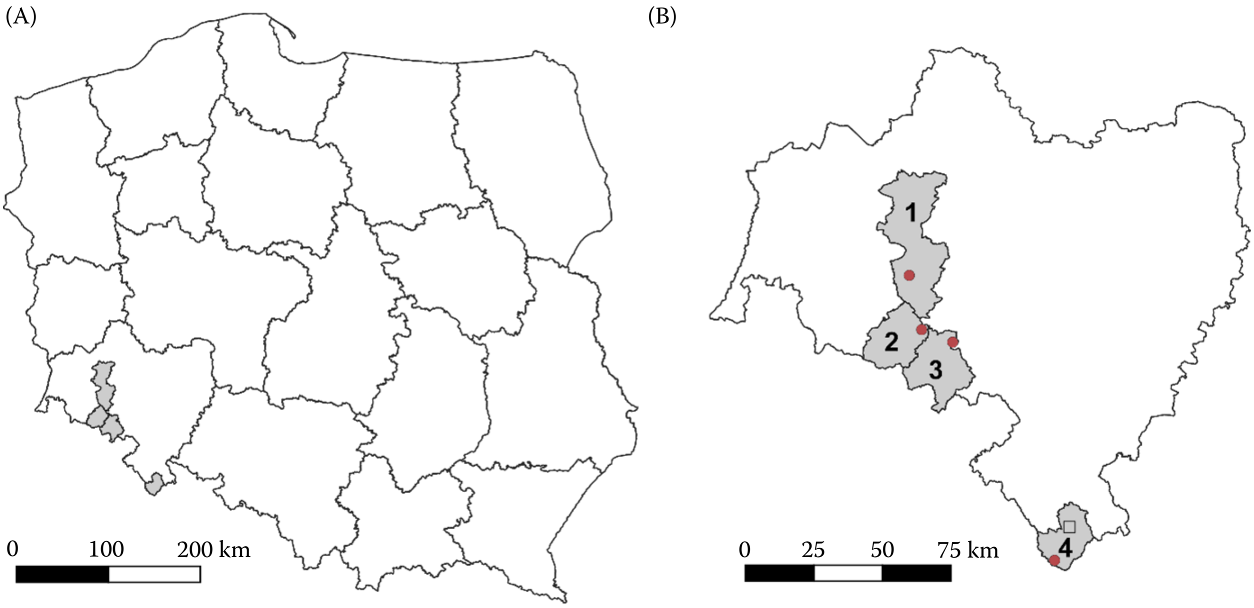

Figure 1. The Republic of Poland with marked borders of (A) State Forests Directorates and (B) the magnified Wrocław Directorate territory

Polygons filled with grey colour – territories managed by Forest Districts: Złotoryja (1), Śnieżka (2), Kamienna Góra (3), and Międzylesie (4), where experimental sites were located (points); square – the nursery's location where seedlings were produced
Source: Own processing based on Forest Data Bank (2022)

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This cuboid has 882 cm^3 in volume (Figure 2). Boxes with seedlings in Kosterkiewicz containers were placed in open-canopy conditions (Figure 3B).

Establishment and measurement of the experiment. In spring 2017, seedlings were transported from nurseries to four experimental sites (Figure 1; Table 2). The experiment was established with error-control, completely randomised block design at all four sites, with five blocks established in each (Figure 4). Each block included five experimental units, each representing one of five experimental treatments (Table 1), giving the following combination of factors: Four sites × five experimental treatments (seedling stock types) × five blocks = 100 experimental units.

In each experimental unit, 100 seedlings were planted: ten seedlings in each of ten furrows, giving an initial spacing of 2.0 × 2.0 m (4 m^2 initial growing space) for each tree in the experiment. The characteristics of each experimental site are given below, with numeration kept from Figure 1 (Table 2). The meteorological characteristics of each experimental site cannot be drawn from the original datasets provided by the Institute of Meteorology and Water Management because of the differences in topography between sites and stations. Hence, we used ClimateEU software (Version 4.63, 2012) (Wang et al. 2006) to generate historical data for each site, based on latitude, longitude and elevation. It must be noted that during

Table 1. Description of seedling stock types (experimental treatments) included in the study

Experimental treatment	Simplified description of production technology
3/0	Seedlings are produced in a conventional bare-root nursery in open-canopy conditions (Figure 3A).
3/0 Sp 3/0 Ns	Seedlings produced in nurseries established under the canopy of the stand of *P. abies* (Ns; Figure 3C) or *P. sylvestris* (Sp; Figure 3D) stand. Soil has been cultivated by rototiller, raked and seedbeds prepared manually. In the nursery under the *P. sylvestris* stand, seedlings were watered manually on several occasions. Under *P. sylvestris* and *P. abies*, the seedlings acquired about 40–65% of full light.
2/1 2/1 K	During the first two years, plants grew in a greenhouse. In the spring of the third vegetative season, seedlings were transplanted. Before sowing, the substrate in the greenhouses was dug, fertilised and limed. Then, depending on substrate moisture, watering was done twice a day for 5 minutes. The greenhouse cover let 40% of light trough. In the 2/1 treatment, plants were transplanted into a conventional bare-root nursery in open canopy conditions for one vegetative season. Treatment 2/1 K consisted of transplanting into Kosterkiewicz containers placed in boxes (Figure 3B) kept in open canopy conditions.

Sp – Scots pine; Ns – Norway spruce; K – Kosterkiewicz containers

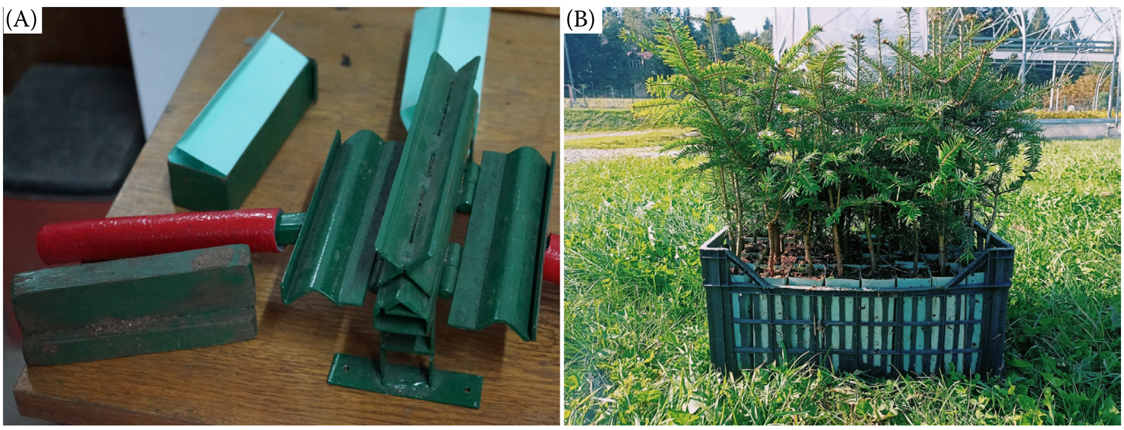

Figure 2. (A) Technological line for Kosterkiewicz containers and (B) transportation box

In (A), at the bottom right is the instrument for shaping the plastic sheet; at the left is the instrument for substrate filling and sapling transplanting; and at the bottom left is a press for thickening the substrate with a sapling

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Figure 3. Different stock types of silver fir seedlings: (A) conventional nursery, (B) Kosterkiewicz containers, (C) nursery under the stand canopy of the Scots pine, and (D) nursery under the stand canopy of the Norway spruce

the stage of experiment planning, canopy cover was left and present on sites 1, 2 and 3. Unfortunately, strong winds in 2017 altered ecological conditions, as described in Table 2. Due to the progress in establishing the experiment, finding new locations was impossible. At each experimental site, weeds were removed twice during each growing season. The timing of weed control was adjusted according to the developmental stage of the weed species.

Inventories have been conducted at the end of the vegetative seasons of 2019 and 2021 when saplings were 6 and 8 years old, respectively. All live saplings' height was measured with a telescopic staff with a ± 0.01 m accuracy. In each experimental unit, 100 seedlings were planted, and the number of measured saplings was equal to the survival rate expressed in percentages.

Data analyses. Two parameters were calculated from the obtained data to assess the performance of saplings originating from differently produced seedlings: first, the mean two-year height increment ($2y\Delta H$), which is the difference between the mean height in 2021 and 2019, and second, the overall average height increment ($av\Delta H$), which is the quotient of the height observed in 2021 and the age of the saplings, see Equations (1) and (2):

$$2y\Delta H = H_{ijk}^{2021} - H_{ijk}^{2019} \tag{1}$$

$$av\Delta H = \frac{H_{ijk}^{2021}}{8} \tag{2}$$

where:

H_{ijk}^{t} – arithmetic mean of height of treatment j in block k in experimental site i observed in year t.

All three performance characteristics were analysed using ANOVA (analysis of variance) which can be expressed in the following linear form, as demonstrated by Equation (3):

$$y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + c_k(\alpha_i) + \varepsilon_{ijk} \tag{3}$$

where:

y_{ijk} – dependent variable, one of the three performance characteristics tested in the study;

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Table 2. Characteristics of experimental sites

Site No.	Forest district, coordinates	Geographical region	Forest site type	Soil	Topography	Elevation (m a.s.l.)	Ecological conditions at planting time	Meteorological conditions (2017–2021): temperature (°C)					precipitation (mm)		
								MAT	I	VII	X–III	IV–IX	*TAP*	X–III	IV–X
1	Złotoryja, 51.05N, 15.84E	Kaczawskie foothills	fresh upland mixed forest	acid brown	flat	350	clear-cut	9.4	−1.8	18.9	3.2	15.6	648	225	423
2	Śnieżka, 50.87N, 15.92E	mountain range of Rudawy Janowickie	fresh mountain mixed forest	podzolic brown	flat	400	clear-cut with a number of scattered trees left	8.5	−3.6	18.1	2.2	14.8	713	270	443
3	Kamienna Góra, 50.84N, 16.08E	the foot of Wałbrzyskie Mountains	fresh mountain mixed forest	acid brown	hillside, exposition: SW	600	nests of 0.18–0.34 ha area in Norway spruce stands	7.5	−4.0	16.7	1.4	13.5	720	280	440
4	Międzylesie, 50.13N, 16.65E	south edge of Bystrzyckie Mountains	fresh mountain forest	acid brown	hillside, exposition: N	550	clear-cut	8.1	−2.6	16.9	2.3	13.9	779	307	472

MAT – mean annual temperature; *TAP* – total annual precipitation; roman letters – calendar months; forest site types follow Poland's forest typology

μ – arithmetic mean;
α_i – experimental site *i*;
β_j – experimental treatment *j*;
$(\alpha\beta)_{ij}$ – interaction effect;
$c_k(\alpha_i)$ – block *k*, nested within the experimental site α_i (considered as random effect);
ε_{ijk} – residual.

The 'aov' function from the 'stats' package was used for the ANOVA statistics. To identify statistically significant differences between experimental treatments, we conducted the Tukey test with the 'emmeans' function from the 'emmeans' package (Lenth 2025). Normality and homogeneity of variances were checked with the 'check_normality' and 'check_homogeneity' functions, respectively, from

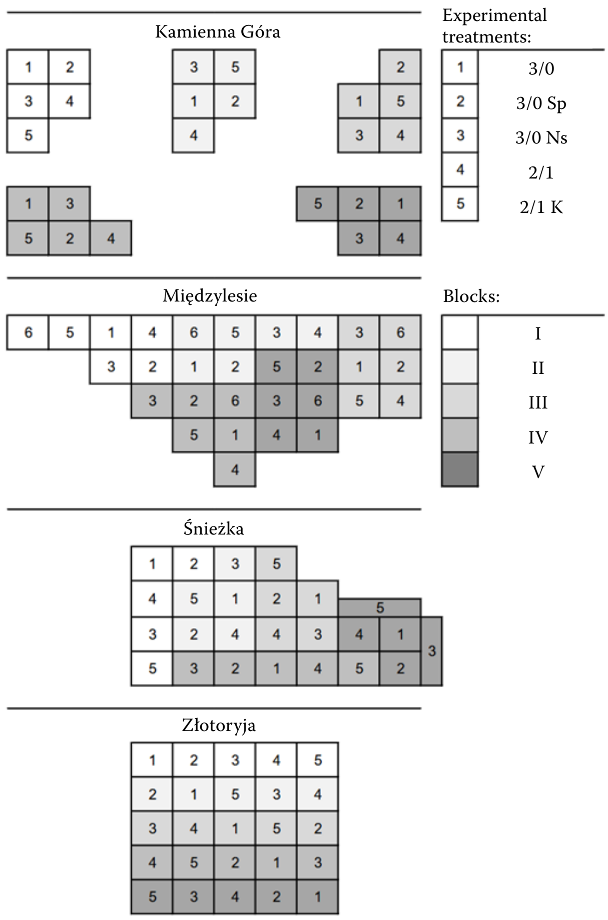

Figure 4. Design of the experiment on the experimental sites

Sp – Scots pine; Ns – Norway spruce; K – Kosterkiewicz containers

The scale of distance between blocks in the Kamienna Góra site is not maintained; the 6th treatment in Międzylesie was not part of the studied experiment; it is an additional treatment comparing the progeny from the seed orchard and the seed stand

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Table 3. Means, standard deviations and ranges of the height and survival rate in two inventories

Variable	Experimental site	3/0			3/0 Ns			3/0 Sp			2/1			2/1 K		
Age		M	SD	*R*	M	SD	*R*	M	SD	*R*	M	SD	*R*	M	SD	*R*
Height																
6 years	Kamienna Góra	37.5	4.2	33.8–44.0	38.3	3.9	33.6–44.2	38.6	2.6	35.6–42.3	46.0	43.4	36.5–47.3	41.1	4.6	33.4–46.0
	Międzylesie	29.2	3.3	26.3–34.5	27.3	1.2	25.9–28.9	31.4	1.7	29.9–34.3	41.5	32.2	26.3–37.3	36.1	3.4	32.6–41.5
	Śnieżka	26.1	3.6	19.8–28.6	22.3	5.4	16.3–30.7	26.8	1.7	24.0–28.6	40.8	25.1	23.8–26.5	33.0	6.2	26.3–40.8
	Złotoryja	42.0	4.4	37.0–48.4	38.7	1.2	37.6–40.2	43.9	5.8	35.9–49.9	54.0	46.8	43.6–50.9	49.8	4.1	44.5–54.0
8 years	Kamienna Góra	71.3	9.3	63.0–87.0	63.6	6.1	54.7–71.5	71.8	3.6	67.1–76.1	79.8	9.3	72.0–95.7	88.3	9.4	77.7–100
	Międzylesie	52.9	7.9	44.3–65.7	48.3	2.2	45.9–51.1	52.9	4.2	50.8–60.5	61.2	7.7	52.0–69.5	63.1	5.0	57.9–70.3
	Śnieżka	42.9	11.5	24.0–54.2	35.8	14.3	23.3–59.9	46.1	6.6	35.8–53.2	39.6	1.9	37.3–41.2	58.5	17.3	39.5–76.4
	Złotoryja	78.8	7.3	69.3–88.9	71.8	5.3	64.6–76.5	84.6	5.3	77.2–90.5	86.6	4.2	81.0–91.2	97.5	11.5	86.5–116.7
Survival (%)																
6 years	Kamienna Góra	90.4	6.3	81–96	92.4	3.9	89–98	92.8	4.0	88–98	91.2	6.4	80–95	93.2	2.6	90–97
	Międzylesie	89.2	6.5	78–94	83.8	12.1	66–95	86.0	8.5	73–95	82.2	11.9	72–97	86.6	13.8	62–94
	Śnieżka	67.4	14.2	49–85	48.4	22.6	15–72	66.8	17.8	48–91	70.2	12.0	52–84	83.0	15.3	57–93
	Złotoryja	88.8	3.3	84–93	83.2	8.8	71–95	91.8	1.9	90–95	89.4	3.1	84–92	92.2	6.4	82–99
8 years	Kamienna Góra	83.8	6.8	76–90	80.0	8.7	70–92	79.8	7.2	70–89	84.6	12.2	69–95	89.8	3.7	85–94
	Międzylesie	65.8	14.0	43–78	49.2	23.9	24–76	66.6	9.2	59–79	55.2	27.1	25–88	70.6	30.8	18–94
	Śnieżka	57.0	14.5	34–74	41.4	22.0	11–66	55.2	11.9	37–64	53.2	12.0	37–69	74.0	11.6	57–86
	Złotoryja	83.4	6.5	74–88	77.2	8.4	66–86	89.0	3.8	85–95	86.2	3.0	82–89	90.2	6.5	82–99

Sp – Scots pine; Ns – Norway spruce; K – Kosterkiewicz containers; M – arithmetic mean; SD – standard deviation; *R* – range (min–max); saplings were six years old in the autumn of 2019 and eight years old in the autumn of 2021

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the 'performance' package (Lüdecke et al. 2021). Model validation indicated no problems. All statistical computations were conducted in R 4.4.0 (R Core Team 2024).

RESULTS

An overview of the data from two inventories conducted in 2019 and 2021 is provided in Table 3. It can be noted that containerised stock (2/1 K) overperformed all tested technologies. The effect of planting stock on saplings' height increments and survival rate was biased towards containerised stock. It was also best adapted to varied site conditions. On the other hand, saplings originating from a nursery under a canopy of Norway spruce demonstrated the worst performance in all analysed traits.

For all three performance characteristics, the three analysed factors explained a statistically significant proportion of the variance (Table 4). The experimental site had the strongest effect, as indicated by the highest values of effect size (η^2). Among the sites, regeneration at the Złotoryja and Kamienna Góra experimental sites outperformed those at Międzylesie and Śnieżka (Figure 5). The blocking factor, which represents variability within the experimental sites, accounted for a smaller portion of the total variance.

Seedlings from different experimental treatments showed similar growth trends for both height increment performance characteristics. Six-year-old silver fir saplings' average two-year height increment was 37 ± 3 (SE) cm for containerised stock, while other stocks' increment was lower by 7–14 cm ± 2 cm (Table 4; Figure 5A): 30 ± 2 for 2/1, 29 ± 2 for 3/0 Sp, 28 ± 2 for 3/0, and 23 ± 3 for 3/0 Ns. The overall height increment was significantly lower, confirming silver fir's very low height increment during the first years of development (Table 4; Figure 5B). The order from best performance to the worst is the same as for the previously mentioned height characteristic: 9.6 ± 0.6 for 2/1 K, 8.4 ± 0.6 for 2/1, 8.0 ± 0.5 for 3/0 Sp, 7.7 ± 0.5 for 3/0, and 6.9 ± 0.5 for 3/0 Ns. Moreover, planting stock affected the saplings' survival in all experimental sites. In the majority of experimental units, the survival rate of saplings originating from containerised stock was higher than 75%, with 81 ± 8% on average (Table 4; Figure 5C), and was better than other treatments: 70 ± 5 for 2/1, 72 ± 3 for 3/0 and 3/0 Sp, and 62 ± 5 for 3/0 Ns.

Table 4. Means, standard deviations, and ANOVA statistics for study variables

Variable	3/0		3/0 Ns		3/0 Sp		2/1		2/1 K		ANOVA			
Experimental site	M	SD	M	SD	M	SD	M	SD	M	SD	effect	*F* ratio	*df*	η^2
$2y\Delta H$														
Kamienna Góra	33.8	11.3	25.3	8.4	33.2	3.9	36.5	7.2	47.2	9.2	ES	23.27***	3, 16	0.54
Międzylesie	23.7	4.9	20.9	1.9	21.5	2.7	28.9	4.1	27.0	2.6	T	14.79***	4, 64	0.14
Śnieżka	16.9	8.3	13.5	9.3	19.3	5.8	14.5	2.0	25.5	11.4	ES × T	1.48	12, 64	0.04
Złotoryja	36.8	5.6	33.2	5.3	40.7	8.0	39.8	2.1	47.7	9.6	B_{ES}	3.21**	16, 64	–
$av\Delta H$														
Kamienna Góra	8.9	1.2	7.9	0.8	9.0	0.4	10.0	1.2	11.0	1.2	ES	56.14***	3, 16	0.67
Międzylesie	6.6	1.0	6.0	0.3	6.6	0.6	9.6	1.0	7.9	0.6	T	24.04***	4, 64	0.15
Śnieżka	5.4	1.4	4.5	1.8	5.8	0.8	5.0	0.2	7.3	2.2	ES × T	1.05	12, 64	0.02
Złotoryja	9.9	0.9	9.0	0.7	10.6	0.6	10.8	0.5	12.2	1.4	B_{ES}	2.63***	16, 64	–
Survival rate (%)														
Kamienna Góra	84	7	80	9	80	7	85	12	90	4	ES	11.30***	3, 16	0.43
Międzylesie	66	14	49	24	67	9	55	27	71	31	T	6.92***	4, 64	0.10
Śnieżka	57	15	41	22	55	12	53	12	74	12	ES × T	0.86	12, 64	0.04
Złotoryja	83	7	77	8	89	4	86	3	90	7	B_{ES}	3.61***	16, 64	–

**$P < 0.01$; ***$P < 0.001$; ANOVA – analysis of variance; M – arithmetic mean; SD – standard deviation; *df* – degree of freedom; η^2 – effect size; 3/0, 3/0 Ns, 3/0 Sp, 2/1, 2/1 K – experimental treatments (T); $2y\Delta H$ – two-year height increment; $av\Delta H$ – overall average height increment; B_{ES} – block nested within experimental site; number of experimental units $N = 100$

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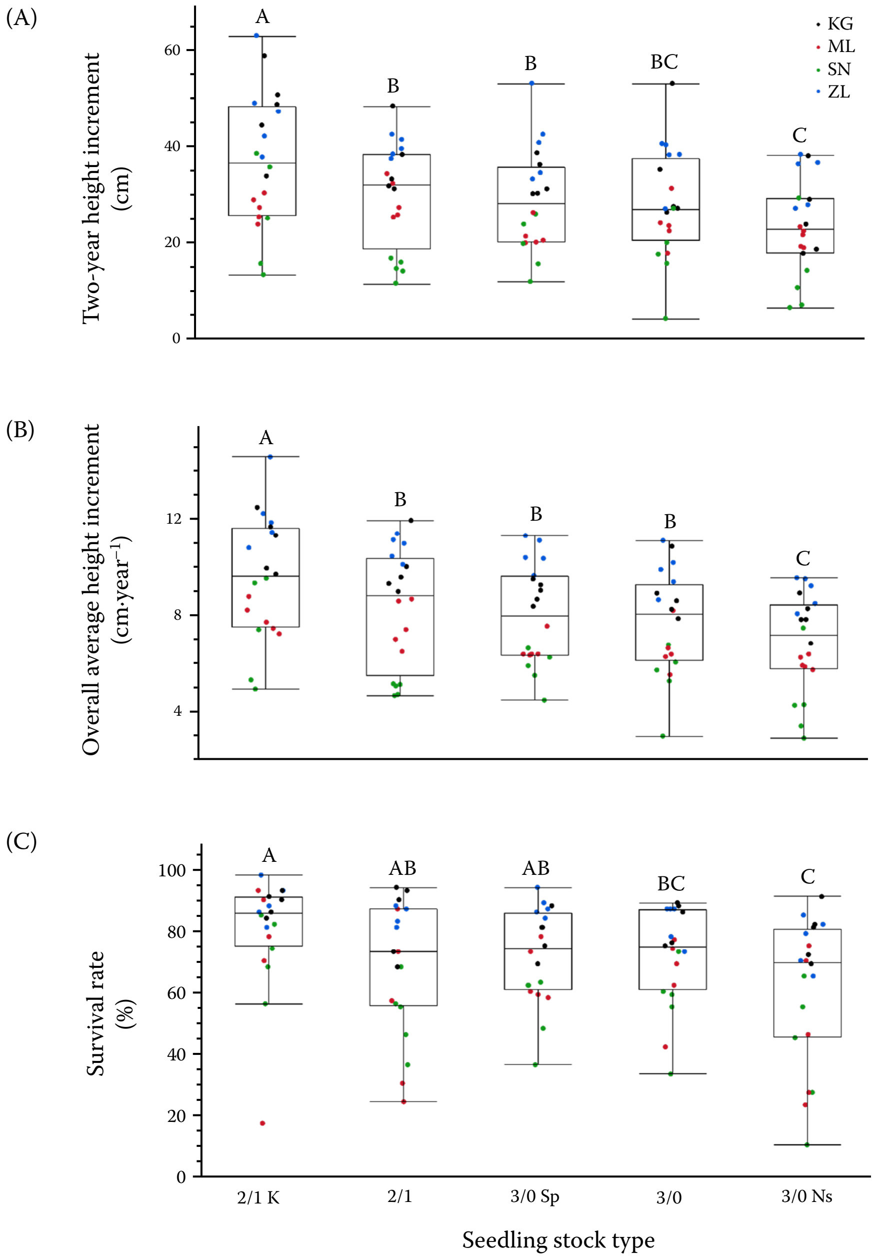

Figure 5. (A) Average two-year height increment of saplings, (B) overall height increment of saplings, and (C) survival rate of saplings

Each point represents the arithmetic mean for the experimental unit; boxes are quartile ranges with a median inside each box; the capital letter above the boxes indicates the results of the Tukey HSD test – levels not connected by the same letter are significantly different (α = 0.05); colours indicate experimental sites (KG – Kamienna Góra, ML – Międzylesie, SN – Śnieżka, ZL – Złotoryja); K – Kosterkiewicz containers; Sp – Scots pine; Ns – Norway spruce

Contrast analyses address our goal questions (Table 5). Saplings originating from a group of not transplanted seedlings (all 3/0) have underperformed compared to those that were transplanted (2/1 and 2/1 K). However, the differences between 3/0 and 2/1 stocks were not significantly different, except for the overall height increment, which showed a marginally significant effect. Nonetheless, the size effect is small enough to be negligible. No significant difference was found between saplings originating from a group of bare-root untransplanted seedlings (3/0, 3/0 Sp, 3/0 Ns), but those grown under Scots pine canopy performed significantly better than those grown

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Table 5. Results of analyses of contrasts (*F* statistics, *df* = 1, 64) for three performance features

Source of variation	Two-year height increment	Overall average height increment	Survival rate
3/0 & 3/0 Sp & 3/0 Ns *vs* 2/1 & 2/1 K	33.95***	61.21***	7.27**
3/0 *vs* 2/1	1.37	5.16*	0.53
3/0 *vs* 3/0 Sp & 3/0 Ns	1.36	1.15	2.63
3/0 Sp *vs* 3/0 Ns	9.10**	15.12***	8.36**
2/1 *vs* 2/1 K	14.73***	18.65***	9.41**

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; *df* – degree of freedom; Sp – Scots pine; Ns – Norway spruce; K – Kosterkiewicz containers

under a canopy of Norway spruce. When comparing both stocks that included transplantation during production, containerised (2/1 K) outperformed bare-root (2/1).

DISCUSSION

Our results do not fully support the first hypothesis that seedlings transplanted during production perform better than non-transplanted ones, as stock 2/1 performs similarly to 3/0. Notably, results indicate that saplings originating from containerised ones were taller and had higher survival rates than other seeding stocks, which aligns with the second hypothesis. Altogether, what stands out is that the abovementioned is true independently of site conditions, supporting the third hypothesis. Conversely, the second group of seedling stock types resulted in slower annual growth and lower survival rates. Consequently, we briefly discuss the implications of production methods concerning site conditions to identify the most adaptable seedling stock type for various environments.

Containerisation. According to the study of Robakowski et al. (2021), there were no differences in average height after planting at one of the four experimental sites following the first vegetative season. Saplings originating from container seedlings had greater root collar diameters than those originating from bareroot seedlings. Our study, based on material collected four years later (in 2021), indicated that the height of saplings originating from container technologies grew faster, achieving an average of 76.9 cm (2/1 K), compared to bareroot saplings, which ranged from 54.9 cm to 66.8 cm (Table 3). Moreover, this effect is noticeable independently of the site conditions. Hence, the study by Grossnickle and El-Kassaby (2016) provides convincing evidence that although bareroot seedlings are initially taller, container seedlings exhibit faster growth. This finding is also applicable to the case of *A. alba*. The survival rate remained similar between the two stock types until the last inventory, when saplings originating from containerised seedlings (2/1 K) showed 10% greater survival than the others. From an economic perspective, this observation is significant because any compensating plantings are costly. This is due to the fact that competing plants begin to grow with increased light availability. In other words, planting when weeds are abundant incurs higher costs.

Structural root attributes are crucial for tree survival in providing adequate water and minerals for growing shoots. Our study found that seedlings originating from containerised stock exhibited lower mortality rates and a higher rate of shoot establishment, suggesting that this seedling stock performs better and establishes root-soil relationships more rapidly. Faster shoot growth rate and generally greater size are attributed to better concentration and root growth potential (Trubat et al. 2010; Villar-Salvador et al. 2012; Mariotti et al. 2015). Conversely, the shorter shoot system observed in other seedling stock types suggests that these seedlings may be experiencing water shortage and allocate assimilates to overcome water stress, as Struve and Joly (1992) and Grossnickle (2012) noted. Although, unfortunately, we did not measure the root distribution in the soil profile as it may vary significantly among sites and depends on experimental treatment, the proper development of taproots and vertical growth of lateral roots in Kosterkiewicz containers finds support in the work of Kosterkiewicz (1991), low variability explained by block factor (4.5–17.6%) underlies that seedling growth may be attributed to the stock type characteristics. This predicts a more profound root occurrence than other seed-

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ling production methods, enabling better access to water sources (Zadworny et al. 2014). Accordingly, differences in shoot growth rate among seedlings of different stock types were primarily due to the regeneration technique applied, as production methods that alter the development of plants can impact their susceptibility to stress (Grossnickle 2012). Seeding survival also appears to be influenced by site conditions or density (Barnard et al. 1995). The impact of initial density was minimised by setting it to the same level at each experimental site. Hence, in our study, survival was related to the seedling stock types, concerning high variability explained by the site conditions (Table 4; Figure 5C). Our results align with those from the study by South et al. (2005), who found that container-grown seedlings survive better than other stock types, even though we do not know the initial plant biomass allocation among seedling stocks. When comparing different regeneration methods, we found an 8–19% higher survival rate in containerised stock than bare-root, regardless of sites.

Transplanting in the nursery. When plants are transplanted from the nursery to field conditions, they experience stress while adjusting to new light levels. This process significantly affects photochemical efficiency, especially among different seedling stock types (Robakowski et al. 2021). Although we observed greater biomass allocation to the shoot system, it is essential to note that this does not necessarily imply light is the limiting factor. In sites suitable for silver fir growth, minimal variation in light availability is expected due to topographical similarities. Replanting is the treatment applied in a nursery, which increases the growing space of seedlings. In effect, greater growing space decreases individual competition and usually promotes the roots' growth. On the other hand, the transplanting treatment generates additional costs. Other studies concerning this treatment produced ambiguous results on the production of silver fir seedlings. For instance, Barzdajn and Kuczkowski (2010), in an observational study of 191 planting sites in the Szklarska Poręba Forest District, compared three-, four- or five-year-old seedlings treated or not with transplanting. They indicated that three-year-old seedlings without transplanting and four-year-old seedlings transplanted after the first or the second year production cycle performed the best when sapling height was taken as a performance indicator. A similar analysis in the Zdroje Forest District, where 110 planting sites were compared, indicated that both three-year-old seedlings without transplanting and four-year-old seedlings with transplanting were better than average. However, saplings originating from Kosterkiewicz containers (2/1 K) performed best (Nicałek 2018). In our study, independently of the site conditions, both applied technologies employing the transplanting after the second year during the seedling production, i.e. 2/1 K (seedlings in Kosterkiewicz containers) and 2/1 (bareroot seedlings), showed the highest survival rate and the most outstanding growth performance expressed by growth in height. In particular, when the abovementioned technologies were compared, the former showed significantly better scores. It is precisely in line with the early results we obtained after the first and the second vegetative seasons in the experimental site in the Śnieżka Forest District (Robakowski et al. 2021).

Implications for restitution programs. Successful tree reintroduction relies on selecting seedling stock that provides optimal conditions for seedling growth. Consequently, the choice of seedling stock type significantly impacts seedling survival and growth after field planting (South et al. 2005), resulting from container volume, fertilisation, and water regimes specific to particular species during nursery cultivation (Pinto et al. 2011). While seedling production costs are higher in containerised nurseries than bare-root systems, several advantages can compensate for these costs. Containerised seedlings have higher survival rates and lower seedling mortality than bare-root seedlings. However, it is essential to recognise that the stock production system and the balance of biomass allocation between aboveground and belowground organs are critical factors for plant development and the overall success of any restitution program (Poorter et al. 2012a, b; Mariotti et al. 2015). Ensuring high-quality seedlings that enable better field growth on low-quality sites – through optimal nursery practices – is a critical factor in recognising the success of restitution programs under specific conditions (Pinto et al. 2011; Grossnickle, El-Kassaby 2016), although initially, the production of silver fir seedlings is more costly than other species. *A. alba* seedlings originating from specific containers exhibited better growth than those obtained from other production sys-

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tems, regardless of site conditions. Considering that a great part of this trait variability was explained by site conditions, improved growth of this seedling stock, regardless of the site, may be attributed to their widespread enhanced adaptation and resistance, thanks to nursery culturing methods. As discussed earlier, seedlings subjected only to transplanting (e.g. 2/1 stock type) performed comparably to those that were not transplanted (i.e. 3/0). This implies a balance between the time required for root and shoot development and the ability of containerised seedlings to meet the silver fir growth demands (Dobrowolska et al. 2017). The enhanced shoot growth observed in our study underscores the importance not only of increased growing space provided by transplanting but also of substrate addition, which likely promotes root system development.

We can tailor specific materials to various sites by using diverse seedling stock. Differences in shoot growth can be attributed to various nursery procedures. The next step would involve testing our seedling stocks in areas outside the current species range, potentially for silver fir reintroduction under ongoing climate conditions. Choosing containers like those proposed by Kosterkiewicz (1991) – cheap and environmentally friendly materials promoting appropriate root distribution – may be a good alternative to plant seedlings well-equipped to withstand ongoing climate changes.

The study results highlight the most challenging growth phase after artificial regeneration, known as a seedling shock (Close et al. 2005), which occurs when seedlings transition from the favourable conditions of the nursery to a harsher field environment. It is premature to make definitive conclusions about the best-performing seedling stock types five years post-planting. Our previous research on the performance of bare-root and containerised stocks of Scots pine compares height growth and survival rate after ten years of planting (Barzdajn, Kowalkowski 2016). We found that bare-root stocks perform similarly to containerised under favourable moisture conditions. Under harsh conditions, the superior initial attributes of containerised seedlings provided an advantage. However, if initial stress occurred, its effects were still visible after ten years. We can only hypothesise that the trends observed in our study will continue in the coming years. Therefore, we plan to continue monitorin all four experimental sites.

CONCLUSION

Unsustainable forest management irremediably depleted the tree species composition in the stands of the Sudety Mountains. Our experimental site selection focuses on regions within the historical range of the silver fir. This allows us to interpret the impacts of different seedling stocks on future stands, considering the species' limited natural migration capacity. Planting is essential to restore the silver fir, a crucial component of upland forests. We demonstrated that containerised seedlings have the highest survival rate and height growth among the five tested technologies in various site conditions. If there are no conditions for the production of containerised seedlings, transplanting may be omitted, and conventional production can be recommended as the second-best choice, e.g. three-year-old seedlings (3/0 stock).

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