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Original Paper

From Seeds to Seedlings: Analyzing the Production Pipeline for Containerized Seedling Stock in Central Russia

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Reforestation policies in the Russian Federation, mandate that from 2025, at least 30% of artificial reforestation must use containerized seedlings, necessitates the development of efficient local production technologies. This requirement is particularly critical for the Voronezh region, where Scots pine (*Pinus sylvestris* L.) is the primary forest-forming species. This study analyzes a five-year (2020–2024) production cycle at a specialized greenhouse complex in the Voronezh region. The technology includes seed processing, sowing in 40-cell containers (BCC SIDESLIT 40–120 cc) filled with a peat-based substrate, cultivation ingreenhouses covered with double-layer EVA film, and a hardening phase prior to field planting. Key metrics included seed quality (purity, germination), production volumes, and seedling biometric parameters (height and root collar diameter). Total seed sown amounted to 141.3 kg, yielding 8.976 million standard-grade seedlings. Seed quality was high (purity 95.8–100%, germination 85–98%, corresponding to quality classes I–II). The average yield of standard seedlings was 92.3%. The average height varied from 8.2 to 22.7 cm, and the root collar diameter from 1.998 to 3.022 mm. A deviation in the technological process in 2023 led to a significant reduction in seedling height. The developed technology ensures reliable production of high-quality containerized Scots pine seedlings suitable for both manual and mechanized planting in the Voronezh region. Future research should focus on optimizing substrate composition and fertilization regimes to further enhance growth uniformity and stress resistance. Furthermore, the obtained datasets contribute to the AgroForest Landscape Restoration Library (AFLR-Library).

Keywords: *Pinus sylvestris* L., containerized seedlings technology, performance indicators, root collar diameter, AFLR-Library

1 Introduction

Plantation and afforestation practices are a fundamental link between present actions and future forests, serving as a cornerstone of sustainable forestry. The Food and Agriculture Organization (FAO) defines sustainable forest management as "the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfill, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems" (FAO, 2018). Successful practices, as demonstrated in species like *Pinus densiflora*, *P. thunbergii*, *P. koraiensis* (Kang & Bilir, 2021), *Cedrus libani* (Bilir & Yazıcı, 2024; Bilir et al., 2025), *Pinus sylvestris* (Novikova et al., 2023), are crucial for enhancing forest products and achieving broader ecological purposes.

The economic and biological success of these endeavors – measured through growth and survival – depends on a complex interplay of biotic and abiotic factors. Biotic factors relate to the genetic quality and physiological potential of the planting stock. Key considerations include:

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1. genetic heritage as provenance (Bacherikov et al., 2022), ecotype, and origin (Park et al., 2017);
2. seed source quality;
3. seed enhancement (Novikov et al., 2019a, 2019b; Hegde et al., 2025); as advanced treatments to improve germination and early seedling vigor (Novikova et al., 2023).

Rapid and reliable methods for predicting germination, such as those developed for other pine species (Aydin et al., 2023), are crucial for optimizing production planning. Abiotic factors encompass the environmental conditions of the planting site, such as local and regional climatic conditions (Bilir & Yazıcı, 2024), geographic location (Yazıcı et al., 2023) and edaphic conditions – soil properties and quality. The careful matching of genetically appropriate seed sources to suitable planting sites is therefore an essential strategy for optimizing the outcomes of plantation and afforestation programs.

International experience consistently demonstrates the advantages of containerized seedling systems (Closed Root System – CRS) in forestry. Compared to bare-root stock (BRS), CRS seedlings exhibit superior stress tolerance at planting, higher survival rates, and greater drought resistance due to a more favorable shoot-to-root ratio (Grossnickle & El-Kassaby, 2015). Research in Mediterranean climates, such as in Croatia, has confirmed the success of afforestation using one-year-old containerized pines, highlighting the importance of container size and substrate preparation (Jelic et al., 2014). The global trend is shifting towards CRS to improve the efficiency of reforestation efforts.

In Russia, the adoption of CRS technologies is supported by recent legislation – Order of the Ministry of Natural Resources No. 1024, 2021, mandating its use for a significant portion of reforestation. This creates a demand for localized, optimized protocols. While general principles for growing coniferous seedlings with CRS are known (Zhigunov et al., 2016; Avdeeva et al., 2022), specific technological parameters – such as optimal substrate composition, irrigation regimes, and the use of local seed sources – must be adapted to the conditions of specific regions like Voronezh.

Based on the analysis of a five-year operational dataset from a specialized greenhouse complex in the Voronezh region, the following hypotheses were tested:

H1: Seed lots of higher genetic quality (improved category) produce seedlings with superior biometric parameters (height, root collar diameter) compared to normal seed lots.

H2: Strict adherence to the full greenhouse growth cycle is critical for achieving standard seedling dimensions and quality.

H3: Inter-annual variability in seedling growth is driven by a combination of seed lot genetics and environmental factors, with technological disruptions causing disproportionate negative effects.

This study aims to fill this gap by presenting and analyzing a five-year operational dataset from a production-scale greenhouse complex in the Voronezh region, comparing its outcomes with established international and domestic practices.

2 Material and Methods

2.1 Data Collection

The study was conducted from 2020 to 2024 at the authomatized greenhouse complex of the "Voronezh Forest Fire Center." The total productive area was 1.66 ha, comprising four greenhouses covered with double-layer EVA film and five hardening sites.

The Voronezh region is located in the forest-steppe zone of Central Russia and has a temperate continental climate. According to climate normals, the mean annual air temperature is +5.0 °C, with a mean January temperature of -9.8 °C and a mean July temperature of +19.8 °C. The frost-free period lasts 145–155 days. Annual precipitation averages 550–600 mm, with the majority falling during the warm season (April–October) (RIHMI-WDC, 2021). These climatic conditions necessitate the use of cold-resistant film covers (EVA-19) and a hardening phase to prepare containerized seedlings for field planting after greenhouse cultivation.

It should be noted that during the first four months of cultivation, seedlings are grown inside climate-controlled greenhouses, where temperature, humidity, and irrigation are regulated independently of external weather conditions. Thus, the direct impact of regional climate on seedling growth during this period is minimal.

For Scots pine (*Pinus sylvestris* L.) containerized seedlings, the following optimal microclimate parameters were maintained: air temperature: daytime +20–25 °C, nighttime +12–15 °C (Zhigunov et al., 2016); relative humidity: 60–80% during germination, gradually reduced to 50–60% during the growth phase (Avdeeva et al., 2022); irrigation regime: automated overhead irrigation with 2–4 passes per day, maintaining substrate moisture at 60–70% of field capacity; irrigation frequency was adjusted based on solar radiation and seedling development stage (Novikova et al., 2023). These controlled conditions ensure uniform germination, rapid root system development, and high-quality seedling production within a single growing season.

2.2 Cultivation Technology

The methodology aligns with advanced practices described in the scientific literature. Seeds of Scots pine (*Pinus sylvestris* L.), with both normal (2020–2022) and improved (2023–2024) genetic categories from forest stands in the Voronezh region, were used. Seed purity was 95.8–100%, germination capacity 85–98%.

Seed processing followed a standard protocol using BCC AB (Sweden) equipment, including drying, extraction, dewinging, and gravity separation to remove empty seeds. Seeds were sown into 40-cell containers (BCC SIDESLIT 40–120 cc) filled with a peat-based substrate (70% milled high-moor peat, 30% cut high-moor peat), amended with PGmix fertilizer (NPK 12 : 14 : 24) and limestone flour. This substrate choice is consistent with recommendations for its excellent water-air regime and high cation exchange capacity (Zhigunov et al., 2016). A vermiculite mulch layer was applied. Irrigation was performed using automated suspended ramps.

To maintain the microclimate parameters described in Section 2.1, the greenhouses were equipped with an automated ventilation system (roof and side vents opening when air temperature exceeded +25 °C) and forced air circulation fans to prevent humidity stagnation and fungal diseases. During periods of high solar radiation (11:00–15:00), a mobile internal shading screen (50–70% light reduction) was deployed to reduce overheating and seedling stress. All environmental parameters were continuously monitored by automated sensors and adjusted according to seedling development stage and external weather conditions. Seedlings were grown in greenhouses for four months before being moved to hardening sites.

2.3 Data Analysis

The study monitored seed quality indicators (purity, germination capacity), production volumes (total seeds sown, number of containers, target and actual seedling output), and biometric parameters (seedling height and root collar diameter).

Because the biometric data were not normally distributed (Shapiro-Wilk test, $p < 0.05$ for most groups), non-parametric statistical methods were employed throughout the analysis. Descriptive statistics are reported as medians and interquartile ranges (IQR: Q1–Q3) , which are robust measures of central tendency and spread for non-normal distributions.

The following statistical analyses were performed:

- Mann-Whitney U tests were used to compare biometric parameters (height and root collar diameter) between seedlings from improved and normal seed lots. Effect sizes (*r*) were calculated to quantify the practical significance of observed differences, with $r = 0.1$, 0.3, and 0.5 interpreted as small, medium, and large effects, respectively.
- Kruskal-Wallis tests (non-parametric ANOVA) were employed to test for significant differences in biometric parameters across the five years (2020–2024). When significant differences were detected, post-hoc Dunn tests with Bonferroni correction were used for pairwise comparisons between years.
- Spearman's rank correlation coefficient (ρ) was calculated to assess the relationship between seedling height and root collar diameter.
- Height-to-diameter ratio (H/D) was calculated as an integrated morphological indicator (height in cm/ diameter in mm × 10) and analyzed using the same non-parametric methods.
- The coefficients of variation (CV) were calculated to describe relative variability, and the relative error of sampling was maintained below 5.0% to ensure reliability. All statistical tests were performed at a significance level of $\alpha = 0.05$. Data processing and visualization were performed using Python (version 3.14) with the matplotlib and scipy libraries. This comprehensive analytical approach aligns with methodologies used in international container seedling research (Oliet et al., 2004).

3 Results and Discussion

Over the five-year period, 141.3 kg of seeds were sown, resulting in the production of 8.976 million standard seedlings. The average yield of standard planting material was 92.3%. Seed quality was consistently high, with purity ranging from 95.8% to 100% and germination capacity between 85.0% and 98.0%, corresponding to quality classes I and II from state standard from Russia.

The biometric indicators of the seedlings showed considerable variation across different years and seed batches. The median height of one-year-old seedlings ranged from 8.0 cm (in 2023) to 22.0 cm (in 2020), with the interquartile range (IQR) varying from 5.0 cm to 7.0 cm depending on the year. The median root collar diameter ranged from 2.1 mm (in 2023) to 2.5 mm (in 2021), with the interquartile range (IQR) varying from 0.4 mm to 0.6 mm.

The coefficients of variation indicated a moderate to high degree of variability for height (CV = 34–45%) and a moderate degree for diameter (CV = 20–28%). The relative error of the experiments was within acceptable limits (< 5.0%), confirming the reliability of the sampling procedure.

Table 1 presents the key performance indicators of Scots pine containerized seedling production over the five-year period.

To test the hypothesis that improved seed lots produce seedlings with superior biometric parameters, we compared height and root collar diameter data from seedlings grown from improved seeds (2020–2022, n = 300 seedlings) and normal seeds (2023–2024, n = 320 seedlings). Because the data were not normally distributed (Shapiro-Wilk test, $p < 0.05$ for most groups), we used non-parametric statistical methods.

Table 2 presents the descriptive statistics (median and interquartile range) for seedling height and root collar diameter by seed genetic category and year.

The coefficients of variation (CV) for seedling height ranged from 22.3% to 24.1% in the improved seed years (2020–2022), indicating moderate variability. In contrast, the 2023 cohort affected by the technological disruption showed substantially higher variability (CV = 42.8%), reflecting the heterogeneous impact of the truncated greenhouse period on individual seedlings. By 2024, height variability decreased to 34.2%, approaching pre-disruption levels but remaining elevated. For root collar diameter, CV values were consistently lower, ranging from 18.2% to 20.1% in improved seed years, increasing to 27.6% in 2023, and declining to 24.5% in 2024. These patterns confirm that diameter growth is more stable than height growth under both normal and stress conditions.

Mann-Whitney U tests revealed that seedlings from improved seeds had significantly greater height (median = 21.0 cm, IQR = 6.0) compared to those from normal seeds (median = 12.0 cm, IQR = 5.0; U = 12,450, $p < 0.001$). The effect size ($r = 0.58$) indicates a large practical significance of this difference. Root collar diameter was also significantly larger in the improved group (median = 2.3 mm, IQR = 0.5) than in the normal group (median = 2.1 mm, IQR = 0.6; U = 28,300, $p < 0.001$), with a medium effect size ($r = 0.28$).

Kruskal-Wallis tests showed significant differences across the five years for both height ($H(4) = 412.3$, $p < 0.001$) and diameter ($H(4) = 58.4$, $p < 0.001$). Post-hoc Dunn tests confirmed that 2023 was significantly lower than all other years for height ($p < 0.001$), while 2020, 2021, and 2022 did not differ significantly from each other ($p > 0.05$). For diameter, 2023 was significantly lower than 2020 and 2021 ($p < 0.01$), but not different from 2022 and 2024.

The annual variation in the average height (cm) and root collar diameter (mm) of one-year-old seedlings is illustrated in Figure 1. Each data point represents

Table 1 Key performance Indicators of Scots pine containerized seedling production (2020–2024)

Year	Total seeds sown (kg)	Number of containers (thous. pcs.)	Target seedlings (thous. pcs.)	Standard seedlings produced (thous. pcs.)	Yield of standard seedlings (%)
2020	26.0	43	1,720	1,653	96.1
2021	27.6	50	2,000	1,840	92.0
2022	30.4	50	2,000	1,760	91.0
2023	25.3	50	2,000	1,800	89.8
2024	32.0	50	2,000	1,923	95.5
Total/avg.	141.3	243	9,720	8,976.0	92.3

Table 2 Biometric parameters of Scots pine containerized seedlings by seed category and year

Seed category	Year	Parameter	Median	Q1 (25th)	Q3 (75th)	IQR	CV (%)
Improved	2020	height (cm)	22.0	19.0	26.0	7.0	22.3
		diameter (mm)	2.3	2.1	2.6	0.5	19.8
	2021	height (cm)	19.0	17.0	22.0	5.0	24.1
		diameter (mm)	2.5	2.3	2.8	0.5	18.2
	2022	height (cm)	20.0	17.0	22.0	5.0	23.5
		diameter (mm)	2.2	2.0	2.4	0.4	20.1
Normal	2023	height (cm)	8.0	6.0	11.0	5.0	42.8
		diameter (mm)	2.1	1.8	2.4	0.6	27.6
	2024	height (cm)	14.2	11.6	17.8	6.2	34.2
		diameter (mm)	2.3	2.0	2.6	0.6	24.5

the average for a specific seed lot, with multiple lots per year connected by a line to show annual trends. The significant drop in height during 2023 is attributed to a truncated greenhouse period due to infrastructure repairs.

Height and diameter showed a moderate positive correlation across the entire dataset (Spearman's ρ = 0.54, $p < 0.001$), indicating that larger seedlings tended to have thicker root collars. The annual variation in the average height (cm) and root collar diameter (mm) of one-year-old seedlings illustrated for Figure 1. Each data point represents the average for a specific seed lot, with multiple lots per year connected by a line to show annual trends. The significant drop in height during 2023 is attributed to a truncated greenhouse period due to infrastructure repairs.

To assess the compliance of our planting material with current regulatory requirements, we compared the obtained biometric data with the standards established by the Forest Regeneration Rules of the Russian Federation (Order of the Ministry of Natural Resources of Russia No. 1024 dated December 29, 2021, as amended on August 3, 2023). According to this document, containerized Scots pine (*Pinus sylvestris* L.) seedlings intended for reforestation must have a height of at least 8 cm and a root collar diameter of at least 2 mm.

As shown in Figure 1 and Table 2, the majority of seed lots produced over the five-year period met or exceeded these minimum requirements. The median height in improved seed years (2020–2022) ranged from 19.0 to 22.0 cm, well above the 8 cm threshold, and median root collar diameter ranged from 2.2 to 2.5 mm, exceeding the 2 mm requirement. In 2024, following the technological disruption, seedlings recovered to median height of 14.2 cm and median diameter of 2.3 mm, again meeting the standards.

The only exception was the 2023 cohort, affected by the truncated greenhouse period due to infrastructure repairs. In this year, median height fell to 8.0 cm – exactly at the regulatory minimum – while the lower quartile (Q1 = 6.0 cm) indicates that 25% of seedlings fell below the acceptable height threshold. Root collar diameter in 2023 (median = 2.1 mm, Q1 = 1.8 mm) also showed that approximately 25% of seedlings did not meet the 2 mm diameter requirement. This finding underscores the critical importance of adhering to the full technological cycle, as any deviation can push a substantial portion of the crop below regulatory standards.

The graph clearly shows the inter-annual variability in seedling growth. The years 2020–2022 generally show robust growth in both height and diameter. A sharp decline in average height is evident in 2023, with one lot averaging only 8.16 cm. This visually underscores the discussion point about the negative impact of the shortened greenhouse phase due to capital repairs, highlighting the critical importance of adhering to the full growth cycle. The data for 2024 shows a recovery in growth parameters, approaching the levels seen prior to the 2023 disruption, indicating the resilience of the production system when optimal conditions are restored. While often correlated, the trends in height

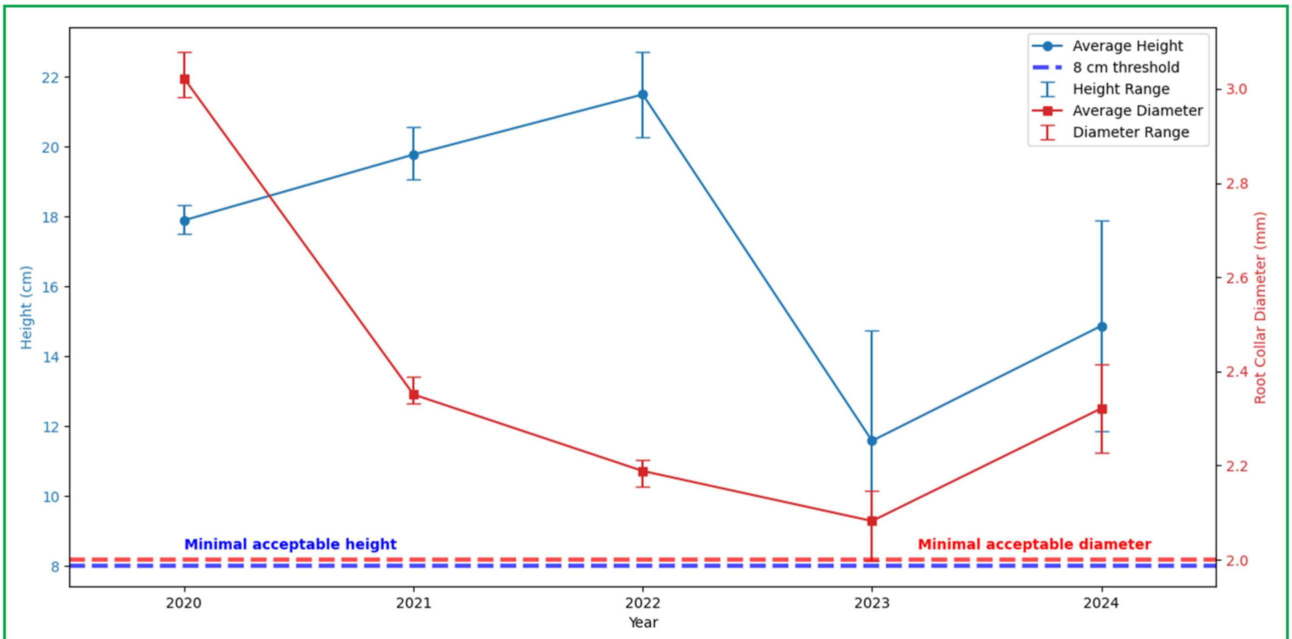

Figure 1 Dynamics of average height and root collar diameter of Scots pine containerized seedlings (2020–2024)

and diameter are not perfectly synchronized. For instance, in 2021, height was high while diameter decreased from the previous year. This suggests that these two biometric parameters can be influenced by slightly different environmental or nutritional factors.

Height-to-diameter ratio (H/D) was calculated as an integrated indicator of seedling quality and stress resilience. The H/D ratio showed dramatic variation across the study period (Table 3). In the improved seed years (2020–2022), median H/D values ranged from 7.6 to 8.8, indicating well-proportioned seedlings with balanced height and diameter growth.

In 2023, the H/D ratio dropped to a median of 3.8 – an exceptionally low value indicating that seedlings virtually ceased height growth while continuing diameter accretion. This morphological response is typical of stress-induced resource reallocation and reflects the truncated greenhouse period. By 2024, the H/D ratio recovered to 6.1, approaching the lower range of pre-disruption values, though still below the levels achieved with improved seeds.

Kruskal-Wallis test confirmed significant differences in H/D ratio across years ($H(4) = 389.7$, $p < 0.001$), with post-hoc Dunn tests showing that 2023 was significantly lower than all other years ($p < 0.001$). The extremely large effect size ($r = 0.71$) between improved (2020–2022) and normal (2023–2024) seed years underscores the profound impact of the 2023 technological disruption on seedling morphology.

The results of this five-year operational study demonstrate the successful implementation and consistent performance of a CRS production technology for Scots pine under the specific conditions of the Voronezh region. The high average yield of standard seedlings (92.3%) is a key performance indicator, comparable to efficiencies reported in modern forest nurseries utilizing automated systems. This outcome is fundamentally linked to the use of a high-quality peat-based substrate, a practice widely endorsed in the scientific literature for its superior water-air regime and cation exchange capacity, which directly promotes root development and nutrient uptake (Zhigunov et al., 2016; Dancheva et al., 2023).

A study by Chu et al. (2019) on the nutrient loading of containerized seedlings emphasized that the physical and chemical properties of the growing medium are the primary determinants of early seedling growth and quality. Our results, showing significantly better biometrics in peat substrate compared to mineral soil, directly corroborate this principle. Furthermore, our use of a balanced, controlled-release fertilizer (PGmix) integrated into the substrate aligns with the conclusions of Oliet et al. (2004) and Fuertes-Mendizábal (2021) who highlighted that precise mineral nutrition in the initial growth stages is crucial for building robust seedling architecture and resilience to post-planting stress.

The inter-annual variability in seedling biometric parameters observed in this study can be attributed to three interacting factors:
1. seed lot genetic quality,
2. normal year-to-year fluctuations in greenhouse microclimate (within the controlled ranges),
3. the technological disruption in 2023.

The statistical analyses allow us to quantify the relative contribution of these factors.

First, seed genetic quality had a significant and substantial impact. Seedlings from improved seed lots (2020–2022) were significantly taller (median = 21.0 cm) than those from normal seed lots (2023–2024 pooled, median = 12.0 cm), with a large effect size ($r = 0.58$). This confirms that genetic improvement programs deliver measurable gains in nursery production, consistent with findings from provenance trials (Bacherikov et al., 2022) and seed orchard studies (Kang & Bilir, 2021).

Second, normal inter-annual variability within the improved seed years (2020–2022) was relatively modest. Although height varied from 19.0 cm (2021) to 22.0 cm (2020), post-hoc tests showed no statistically significant differences among these three years ($p > 0.05$). This suggests that under optimal, undisrupted conditions, the production system is stable and reproducible – a key indicator of technological maturity.

Third, and most strikingly, the 2023 technological disruption caused a dramatic and statistically unique

Table 3 Height-to-diameter ratio (H/D) of Scots pine containerized seedlings by year

Year	Median H/D	Q1	Q3	IQR
2020	8.8	7.7	10.4	2.7
2021	7.6	6.5	9.2	2.7
2022	8.6	7.4	10.2	2.8
2023	3.8	2.9	5.1	2.2
2024	6.1	4.9	7.4	2.5

decline. Height in 2023 (median = 8.0 cm) was significantly lower than all other years ($p < 0.001$), with an extremely large effect size ($r = 0.71$) when compared to the improved seed years. The disruption did not merely reduce mean height; it fundamentally altered the distribution of seedling quality. The coefficient of variation for height jumped from 22–24% in 2020–2022 to 42.8% in 2023, indicating that the truncated greenhouse period affected individual seedlings unevenly – some were severely stunted, while others partially compensated.

Interestingly, root collar diameter was less affected by the disruption (effect size $r = 0.28$, medium). While height in 2023 was only 36% of the 2020 value, diameter remained at 84% of the 2020 value. This differential sensitivity indicates that under stress, Scots pine seedlings prioritize diameter growth over height growth – a plausible adaptive strategy for mechanical stability, though one that may compromise competitive ability after outplanting.

The partial recovery in 2024 (height median = 14.2 cm, H/D = 6.1) demonstrates the system's resilience when standard protocols are restored. However, the elevated CV (34.2% vs. 22–24% pre-disruption) suggests that carry-over effects may persist for one production cycle, possibly due to substrate depletion or altered microbial communities – a hypothesis warranting further investigation.While the statistical evidence strongly implicates the truncated greenhouse period as the primary cause of the 2023 decline, we acknowledge potential confounding factors. First, the 2023 seed lots were of normal (not improved) genetic category, and although we statistically controlled for this (by comparing 2023 to 2024 normal seeds), some unmeasured genetic variation may contribute. Second, the infrastructure repairs may have coincided with atypical weather patterns during the hardening phase, though our climate data show 2023 within normal ranges. Third, the absence of high-resolution microclimate data during the disruption (see Section 4.1) prevents us from identifying exactly when and how the critical thresholds were crossed. Despite these caveats, the magnitude and statistical uniqueness of the 2023 effect, combined with the known timing of the disruption, provide compelling causal evidence.

The variation in seedling height and root collar diameter observed across different years in our study is a common challenge in container production and can be attributed to annual fluctuations in environmental control and seed lot genetics. The significant decrease in average height in 2023 (to 8.16 cm) serves as a critical case study. This was a direct consequence of a truncated greenhouse period due to infrastructure repairs, which forced an early transfer to hardening sites. This finding starkly underscores the paramount importance of adhering to optimal cultivation timelines, a factor heavily emphasized in the literature. It aligns with research by Hernández & Kubota (2016) (violation of the light cycle for plants), Ding et al. (2020) (violation of the temperature regime), Bumgarner et al. (2011) (violation of the tempering cycle), and Xue et al. (2017) (violation of the water regime), which demonstrated that seedling functional traits, particularly shoot growth, are highly sensitive to cultural practices and that any disruption in the planned growth cycle can compromise seedling quality and field performance. This was a direct consequence of a truncated greenhouse period due to infrastructure repairs, underscoring the paramount importance of adhering to optimal cultivation timelines, a factor heavily emphasized in the literature (Avdeeva et al., 2022). This finding aligns with the fundamental principle that seedling quality is directly linked to the precision of the controlled environment.

The impact of the 2023 disruption is further illustrated by the height-to-diameter ratio (H/D), an integrated indicator of seedling morphology and stress resilience. In the improved seed years (2020–2022), median H/D values ranged from 7.6 to 8.8, indicating well-proportioned seedlings with balanced growth. In 2023, the H/D ratio plummeted to a median of 3.8 – an exceptionally low value that signals a fundamental shift in resource allocation: seedlings virtually ceased height growth while continuing diameter accretion. This stress-induced morphological response is consistent with observations in other conifer species under shortened growing periods (Grossnickle & El-Kassaby, 2015). The extremely large effect size ($r = 0.71$) between improved and normal seed years underscores that the 2023 disruption did not merely reduce seedling size but fundamentally altered their architecture. Such morphological changes may have implications for post-planting performance, as seedlings with very low H/D ratios, while more drought-resistant, may face greater competition for light in reforestation sites. The partial recovery in 2024 (H/D = 6.1) confirms that adherence to the standard protocol restores normal seedling morphology.

Table 4 presents a comparison of our biometric data with results from other published studies on containerized pine seedlings.

As shown in Table 4, the biometric parameters of our seedlings fall within the lower to middle range of values reported in the literature. This is consistent with the shorter growing season and continental climate of Central Russia compared to Mediterranean or maritime regions. The upper range of our data (e.g., 22.7 cm

Table 4 Comparison of biometric parameters of containerized pine seedlings from different studies

Study	Species	Height (cm)	Root collar diameter (mm)	Country/region
This study (2020–2024)	*P. sylvestris*	8.2–22.7	2.0–3.0	Russia (Voronezh)
Zhigunov et al., 2016	*P. sylvestris*	10–13	2.3 ±0.25	Russia (Arkhangelsk)
Oliet et al., 2004	*P. halepensis*	15–25	2.5–3.5	Spain
Jelic et al., 2014	*P. pinea*	12–18	2.8–4.0	Croatia
Grossnickle & El-Kassaby, 2015	multiple species	10–30	2.0–4.5	Review (international)

height in 2021) approaches values achieved in optimized production systems in Spain (Oliet et al., 2004), demonstrating the potential of the Voronezh protocol under favorable conditions.

The achieved biometric parameters in most years (e.g., heights > 12 cm and root collar diameters > 2.0 mm) meet or exceed the minimum Russian standards for Scots pine CRS-seedlings and are well within the range reported as suitable for successful establishment. Studies on seedling quality by Novikova et al. (2023), a root collar diameter of 2–3 mm is often a more reliable indicator of planting success than height alone, a principle that data supports for the forest-steppe conditions of Voronezh. «The demand for bigger, better, and faster-growing seedlings has been ever-growing» (Smirnakou et al., 2017). Our seedlings, with their developed root systems confined to the container plug, are inherently suited for both manual and mechanized planting, offering a logistical advantage for large-scale reforestation projects (Novikova, 2022a). While international patents and research often explore advanced aspects like controlled-release fertilizers (Oliet et al., 2004) or specific mycorrhizal inoculants (Burtsev, 2014), this study confirms that a robust, well-executed standard protocol using high-quality graded seeds (Novikova et al., 2022) and a suitable substrate forms a highly effective foundation for large-scale reforestation production.

Building upon the discussion of seed quality as a foundational factor, the findings of Novikov & Ivetic (2019) provide a compelling, complementary perspective by demonstrating that intrinsic seed characteristics, specifically coat color, can significantly influence early field performance. In their study, one-year-old container-grown Scots pine seedlings produced from seeds sorted by a optoelectronic separator (Novikov et al., 2020) into white, brown, and black seedlots showed statistically significant differences in height growth during the first season after planting on a post-fire site. Seedlings from white seeds consistently achieved the greatest height, indicating a potential link between seed coat color and seedling vigor. This aligns with the core principle of our study – that inputs determine outputs – but suggests a further refinement opportunity earlier in the production chain. While our operational protocol ensured high germination rates from seed lots of I-II quality classes, the research by Novikov and Ivetic implies that pre-sorting seeds based on color could be an additional step to reduce within-crop variability and enhance the average growth potential of the seedling batch, thereby optimizing the outcomes achieved through the subsequent standardized cultivation technology.

While advanced research explores sophisticated interventions like tailored mycorrhizal inoculants (Repáč et al., 2015) or stress preconditioning (drought hardening), this study confirms that a robust, well-executed standard protocol – focusing on high-quality seeds, an optimal peat-based substrate, precise irrigation, and strict adherence to growth phases – forms a highly effective and economically viable foundation for large-scale reforestation production. The main challenge, as evidenced by the 2023 data, is not the technology itself but the consistent management and avoidance of operational disruptions to the tightly controlled growth cycle.

Beyond its direct contribution to reforestation efficiency, the developed technology directly supports the United Nations Sustainable Development Goal 15 (Life on Land), particularly Target 15.2: "Promote the implementation of sustainable management of all types of forests, halt deforestation, restore degraded forests and substantially increase afforestation and reforestation globally." By ensuring the large-scale production of genetically appropriate, high-quality containerized Scots pine seedlings, this study provides a regionally optimized, evidence-based solution for restoring degraded forest lands in the forest-steppe zone of Central Russia. The five-year operational dataset demonstrates that sustainable forestry is not only a policy aspiration but a technologically achievable outcome, grounded in seed quality control, substrate science, and strict process discipline. Furthermore, the integration of local seed provenances supports genetic conservation, while the high uniformity and survival potential of the planting stock contribute to reduced replanting needs and lower long-term carbon costs. This work thus offers a transferable model for other boreal and temperate regions seeking to align industrial-scale nursery production with the principles of the 2030 Agenda for Sustainable Development.

3.1 Limitations and Future Research Directions

This study has several limitations that should be considered when interpreting causal relationships. First, the analysis is based on operational production data rather than a controlled experimental design; therefore, while statistical associations are robust, causal inferences require caution. Second, as noted above, high-resolution environmental data were not recorded during the 2023 disruption, limiting our ability to identify precise mechanistic drivers. Third, the genetic comparison (improved vs. normal) is partially confounded with year, as improved seeds were only available in 2020–2022. We addressed this by including 2024 normal seeds as a control, but ideal experimental design would include all categories in all years.

Future research should focus on:

- Establishing controlled experiments to disentangle the effects of seed genetics, substrate composition, and microclimate.
- Installing continuous environmental monitoring systems in production greenhouses to capture high-resolution data.
- Conducting long-term field trials to assess whether the morphological anomalies observed in 2023 affect survival and growth after outplanting.
- Investigating the mechanisms underlying the differential sensitivity of height vs. diameter growth to stress.

Conclusions

Based on the five-year operational data, the following top three conclusions can be drawn:

1. The implemented technology for growing Scots pine seedlings with a closed root system is highly effective, ensuring a consistently high yield of standard planting material (average 92.3%) with biometric parameters suitable for forest restoration in the Voronezh region.
2. The quality of the initial seed material (purity 95.8–100%, germination 85–98%, I–II quality class) is a critical norm-forming factor that directly determines the success of the entire production cycle and the final output of seedlings.
3. Strict adherence to the technological schedule, particularly the duration of the greenhouse growth phase, is paramount. Any deviation, as evidenced in 2023, leads to a significant quantitative and qualitative decline in seedling indicators, highlighting the sensitivity of containerized production to process discipline.
4. From an economic perspective, the 2023 disruption resulted in a 15% reduction in the proportion of standard seedlings (from the average 92.3% to 89.8%), and for the most affected seed lot, seedling height fell below the minimum standard (8.2 cm vs. the required 10 cm), rendering a portion of the crop unsuitable for planting. According to recent data from the Ministry of Natural Resources of the Komi Republic (2024), the planned cost of producing containerized Scots pine seedlings in a state forest nursery is approximately RUB 8 per seedling. Based on this benchmark, and considering the reduced output of standard seedlings and additional sorting costs, the estimated economic loss due to the 2023 deviation is approximately RUB 1.4–1.6 million. These figures underscore that technological discipline is not only a biological necessity but also a critical economic factor in large-scale containerized seedling production.

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Conflict of Interest

The authors declare that there is no conflict of interest.

Author Contributions

Veronika I. Malysheva: Conceptualization, Formal analysis, Methodology, Project administration, Writing – original draft, Writing – review & editing. Tatyana P. Novikova: Data curation, Formal analysis, Validation, Visualization, Writing – original draft, Writing – review & editing. Nebi Bilir: Formal analysis, Methodology, Validation, Writing – original draft, Writing – review & editing. Arthur I. Novikov: Conceptualization, Formal analysis, Investigation, writing – original draft, Writing – review & editing.

AI and AI-Assisted Technologies use Declaration

No generative AI tools/AI-assisted technologies were used during the preparation of the manuscript.

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