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Double-Cropping of *Pinus sylvestris* L. Containerized Seedlings under Short Growing Season Conditions at High Latitudes

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Abstract. The quality of forest crops significantly depends on the characteristics of the planting stock. To obtain high-quality conifer seedlings, the process of container cultivation is used and optimized and a double-cropping mode is introduced. The aim of this study has been to conduct a comparative analysis of one-year-old containerized seedlings of *Pinus sylvestris* L. according to morphometric parameters under a double-cropping regime under short growing season conditions at high latitudes. The experiment has been carried out in a forest nursery in southern Karelia, Russia. The duration of the first rotation (1rot) has been 146 days, the second one (2rot) – 91 days, the control one (0rot) – 132 days. The following parameters of seedlings have been determined: seedling height (SH, cm), root length (cm), bud length (mm), root collar diameter (RCD, mm), tree dry mass (TDM, g), shoot dry mass (SDM, g), root dry mass (RDM, g) and needle dry mass. The integral quality indices have been assessed, such as: shoot : root dry mass ratio (SRR) = SDM/RDM, sturdiness quotient (SQ) = SH(cm)/RCD(mm) and Dickson Quality Index (DQI) = TDM/(SH + SRR). The lowest values of seedling dry mass have been revealed in the 2rot variant. For all variants, the difference between the mean SQ and DQI values has been statistically significant at the $p < 0.05$ level. SRR was the lowest in the 1rot seedlings. The high correlation coefficients between the TDM and RCD for all variants confirm the high significance of the latter index. The results indicate the need to adjust the time regime and use additional agricultural practices to obtain high-quality planting stock.
Keywords: *Pinus sylvestris* L., seedling quality, morphometric parameters, quality index, DQI, forest nursery, double-cropping

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Научная статья

Двухротационное выращивание контейнерных сеянцев *Pinus sylvestris* L. в условиях короткого вегетационного периода в высоких широтах

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Аннотация. Качество лесных культур существенно зависит от характеристик посадочного материала. Для получения качественных сеянцев хвойных пород используется и оптимизируется процесс контейнерного выращивания, внедряется его двухротационый режим. Целью исследования было проведение сравнительного анализа 1-летних контейнерных сеянцев *Pinus sylvestris* L. по морфометрическим параметрам при двухротационном режиме выращивания в условиях короткого вегетационного периода в высоких широтах. Эксперимент проводили в лесном питомнике на юге Республики Карелии. Продолжительность для варианта 1-й ротации – 146 дней, 2-й – 91 день, для контрольного – 132 дня. Определяли параметры сеянцев: высоту, длины корня и почки, диаметр у корневой шейки, сухую массу всего сеянца, его надземной части, корня, хвои. Оценивали интегральные показатели качества: соотношение сухой массы надземной и подземной частей; коэффициент выносливости, равный отношению

высоты сеянца к его диаметру у корневой шейки, а также индекс качества Диксона. Самые низкие массы сеянцев выявлены в варианте 2-й ротации. Разница средних коэффициентов выносливости и индексов качества Диксона между всеми вариантами была статистически значимой на уровне р < 0,05. Соотношение сухой массы надземной и подземной частей оказалось самым низким у сеянцев 1-й ротации. Высокие коэффициенты корреляции между массой сеянца и диаметром корневой шейки для всех вариантов подтверждают значимость последнего показателя. Результаты свидетельствуют о необходимости корректировки временного режима и использования дополнительных агроприемов для получения качественного посадочного материала.
Ключевые слова: *Pinus sylvestris* L., качество сеянцев, морфологические признаки, индекс качества, DQI, лесной питомник, двухротационное выращивание
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Introduction

The quality of the created forest plantations, especially at an early growth stage, significantly depends on the planting stock characteristics [7, 10, 16–18, 20, 21, 31, 38, 43]. Along with increased growth energy, seedlings must have increased resistance to unfavorable environmental factors [41]. By using high-quality seedlings, it is possible to improve establishment and growth, as well as reduce planting density and thinning costs. The process of growing containerized planting stock is being actively implemented and optimized [5, 24, 34].

In the Republic of Karelia, containerized seedlings have been produced for more than three decades. To ensure successful seedling establishment in the field, understanding the impact of nursery practices on seedling quality is essential [29].

The modern practices of coniferous seedlings cultivation involve double-cropping containerized seedlings in a single year [9, 15]. First-rotation sowing is carried out with an increase in the duration of daylight, in the second rotation – with the maximum duration of daylight [15].

However, in Russian mid-boreal forest nurseries, multi-rotation cultivation poses challenges due to the short growing season and possible asynchrony of environmental factors (decrease in temperature and photoperiod duration) suppressing the shoot growth and triggering the process of apical bud formation, as well as the development of stress resistance [3, 8, 15, 27]. There is a risk that the seedlings will be unprepared for the stress of planting and winter conditions.

For Karelia, which is experiencing a shortage of coniferous seedlings for reforestation, the intensification of the cultivation process is an urgent issue. Before the widespread introduction of double-rotation cultivation, it is necessary to conduct production testing of this regime under conditions of a short growing season, obtain data on the morphometric parameters of seedlings and, based on an analysis of the results obtained, draw a conclusion on the possibility of introducing the tested regime or the need to adapt it to these conditions. It is important to identify which indicators may not meet the standard ones in order to effectively look for ways to adapt the method. The most commonly used morphometric standards for seedling quality are dry mass and linear dimensions of the whole seedling and its organs [18, 21, 25, 35]. Integral indices are widely used to assess the quality of seedlings of woody plants of various species: sturdiness quotient (SQ), shoot:root dry mass ratio (SRR) and Dickson Quality Index (DQI) [2, 13].

The aim of this study has been to conduct a comparative analysis of one-year-old containerized seedlings of Scots pine (*Pinus sylvestris* L.) according to morphometric parameters under a double-cropping growing regime under conditions of a short growing season at high latitudes.

Research Objects and Methods

The Experiment Design. Double-cropping cultivation of one-year-old containerized seedlings *Pinus sylvestris* L. was carried out in a forest nursery (in the village of Vilga, southern Karelia, Russia, 61°82′N, 34°16′E) during the 2020 growing season. Scots pine seeds of quality class 1 (germination rate of at least 90 %) harvested in the Medvezhy-egorsk central forestry (62°55′ N) have been used. The seedlings have been grown in Plantek 81F rigid plastic trays (81 cells per tray, 546 cells per m^{-2}, cell volume 85 cm^3, depth 10 cm). The containers have been filled with a substrate consisting of slightly decomposed high-moor sphagnum peat, dolomite meal and a complex fertilizer as the main additive. Two seeds have been sown in each cell. After germination, one plant per cell has been randomly retained and the rest have been removed. The seedlings have been grown in a greenhouse according to a standard protocol with foliar top-dressing with complex fertilizers and regular watering. The electrical conductivity of the substrate during cultivation has been maintained at the level of 1.5–1.8 mS/cm. Fungicides have been used to prevent mold infection.

In the variants of the first (1rot) and second (2rot) rotations, sowing was carried out on May 2 and June 26, respectively (Table 1). The control variant (0rot – no rotation within the season) was sown on May 16. Containers with the 1rot seedlings were moved from the greenhouse to the hardening plot on June 20. Containers with the 2rot seedlings were placed in the greenhouse on June 26. On August 25, they were transferred to the hardening plot (Table 1). The cultivation of 0rot seedlings in the greenhouse and in the hardening plot has been carried out according to a standard protocol [43].

Table 1

The experiment design for growing one-year-old containerized seedlings of Scots pine (*Pinus sylvestris* L.)

EV	May	June	July	Aug	Sept	GS	Sum over season		
	GGD/OGD, days						TGD, days	TGD′, %	GGD′, %
1rot	30/0	20/10	0/31	0/31	0/24	50/96	146	111	34.25
2rot	0/0	5/0	31/0	25/6	0/24	61/30	91	69	67.03
0rot	16/0	30/0	31/0	25/6	0/24	102/30	132	100	77.27

Note: EV – experiment variants; GGD (numerator) – greenhouse growing duration; OGD (denominator) – open growing duration; GS – growing season; TGD – total growing duration; $TGD_i' = TGD_i/TGD_{0rot} \cdot 100$; $GGD_i' = GGD_i/ TGD_i \cdot 100$; i – experiment variant.

The Morphometric Methods. On September 24, 30 seedlings have been randomly selected from each variant when froming a sample for morphometric measurements. A total of 90 Scots pine seedlings have been selected. Each seedling has been divided into stem, needles, bud and root. The root system of the seedlings was washed with tap water to remove all soil particles. The height from the root collar to the base of the terminal bud (SH, cm), root length (RL, cm), bud length (BL, mm) and root collar diameter (RCD, mm) have been measured in seedlings. The wet masses of seedling organs have been determined gravimetrically, the water content (%) in the organs has been determined, and the dry masses have been calculated for: the tree (TDM, g), the shoot (SDM, g), the root (RDM, g), the needles (NDM, g) and the buds (BDM, g). To quantify the quality of seedlings, the integral indicators are: SRR = = SDM/RDM, SQ = SH(cm)/RCD(mm) and DQI = TDM/(SH + SRR).

The Data Analysis. Morphometric parameters of one-year-old *Pinus sylvestris* L. containerized seedlings have been characterized by the mean ± standard deviation (SD), as well as minimum and maximum values depending on the growing regime variant: 1rot, 2rot or 0rot. The data has been analyzed using one-way ANOVA to indentify differences in the mean parameters between the three growing regimes. The Tukey test has been used for pair-wise comparisons (as a posteriori test) of growing regimes. All probabilities were tested at a significance level of 0.05. The variables have been tested for correlations using the Pearson correlation analysis. The Pearson correlation coefficients calculated for each pair of morphometric parameters are presented in correlation matrices according to the experiment variants. Paired linear regression analysis has been used to examine the relationship between variables. A higher coefficient of determination (R^2) has been used to select the best regression models. To study the relationship between the morphometric parameters of the seedlings and the time mode of the growing regime, normalized values of the total growing duration (TGD′) and the greenhouse growing duration (GGD′) have been used (Table 1).

The variables have been tested for correlation with the morphometric parameters of the seedlings. To study the dependence of the morphometric parameters of seedlings on the time mode of the growing regime, multiple regression models have been constructed with two explanatory variables of the form: $y_i = \alpha + \beta \cdot TGD_i' + \beta \cdot GGD_i' + \varepsilon$.

Results and Discussion

The Morphometric Parameters of the Seedlings. The SH in the control (0rot) variant has been significantly higher than that in the 1rot and 2rot variants (Table 2). The SH did not differ significantly between the 1rot and 2rot ($\alpha = 0.05$), amounting to 64 and 72 % of the control, respectively.

The RCD has been significantly smaller in the 2rot variant compared to that in the 1rot one.

The masses of both the whole seedling and its individual organs have been significantly lower at the 2rot variant compared to the 1rot and 0rot ones ($\alpha = 0.05$). The mass of seedlings and their individual organs, with the exception of the RDM, has had similar values in the 1rot and 0rot variants.

Table 2

The morphometric parameters of one-year-old *Pinus sylvestris* L. containerized seedlings (mean ± SD; minimum and maximum values) according to the experiment variants

EV	Value	TDM, g	SDM, g	NDM, g	RDM, g	SH, cm	RCD, mm	BL, mm	RL, cm
1rot	Mean	1.05a	0.54a	0.43a	0.51a	6.3a	1.94a	6.70a	139a
	±SD	0.08	0.05	0.05	0.04	0.6	0.08	0.50	11
	Min	0.75	0.33	1.60	0.01	4.0	0.25	0.33	100
	Max	1.54	0.83	2.40	0.06	9.0	0.71	0.77	200
2rot	Mean	0.62b	0.39b	0.31b	0.23b	7.3a	1.70b	4.50b	188b
	±SD	0.05	0.03	0.03	0.02	0.5	0.07	0.40	17
	Min	0.42	0.23	1.40	0.01	5.3	0.17	0.13	110
	Max	0.83	0.55	2.10	0.01	9.2	0.44	0.35	290
0rot	Mean	0.91a	0.57a	0.43a	0.34c	10.4b	1.82ab	5.50c	139a
	±SD	0.16	0.10	0.08	0.07	1.1	0.21	0.70	19
	Min	0.44	0.24	1.20	0.01	3.0	0.14	0.16	95
	Max	1.67	1.07	2.60	0.02	7.0	0.76	0.60	245
F-value*		27.31	11.49	10.22	57.57	39.77	5.03	22.51	15.42
p-level		0.000	0.00004	0.0001	0.0000	0.0000	0.009	0.0000	0.0000

Note: Here and in Table 4 different letters indicate a significant difference between the variants as assessed using the Tukey test (α = 0.05); *df* = 77.

The Pearson linear correlation analysis has been used between all the observed variables (Table 3).

Table 3

The Pearson correlation coefficients between the morphometric parameters of one-year-old *Pinus sylvestris* L. containerized seedlings according to the experiment variants (p ≤ 0.05)

	TDM	SDM	SH	RCD	BDM	BL	NDM	RDM
1rot								
SDM	0.894	1.000						
SH	0.010	0.182	1.000					
RCD	0.719	0.659	0.196	1.000				
BDM	–0.002	0.073	0.042	–0.090	1.000			
BL	–0.370	–0.303	–0.011	–0.075	0.056	1.000		
NDM	0.842	0.968	0.150	0.540	–0.022	–0.366	1.000	
RDM	0.791	0.433	–0.229	0.547	–0.103	–0,332	0.371	1.000
RL	0.172	0.081	–0.029	0.091	–0.073	–0.156	0.036	0.235
2rot								
SDM	0.937	1.000						
SH	0.226	0.299	1.000					
RCD	0.552	0.562	0.298	1.000				

The end of Table 3

	TDM	SDM	SH	RCD	BDM	BL	NDM	RDM
BDM	–0.245	–0.153	0.103	–0.121	1.000			
BL	–0.240	–0.177	–0.067	0.009	0.153	1.000		
NDM	0.911	0.973	0.148	0.535	–0.155	–0.115	1.000	
RDM	0.825	0.574	0.046	0.383	–0.326	–0.274	0.557	1.000
RL	–0.100	–0.123	–0.146	–0.043	–0.233	–0.116	–0.116	–0.034
				0rot				
SDM	0.977	1.000						
SH	0.618	0.554	1.000					
RCD	0.874	0.827	0.800	1.000				
BDM	0.039	–0.030	0.374	0.144	1.000			
BL	0.498	0.469	0.882	0.798	0.232	1.000		
NDM	0.928	0.963	0.357	0.696	–0.112	0.284	1.000	
RDM	0.941	0.846	0.660	0.865	0.145	0.497	0.783	1.000
RL	0.135	0.056	0.439	0.187	0.266	0.275	–0.006	0.249

Note: Here and in Table 5 the significance of the correlation between the parameters measured is indicated by the intensity of the coloring.

A strong correlation has been found between the following indicators: the TDM, SDM, NDM and the RCD. No significant correlation between the bud dry mass and the RL with other parameters has been found in all the experiment variants. The correlation coefficients between the variables in the 1rot and 2rot variants have been lower than in the 0rot variant.

The Integral Quality Indices. For all analyzed variants, the difference in the average SQ values has been statistically significant at the level of $p < 0.05$ and has amounted to 57 and 72 % of the control for the 1rot and 2rot variants, respectively (Table 4).

Table 4

The integral quality indices SQ, SRR, DQI of one-year-old *Pinus sylvestris* L. containerized seedlings (mean ± SD) according to the experiment variants

Value	SQ			SRR			DQI		
	1rot	2rot	0rot	1rot	2rot	0rot	1rot	2rot	0rot
Mean	3.3a	4.2b	5,8c	1.1a	1.7b	1.7b	0.23a	0.10b	0.12c
±SD	86	1	0.9	0.3	0.3	0.3	0.06	0.02	0.05
F-value*	46.67			33.07			62.5		

Note: *df* = 77.

The SRR of the 1rot seedlings has been more than one and a half times lower than that of the seedlings of the other two variants. The SRR values have been equal in the 2rot and 0rot variants. The DQI values for all variants have had significant differences and ranged from 0.10 to 0.23.

A high correlation has been found between DQI and the following variables: the TDM, SDM, NDM and RCD, and a significant correlation with the SH in the 0rot variant (Table 5).

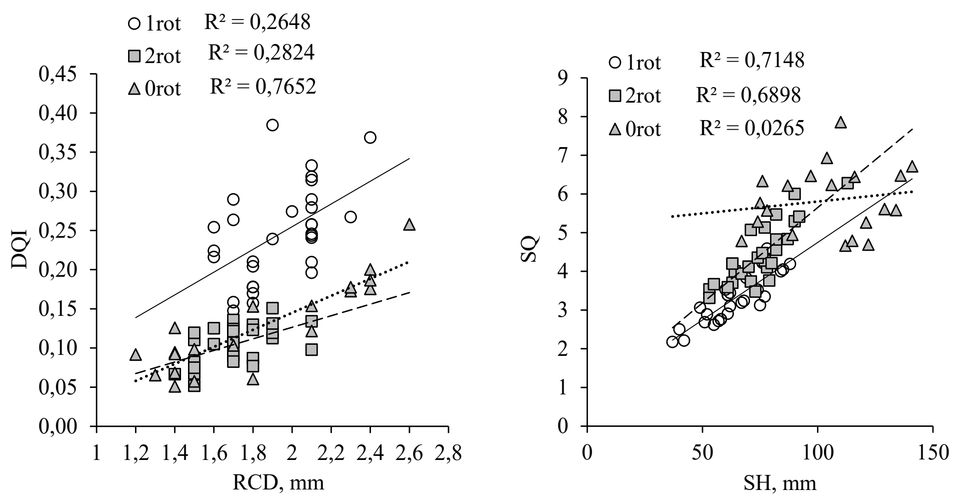
Table 5

The Pearson correlation coefficients between the integral quality indices SQ, SRR, DQI and the morphometric parameters of one-year-old *Pinus sylvestris* L. containerized seedlings according to the experiment variants

	SQ			SRR			DQI		
	1rot	2rot	0rot	1rot	2rot	0rot	1rot	2rot	0rot
TDM	–0.287	–0.124	–0.507	0.279	0.031	–0.065	0.748	0.829	0.974
SDM	–0.109	–0.054	–0.514	0.671	0.366	0.137	0.484	0.670	0.938
SH	0.893	0.831	0.163	0.403	0.284	–0.207	–0.586	–0.266	0.517
RCD	–0.251	–0.276	–0.447	0.235	0.150	–0.146	0.505	0.531	0.875
BDM	0.071	0.186	0.240	0.146	0.174	–0.307	–0.094	–0.330	–0.015
BL	–0.008	–0.049	0.012	–0.059	0.103	–0.053	–0.274	–0.140	0.452
NDM	–0.084	–0.191	–0.586	0.686	0.353	0.158	0.443	0.724	0.903
RDM	–0.429	–0.203	–0.446	–0.356	–0.518	–0.377	0.843	0.855	0.938
RL	–0.043	–0.117	0.309	–0.065	0.070	–0.521	0.197	–0.017	0.063

In the 1rot and 2rot experiment variants, a significant correlation has been found between the DQI values only with the following variables: the TDM, SDM, NDM and the RCD. There has been no correlation between DQI and the SH in these variants.

The regression analysis has shown that the DQI value has been significantly and positively correlated with the RCD only in the 0rot variant ($R^2 = 0.77$; see Fig. below).



Paired linear regression analysis of the ratios of integral quality indicators DQI and SQ and morphometric variables (linear dimensions) of one-year-old containerized *Pinus sylvestris* L. seedlings according to the experiment variants

The Relationship between the Morphometric Parameters of the Seedlings and Temporal Indicators of the Growing Regime. The dependence of the morphometric parameters of the seedlings on the normalized temporal indicators of the growing regime TGD′ and GGD′ has been studied.

The TDM, SDM, NDM, RDM, RCD, BL and the integral quality index DQI have positively correlated with the total growing duration (TGD′). A strong positive correlation with TGD′ has been observed for the TDM and RDM, as well as DQI (Table 6).

Table 6

The Pearson correlation coefficients between the morphometric parameters of one-year-old containerized *Pinus sylvestris* L. seedlings and the normalized temporal indicators of the growing regime TGD′ and GGD′, (p<0.05)

	TDM	SDM	NDM	RDM	SH	RCD	BL	QS	SRR	DQI
TGD′	0.643	0.450	0.447	0.730	–0.097	0.330	0.579	–0.260	–0.517	0.680
GGD′	–0.422	–0.141	–0.190	–0.646	0.645	–0.264	–0.496	0.785	0.664	–0.770

The SH, as well as the QS and SRR indicators have positively correlated with the duration of the seedlings’ stay in the greenhouse (GGD′). The RDM and DQI have shown a strong negative relationship with GGD′. The TDM, BL and RCD have shown a moderate negative relationship with GGD′.

To study the dependence of the morphometric characteristics of seedlings on the normalized total growing duration and the greenhouse growing, multiple regression models have been constructed (Table 7).

Table 7

The parameters of the multiple regression models with two explanatory variables of the form: $y_i = \alpha + \beta_1 * TGD'_i + \beta_2 * GGD'_i + \varepsilon$, y – the morphometric parameters of one-year-old containerized *Pinus sylvestris* L. seedlings

y	α			β_1			β_2			R^2	F
	Coef	t-stat	p-value	Coef	t-stat	p-value	Coef	t-stat	p-value		
TDM	17.80	0.076	0.940	9.590	5.589	0.000	–0.840	–0.483	0.630	0.415	27.31
RDM	110.5	1.080	0.284	4.434	5.911	0.000	–2.723	–3.574	0.001	0.599	57.57
SH	–44.63	–2.613	0.011	0.600	4.794	0.000	1.223	9.620	0.000	0.550	47.07
QS	–1.839	–2.352	0.021	0.024	4.203	0.000	0.072	12.36	0.000	0.688	84.80
SRR	1.111	3.292	0.002	–0.004	–1.743	0.085	0.013	5.282	0.000	0.462	33.06
DQI	0.167	3.354	0.001	0.001	4.098	0.000	–0.003	–6.845	0.000	0.666	76.67

The proportion of variance due to regression in the total variance of the “y” indicator, characterized by the determination coefficient R^2, exceeded 50 % ($R^2 > 0.5$) in the RDM, QS and DQI models, which allows them to be considered significant (for $\alpha < 0.05$).

The Morphometric Parameters of the Seedlings. The morphometric parameters of the seedlings and their organs at the end of the growing season have reflected the growth activity depending on the conditions and duration of cultivation. Many studies show that the seedling RCD, the shoot height, and the SRR strongly correlate with the establishment rate during planting [10, 20].

A comparative analysis of the seedlings in our experiment has revealed significant differences in the linear dimensions and biomass of plants depending on the rotation regime. In terms of height, the seedlings of the 1rot and 2rot variants have been significantly inferior to the 0rot (control) variant, amounting to 64 and 72 %, respectively. The RCD has been significantly lower in the 2rot variant compared to the 1rot one, but has not differed significantly from the 0rot one. In terms of bud length, the 2rot seedlings have also had the lowest value (83 % of the 0rot variant); the leader has been the 1rot variant (123 % of the 0rot variant). In terms of the mass of both the whole seedling and individual organs, the worst results have been obtained in the 2rot variant. There have been no significant differences in the TDM, SDM and NDM between the 1rot and 0rot variants. The RDM in the 1rot variant has been 1.5 times higher than in the 0rot variant, and more than twice as high as in the 2rot variant.

Allometric models can be useful in practice for estimating the seedling mass based on available linear dimension data. Models have been developed to predict seedling biomass, including total biomass, aboveground and underground biomass of tropical woody plant seedlings based on the RCD, SH, and wood density [37]. Understanding the existing correlations between morphometric parameters is necessary to build similar models that will help develop better production methods and ensure high quality seedlings [4].

The Pearson linear correlation analysis has been performed between all the observed variables. There has been no significant correlation between the bud dry mass and the RL with other indicators in all experiment variants, so they have been excluded from further consideration. The bud length has shown an ambiguous correlation with other indicators between the experiment variants. Thus, in the 1rot and 2rot variants, its correlation with most indicators is weak negative, and in the 0rot variant it is strong or moderately positive.

Of greatest interest has been the identification of a correlation between the linear dimensions of the above-ground part, which can be determined without damaging the plant, and the values of the dry mass of the organs of the whole seedling. The SH has shown a moderate positive relationship with the biomass indices only in the 0rot variant. The RCD, on the contrary, has shown a high and medium positive correlation with the parameters of both the above-ground and underground parts of the seedlings in all variants, with the exception of a weak negative correlation with the RDM in the 1rot variant. The 1rot and 2rot variants generally have lower correlation coefficients between the variables.

The Integral Seedling Quality Indices. Morphometric parameters used to assess the quality of seedlings should be studied comprehensively rather than individually. If considered separately, there is a risk of selecting taller and weaker seedlings and rejecting smaller and stronger ones that may have better establishment rates. In order to minimize possible errors that may arise when using only one or two parameters, the work has used integral seedling quality indices based on two or more of the most significant morphometric parameters [1, 13, 14, 32, 35, 40].

Many studies show that the seedling RCD, shoot height, SRR and other integral indices strongly correlate with establishment and growth rates upon planting [10, 20]. The integral indices (SRR, SQ, and DQI) have been evaluated in this study for three growing regimes. The best results for all three integral indices have been obtained in the 1rot variant.

The SRR is considered an effective and reliable indicator for assessing the quality of seedlings [4]. The seedlings with a very high SSR indicate a disproportionate development of the above- and underground parts of the seedlings, which leads to uneven water distribution in the plant and its poor establishment. Their initial growth is inhibited after planting in the field [6, 36].

The low ratio of the dry mass of the above-ground part of the seedling to the dry mass of the root (SSR) has been shown to be particularly important for establishment upon planting under soil moisture deficiency conditions [20]. This can be explained by the increased water and nutrient consumption provided by the larger root system compared to the lower requirements of a smaller above-ground part. On the other hand, a very low SSR may indicate insufficient shoot growth [28, 38]. The SSR ratio varies depending on the plant species and age. In coniferous seedlings, this ratio usually exceeds 1. The recommended SRR for many conifers grown in nurseries is within 2.5 [26].

The lowest SRR value in our experiment has been obtained in the 1rot variant. In the seedlings of the 2rot and 0rot variants, the values of this ratio have not differed significantly, but have been noticeably higher than in the seedlings of the 1rot variant. Our results show that the 1rot seedlings, characterized by a low ratio of aboveground mass to root mass due to a more developed root system, have a higher chance of establishing when transplanted to a forest cultivation area. The RCD of the stem at the seedling stage can help predict future growth quality after transplantation, but only in combination with SH does it provide information on whether the seedlings are highly vigorous, vigorous or weak [10, 22, 28].

SQ is an important morphometric indicator of seedling quality [11, 12, 26, 28]. In our experiment, the lowest SQ value has been obtained in the 1rot variant and amounted to 57 % of the 0rot variant. A lower SQ indicates a stronger and higher quality plant. The SQ can be used to assess the survival and growth of seedlings [28]. In the 2rot variant, the SQ has also been lower than in the 0rot one (72 % of the 0rot variant).

DQI takes into account several variables and can therefore provide important information about the overall quality of seedlings [25, 28, 39]. It includes five morphometric parameters (the TDM, SDM, RDM, SH and RCD) and serves as an effective indicator of quality and is often used in seedling research. A higher DQI value indicates a more desirable phenotype, stability and balance of biomass distribution in seedlings [28]. The DQI values for all experiment variants had significant differences. The best DQI value has been found in the 1rot variant; it has been two or more times higher than in the 2rot and 0rot variants.

The Regression Models of the Relationship between Seedling Quality Coefficients and Morphometric Indicators. For the construction of regression models, suitable variables have been identified using correlation analysis. For Dixon quality index, a high positive correlation has been found with the following variables: TDM, SDM, NDM, RDM, RCD, and a significant one with the SH in the 0rot variant; a high positive correlation with the TDM and RDM in the 1rot and 2rot experiment variants. No correlation has been found between DQI and the SH.

The high correlation of morphometric parameters and the calculated DQI in the 0rot variant has indicated a good balance of the seedling organs in terms of mass and linear dimensions in this experiment variant.

Regression models have been constructed to identify the relationship between the DQI and SQ quality indices and some morphometric parameters. A statistically significant dependence of DQI on the TDM ($0.95 \geq R^2 \geq 0.58$) and RDM ($0.88 \geq R^2 \geq 0.61$) has been shown in all experiment variants. The relationship between DQI and RCD has been found only in the 0rot variant ($R^2 = 0.77$). A strong positive relationship between the SQ and SH has been obtained in the 1rot ($R^2 = 0.71$) and 2rot ($R^2 = 0.67$) variants.

Since the coefficients used here, primarily DQI, are considered good indicators of seedling quality, allowing to predict field survival and further growth, as shown by many studies [4, 10, 20], the absence of a strong or moderate correlation between the linear dimensions of the shoot and these quality indices obviously does not allow to use only non-damaging methods for a reliable assessment of seedling quality. To obtain a more reliable assessment, it is also desirable to determine the biomass of organs, as well as their physiological parameters.

The Morphometric Parameters of the Seedlings Depending on the Temporal Growing Regime. Quantitative indicators of the biomass of a seedling and its organs at the end of the growing season characterize growth activity and depend on the conditions or duration of their cultivation. A comparative analysis of the morphometric parameters of seedlings and their organs, carried out in this experiment, has made it possible to reveal differences depending on both the total duration of cultivation during the season and the duration of cultivation under different conditions: in a greenhouse or in open ground.

The dependence of the morphometric parameters of seedlings on the normalized temporal indicators of the growing regime TGD′ and GGD′ has been studied. Some linear dimensions and dry mass of the seedling and its individual organs, as well as the DQI integral quality index, have positively correlated with TGD′. In particular, the TDM, RDM and DQI have strongly positively correlated with TGD′ (R = 0.643, 0.730 and 0.680, respectively). A strong positive correlation has been observed for the SH, QS and SRR with GGD′ (R = 0.645, 0.785 and 0.664, respectively). A strong negative relationship has been found between the RDM and DQI with GGD′ and a moderate negative one between the TDM, BL and RCD with GGD′.

Multiple regression models of the form: $y_i = \alpha + \beta_1 \cdot TGD_i' + \beta \cdot GGD_i' + \varepsilon$, with two explanatory variables have been constructed to study the dependence of the morphometric parameters of seedlings on TGD′ and GGD′. The significance of the models for the RDM, SH, QS and DQI indices (for $\alpha < 0.05$) has been shown, since the proportion of variance due to the total variance of the four studied indicators, characterized by the determination coefficient R^2, has exceeded 50 % ($R^2 > 0.5$).

The analysis of multiple regression models has shown that 60 % of the variations in root mass, 55 % of the variations in SH, 69 % of the variation in QS and 67 % of the variations in DQI have been explained by TGD′ and GGD′. The regression model for the root mass indicates a positive relationship with TGD′ and a negative relationship with GGD′. That is, the long stay of seedlings in the greenhouse significantly negatively correlates with the mass of the roots. The SH, on the contrary, has depended positively on both GGD′ and TGD′, and to a greater extent on GGD′.

DQI has depended positively on the TGD′ and negatively on the GGD′. The results obtained show that in order to obtain high-quality planting stock with a high DQI quality coefficient, a relative stay in the greenhouse in all experiment variants is sufficient, however, the total duration of cultivation in the 2rot variant should be increased.

The morphometric parameters of planting stock must be taken into account when choosing the soil conditions of the site planned for planting. When planted in damp areas characterized by well-developed surrounding herbaceous vegetation, seedlings with a tall and massive above-ground part, with a large photosynthetic surface area, have an advantage in a fierce competition for light. They can be recommended for creating forest plantations in such areas. In our experiment, seedlings of the 0rot variant, having the greatest SH, but the worst SRR indicators, are better suited to damp areas with conditions favorable for their growth.

On the contrary, the seedlings of smaller size, but having a small transpiring surface area relative to the absorbing root system, with low SRR values, are more easily established in areas exposed to water stress [17, 26]. The 1rot seedlings with the lowest SRR value are better suited for dry areas with poor vegetation.

When choosing the edaphic conditions for a planting site, it is necessary to take into account the morphometric parameters of seedlings grown under different growing regimes in order to maximize their post-planting survival and further growth. Periods of spring drought may become more frequent due to global warming, which must be taken into account when improving methods for growing planting stock adapted to conditions of water deficiency [30]. The selection of seedlings with the desired genetic, morphometric and physiological parameters is necessary to maximize the use of site resources [16, 23, 30, 33]. The phenotypic characteristics formed during the cultivation of seedlings in forest nurseries ensure their preliminary adaptation to the planting site.

Conclusions

A production test of the double-rotation cultivation of one-year-old *Pinus sylvestris* L. containerized seedlings has been conducted in a forest nursery under conditions of a short growing season at high latitudes. The morphometric characteristics of seedlings have been obtained and analyzed, and the possibility of introducing the tested regime into forest nursery practice without adaptation to these climatic conditions has been assessed.

The absence of a significant correlation between the linear dimensions of the above-ground part and DQI and other integral indices in two experiment variants indicates the insufficiency of non-damaging assessment methods for obtaining objective information on the quality of seedlings. For a more accurate assessment, it is advisable to determine the mass of seedling organs and physiological parameters.

A comparative assessment of the of the morphometric parameters of pine seedlings of three cultivation variants, including the use of integral quality indices, has shown that in order to obtain high-quality standard planting stock in northern latitudes, it is necessary to adapt the double-rotation cultivation regime by adjusting the time regime and applying additional agricultural techniques.

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