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**ORIGINAL PAPER**

# Effect of precise control of irrigation and substrate compaction on seedling growth and root distribution in Norway spruce

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## ABSTRACT

We analyzed the growth of 1-year-old Norway spruce seedlings in a container nursery with three experimental variants differing in substrate compaction and water supply during irrigation (moisture level control). The nursery material was produced in Hiko V-120SS containers. Each seedling's height and root collar diameter (RCD) were measured. In addition, the dry mass of the shoots and needles was also determined. The lump of substrate was divided into three equal parts, and the dry mass of the root system was determined separately for three levels of cavity depth (upper, middle and lower). Seedlings grown in the variant with compacted substrate and precise control of substrate moisture level had the maximum height and RCD value. However, the average sturdiness quotient (SQ) of the seedlings in all variants was very high, explaining their low resistance to abiotic factors after planting. Similarly, the ratio of the above-ground part's dry mass to the root system's weight (S/R index) was very high, indicating the limited suitability of the seedlings for cultivation in all soil moisture conditions. Controlled irrigation for precise control of moisture level had no significant effect on the growth of seedlings. Similarly, the SQ and Dickson quality index values did not differ significantly. It is, therefore, possible to reduce the cost of seedling cultivation using a soil moisture control system that reduces the amount of water supplied to the production field without any adverse effects on the quality of the seedlings. The dry mass distribution in the root system was almost identical in all experimental variants. Most of the roots were found in the upper part of the root lump, *i.e.*, to a depth of about 3.7 cm. On average, 60% of the total mass of the entire root system was located in this zone; hence, the container used to grow the spruce seedlings did not limit the growth of the root system.

## KEY WORDS

Dickson quality index, dry mass, Hiko container, *Picea abies*, sturdiness quotient

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## Introduction

About 85-90% of the seedlings used to establish the majority of cultivation in State Forests in Poland are produced annually in field forest nurseries (Banach *et al.*, 2017). However, renewal or afforestation using such seedlings is fraught with challenges in demanding environmental conditions. Cultivations are often lost; therefore, seedlings with higher adaptive potential, *i.e.*, seedlings with covered root systems, are recommended (Szabla and Pabian, 2009).

Seedlings used to establish cultivations must be viable, undamaged, and proportionate, *i.e.*, of similar length in the root and above-ground parts. However, when cultivating seedlings in a container, it is possible to obtain disproportionate seedlings. This is because the container's depth limits the root system's growth. Depending on environmental conditions, excessive growth of seedlings during cultivation in the nursery may have different effects on their adaptation to cultivation (Tsakaldimi *et al.*, 2005; Grossnickle, 2012); for cultivations at higher altitudes, this results in a lower annual growth rate (Banach *et al.*, 2015). Nevertheless, seedlings with a covered root system have an advantage over bareroot seedlings as they can be easily removed without damage and sorted and transported without reduction of vitality. The most common planting errors are eliminated, especially root collapse and incorrect planting depth (Buraczyk and Szeligowski, 2008).

The root system is an important part of woody plants as it provides water and minerals and stabilizes the trees during their growth. At the nursery growing stage, its development depends on many factors, such as the type of nursery medium, compaction, fertilization, irrigation, etc. (Grossnickle, 2012; Banach *et al.*, 2021; Błońska *et al.*, 2022; Pająk *et al.*, 2022b). In adult spruces, the root system is the same in all habitats, and the central part comprises horizontal roots growing in the upper soil layer, usually at a depth of up to 30 cm (Skrzyszewski, 1994; Paterson, 1996). In spruce, such a root system develops during early ontogenetic development, as indicated by studies carried out on natural regeneration. These spruces are characterized by intense, horizontally growing side roots close to the soil surface (Puhe, 2003).

Sprinkler irrigation is widely employed in nurseries and is particularly important when growing seedlings in containers, as the small volume of the substrate in a single cavity (cell) dries quickly. Excessive irrigation, resulting in more water than the substrate can keep, may cause excessive growth of fungal pathogens and algae, adversely affecting the seedlings and requiring chemicals to control them (Sutherland, 1991; Fisher, 2009; Ash, 2017). It may also lead to a decrease in soil fertility as nutrients may leach beyond the reach of root systems. This is especially true for nursery substrates, which contain few nutrients and need to be properly fertilized for normal seedling growth (Banach *et al.*, 2021; Staszel-Szlachta *et al.*, 2022). The solution is to limit the amount of water supplied to the nursery's production field so there is no risk of reducing the viability or inhibiting the growth of seedlings. The possibility and validity of such a procedure by the results of a 3-year study carried out in a container nursery (Durło *et al.*, 2018).

Results of studies conducted in forest nurseries indicate the influence of soil compaction on seedling growth (Arvidsson, 1999; Brais, 2001; Fleming *et al.*, 2006; Miransari *et al.*, 2009; Kormanek and Banach, 2011; Kormanek *et al.*, 2015a, 2023). An increase in soil density usually affects seedlings negatively; however, the growth may be hindered only after the density reaches a critical level (Maupin and Struve, 1997). Studies on the influence of artificially compacted nursery substrates on the growth of seedlings of forest tree species are few but indicate this factor's importance in seedling cultivation. Usually, a more compact nursery substrate positively affects the dry mass of seedlings, particularly the root system (Zahreddine *et al.*, 2004; Kormanek *et al.*, 2013; Pająk *et al.*, 2022a).

This study aimed to analyze the effect of precisely controlled moisture levels, and thus, the amount of water supplied to the production field and the increased compaction of perlite and peat substrates on the morphological parameters and dry mass of 1-year-old spruce seedlings. In addition, the root system dry mass was analysed in three root lump zones (upper, middle, and lower). The suitability of the Norway spruce *Picea abies* (L.) H.Karst. seedlings for cultivation was also evaluated based on the analyzed parameters like the sturdiness quotient (SQ) and Dickson quality index (DQI). Three research hypotheses were tested: 1) increased soil compaction will improve the growth parameters of the seedlings; 2) limiting the amount of water supplied to the production field will not affect the growth and value of indices determining the suitability of spruce seedlings for cultivation; 3) a change in the conditions of spruce seedling cultivation will affect the allocation of roots in different root lump zones.

## Material and methods

One-year-old Norway spruce seedlings were grown in Nędza container nursery in Rudy Raciborskie Forest District (latitude N 50°10'08", longitude E 18°19'04") during 2015. The experimental material was produced in Hiko V-120SS nursery containers of high-density polyethylene, 352×216×110 mm in dimensions, with 40 cavities. The seeds used in the study originated from the harvest made in 2010 in the commercial seed stand (MP/1/49314/10) growing in the Wisła Forest District (Beskidek forest range, latitude N 49°34'00", and longitude E 18°55'60") area. The seedlings were grown in three experimental variants, which differed concerning substrate preparation and irrigation control. For the V-1 variant, the substrate compaction was increased and optimum moisture content was maintained by precise control over the amount of water supplied; compaction for the V-2 variant was unchanged, and moisture content was maintained at optimum as for the V-1 variant; the V-3 variant employed the standard seedling cultivation procedure used in this container nursery, *i.e.*, no change in substrate compaction and an organoleptic method for moisture control. For this variant, the need for artificial sprinkling was based on the experience of the person supervising the production. It was done when the substrate was separated from the container walls.

In a study conducted in 2014, periods with high air and low water capacities of perlite and peat substrates in containers were observed during the growing of spruce seedlings (Hiko V-120SS). In the experiment carried out in 2015, substrate compaction was increased to improve these parameters. Preliminary tests were performed to determine the optimal level of compaction; containers were filled on the production line of the Swedish company BCC AB with different combinations of compaction unit settings. Compaction was considered optimal for a water capacity of 65-75% and an air capacity of 20-25%. Optimal compaction was obtained by lowering the compaction unit by 1 cm about the standard one and slowing the container movement on a vibrating belt conveyor (Kormanek *et al.*, 2021, 2023). For the V-1 variant, the substrate was characterized by the following parameters: total porosity – 90.8%, volume density – 0.118 g·cm$^{-3}$, water capacity – 67.7%, and air capacity – 23.1%. For V-2 and V-3 variants, these characteristics were as follows: 92.0%, 0.103 g·cm$^{-3}$, 51.1%, and 40.8%, respectively (Kormanek *et al.*, 2015b, 2021). At the beginning and end of the growing season, substrate compaction was again determined using the Eijkelkamp cone penetrometer with 1/8 inch cone (ASAE, 1998). The substrate showed the highest compaction immediately after the container filling (about 86 kPa) and after the growth season (about 210 kPa) for the V-1 variant. The lowest compaction was noted in the substrate for the V-3 variant (about 47 and 172 kPa, respectively). The substrate for the V-2 variant had intermediate values – approx. – 47 and 187 kPa (Fig. 1).

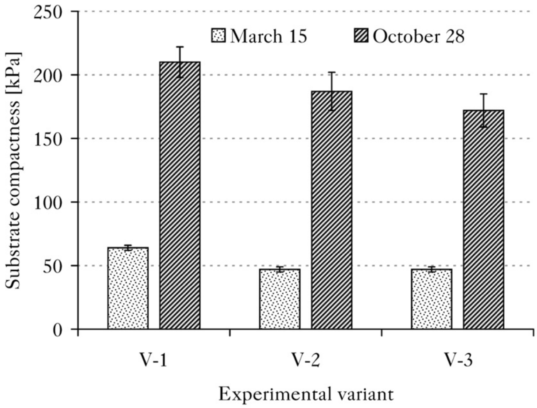


**Fig. 1.**
Mean values of compaction (±SE) of the substrate contained in cavities for each experimental variant after container filling (March 15) and at the end of the growth season (October 28); explanation of abbreviations – see Table 1

The amount of water supplied to the production area was precisely controlled by the modified ramp HAB-T1 BCC sprinkler system. The necessity for sprinkling was determined by measuring the moisture content of the substrate in container cavities with TDR (Time Domain Reflectometer) probes using an external, autonomous control and measurement system with radio telemetric meteorological modules. 2015 was a year of low precipitation, as the precipitation abundance index (GRo) was only 2.69, meaning that water had to be continuously supplied to the production fields. In the case of irrigation control (V-1 and V-2), the substrate moisture within the production field was maintained at a level not exceeding 85% (±4%). During the production season (from 22 March to 15 October), about 9% less water was administered to variants V-1 and V-2 compared to variant V-3, in which the substrate moisture content was not lower than 74% (±7.6%). Therefore, the water content values during the whole experiment were balanced and close to each other.

Mixed fertilizers were used for the cultivation of spruce seedlings of each variant, initially 2.5 kg of Osmocote bloom fertilizer ($NO_3$-N – 5.3%, $NH_4$-N – 6.7%, $P_2O_5$ – 5.2%, $K_2O$ – 18%, MgO – 1.5% and microelements comprising B, Cu, Fe, Mn, Mo, Zn) per 1 $m^3$ of the substrate, followed by 17.55 $dm^3 \cdot ar^{-1}$ of the production area of foliar fertilizer Floralesad ($NO_3$-N – 1.2%, $NH_2$-N – 8.0%, $P_2O_5$ – 3.5%, $K_2O$ – 5.0%, MgO – 0.5% and microelements comprising S, Fe, B, Cu, Mn, Mo, Zn), in 20 decreasing doses, from 2.12 to 0.71 $dm^3$.

In mid-March, for each variant 35 Hiko V-120ss containers were filled with peat-perlite substrate (95/5 vol.). The maximum degree decomposition of peat moss was 15%, and the organic matter content exceeded 85% (Kormanek *et al.*, 2023). After placing the containers in the production field, 15 containers from each variant were randomly selected and numbered. Fourteen containers were taken consecutively to evaluate changes during the growing season. At the end of October (224 days after seeds sowing), the last container was taken for the study presented in this paper. During the production season for seedlings grown in variants V-1 and V-2, controlled water dosing was applied using an innovative system – Pat.232534 (Kormanek *et al.*, 2018), while in variant V-3 irrigation was carried out according to the experience of nursery staff. Each seedling was tagged and numbered, and height (SH) was measured with an accuracy of ±1 mm and root collar diameter (RCD) was measured with an accuracy of ±0.1 mm. Each seedling was cut at the RCD, separating the substrate and root system from the above-ground part, which was also separated into assimilation apparatus and shoot. The root lump was cut into three parts of equal length: upper zone – A, middle zone – B, and lower zone – C. Roots were separated from each root lump segment by removing the substrate under running water. The last stage of the measurement was determining the dry mass of the individual parts of each seedling. Drying was carried out in a Memmert UF110 laboratory dryer at 65°C for 48 hours, and the dry mass was determined with an accuracy of ±0.001 g using a Radwag PS 210 laboratory scale. The dry mass of the whole seedling (TDM – total dry mass), stem (SDM – stem dry mass), needles (NDM – needle dry mass), root system (RDM – root dry mass), and roots in three separated segments – upper, middle and lower (RDM-A, RDM-B, and RDM-C, respectively) were determined. These segments were obtained by cutting of substrate lump into three equal parts. The percentage share of needles, shoot, and root system in the dry mass of the entire seedling and the share of roots in individual segments of the lump in the dry mass of the root system were determined.

The SQ and the DQI were calculated for each seedling (Dickson *et al.*, 1960; Binotto *et al.*, 2010; Ivetić *et al.*, 2016):

$$SQ = \frac{SH}{RCD} \tag{1}$$

$$DQI = \frac{TDM}{\frac{SH}{RCD} + \frac{SNDM}{RDM}} \tag{2}$$

where:

*TDM* – total dry mass of the seedling [g],
*SH* – seedling height [cm],
*RCD* – diameter of root collar [mm],
*SNDM* – dry mass of shoot with needles [g],
*RDM* – root system dry mass [g].

SQ is an important element in predicting the survival of the seedling and its subsequent growth during cultivation (Mańas *et al.*, 2009). A higher value indicates frailer seedlings, and a lower value indicates bulkier seedlings (Haase, 2007). Seedlings with low index values are characterized by higher resistance to abiotic factors and better survival and growth in water-deficit conditions (Johnson and Cline, 1991). A maximum SQ value of 7.0, which results from the conversion of limit parameters of good quality seedlings contained in the PN-R-67025 standard (1999), was assumed to evaluate the seedlings. Like SQ, DQI also indicates the plant's potential for survival and growth and considers the total mass of the seedling, the SQ index, and the distribution of dry mass in under-ground and above-ground parts. Higher DQI values indicate a potentially better adaptation of seedlings to cultivation (Olivo and Buduba, 2006). Next, the root mass density (RMD), which gives information about the dry mass of the root system [mg] per 1 $cm^3$ of root lump, was calculated. The index was calculated by dividing the dry mass of the root system of the seedling by the volume of the substrate lump (Salonius *et al.*, 2000; Bernier *et al.*, 2005; Kahlon *et al.*, 2012), which for the Hiko V-120SS container was 120 $cm^3$. The proportion of dry mass of the above-ground part (SNDM) to RDM was calculated using the dry mass value of the particular parts of the seedling. This ratio (S/R) is a measure of the equilibrium between the transpiration area (shoot + needles) and the water absorption area (roots) in seedlings. According to Racey *et al.* (1983), it can also be determined using the volumes of the above-ground part and the root system; however, calculating the ratio with dry mass values gives a more accurate result. This ratio should be 3:1 or less for seedlings with open root systems and 2:1 or less for good-quality container seedlings (Thompson, 1985; Haase, 2007).

For each experimental variant, the mean value of the parameter was calculated for the cultured spruce seedlings. To determine the significance of the differences between the mean values of the parameters of spruce seedlings grown in containers differing in substrate compaction (V-1 and V-2) and irrigation necessity determination methods (V-2 and V-3), a one-way analysis of variance (ANOVA), fixed model, was performed. Similarly, two-factor ANOVA (fixed model) was performed for analyzing the dry mass in the three root lump zones. The calculations were performed with the Statistica 12 (StatSoft Inc., 2014) software. Diagrams showing the regression relation between DQI and the analyzed traits were also prepared for seedlings from all experimental variants.

## Results

Seedling growth. The spruce seedlings grown in the annual production cycle in the variant with compacted substrate and precise control of moisture content (V-1) were characterized by the highest height (29.0 cm) and thickness of the root collar (3.5 mm). Statistically significant differences between the experimental variants were obtained only for RCD. The mean dry mass of the seedlings ranged from 2.594 (V-1) to 2.625 g (V-3), and seedlings grown in particular variants did not show any significant differences in this respect (Table 1).

Depending on the experimental variant, the dry mass of needles and shoot ranged from 36% to 39% of the TDM of the seedling. The dry mass of the whole root system ranged from 24% to 28%, with the highest share being found in variant V-3. The results of ANOVA did not indicate any significant influence of the tested experimental variants on dry mass (Fig. 2).

Root allocation in substrate lumps. The dry masses of the three segments of the root lump were similar in all experimental variants. The dry mass of roots attained their highest values in the range of 58% to 60% in the upper lump segment; the lowest values were observed in the lower lump segment, ranging from 16% to 18% of the dry mass of the entire root system. The middle segment was characterized by dry mass with values slightly higher than the lower segment and ranged from 23% to 24% (Fig. 2).

**Table 1.**

Mean values (±SE) of analyzed characteristics of 1-year-old Norway spruce seedlings of different experimental variants grown using container technology

| Parameter | | Experimental variant | | | *F*-test (*p*-level) | |
|---|---|---|---|---|---|---|
| | | V-1 | V-2 | V-3 | V-1 *versus* V-2 | V-2 *versus* V-3 |
| SH [cm] | | 29.0 ±0.7 | 27.4 ±0.8 | 26.8 ±0.8 | 2.32 (0.13) | 0.25 (0.62) |
| RCD [mm] | | 3.5 ±0.1 | 3.2 ±0.1 | 3.3 ±0.1 | 4.86 (0.03) | 0.01 (0.93) |
| SQ | | 8.43 ±0.19 | 8.43 ±0.20 | 8.19 ±0.19 | 0.01 (0.98) | 0.70 (0.41) |
| Dry mass [g] | TDM | 2.594 ±0.110 | 2.618 ±0.132 | 2.625 ±0.116 | 0.02 (0.89) | 0.01 (0.97) |
| | SDM | 1.014 ±0.045 | 0.962 ±0.051 | 0.938 ±0.047 | 0.57 (0.45) | 0.12 (0.73) |
| | NDM | 0.950 ±0.040 | 1.003 ±0.052 | 0.948 ±0.045 | 0.66 (0.42) | 0.64 (0.43) |
| | RDM | 0.630 ±0.036 | 0.652 ±0.036 | 0.739 ±0.040 | 0.19 (0.67) | 2.51 (0.12) |
| | RDM-A | 0.380 ±0.020 | 0.387 ±0.023 | 0.428 ±0.023 | 0.04 (0.74) | 1.69 (0.20) |
| | RDM-B | 0.148 ±0.010 | 0.149 ±0.014 | 0.191 ±0.025 | 0.01 (0.97) | 2.16 (0.15) |
| | RDM-C | 0.102 ±0.013 | 0.117 ±0.009 | 0.119 ±0.009 | 0.95 (0.33) | 0.03 (0.86) |
| RMD [mg·cm$^{-3}$] | | 6.3 ±0.4 | 6.5 ±0.4 | 7.4 ±0.4 | 0.19 (0.67) | 2.51 (0.12) |
| DQI | | 0.225 ±0.011 | 0.230 ±0.013 | 0.244 ±0.011 | 0.08 (0.77) | 0.75 (0.39) |
| S/R | | 3.24 ±0.11 | 3.08 ±0.08 | 2.67 ±0.10 | 1.56 (0.22) | 11.05 (<0.01) |

SH – seedling height; RCD – root collar diameter; SQ – sturdiness quotient; TDM – total dry mass; SDM – stem dry mass; NDM – needle dry mass; RDM – root system dry mass (A – cavity upper zone, B – cavity middle zone, C – cavity lower zone); RMD – root mass density, DQI – Dickson quality index; S/R – shoot-root ratio; V-1 – seedlings grown in substrate with increased compaction and optimum moisture; V-2 – seedlings grown in substrate with standard unchanged compaction and optimum moisture; V-3 – seedlings grown in substrate with standard unchanged compaction and organoleptic moisture control

The differences in the dry masses of the spruce root system cultivated in the three experimental variants were significant ($p$<0.05). Similarly, the masses of the roots in the three root lump zones differed significantly ($p$<0.01). In each variant and the same zone, the dry mass of roots (Fig. 2) did not differ significantly. Comparing the pairs of variants V-1 and V-2 and V-2 and V-3, differing in soil compaction and moisture levels, respectively, no significant effect of the variant was found; however, a significant difference ($p$<0.01) was present between the three root lump zones (Table 2).

RATIO OF DRY MASS OF THE ABOVE- AND THE UNDER-GROUND PART. The ratio of the dry mass of the above-ground part and the dry mass of the root system (S/R index) ranged from 2.67 for variant V-3 to 3.24 for variant V-1 (Table 1), and the obtained differences between the mean values were significant (p<0.01). The index analysis for individual seedlings about the maximum permissible value (2:1) showed that only five seedlings in variant V-3 could be assessed positively. In the remaining seedlings, the dry mass of the above-ground part was too high concerning the upper limit for container seedlings. It even exceeded the maximum value for open-root seedlings (Fig. 3).

STURDINESS QUOTIENT. The average SQ of the seedling variants did not differ significantly and ranged from 8.2 to 8.4 (Table 1), and, for about 86% of spruce seedlings, exceeded the value of 70, taken as the maximum permissible value. Most of the cultivated seedlings were characterized by the SQ index between 7.0 and 10.0, indicating that they were frail and, as a result, there might be a problem with their adaptation to cultivation, especially in low soil moisture conditions. The highest number of seedlings with poor SQ values was obtained for variant V-1 (91.9%) and the lowest for variant V-3 (80.6%). Intermediate values were obtained for variant V-2 (Fig. 4).

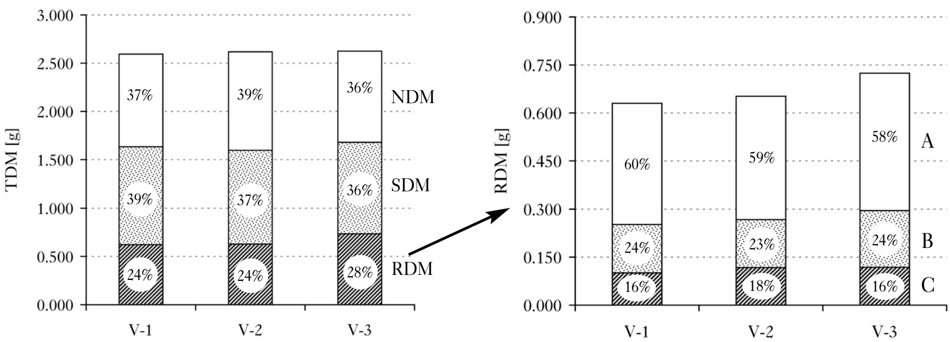


**Fig. 2.**

Share of part of seedling in the TDM and share of roots in three segments of root lumps in total RDM in experimental variants; explanation of abbreviations – see Table 1

**Table 2.**

Analysis of variance, with experimental variants and the root lump zones, of the dry mass in the spruce root system; explanation of abbreviations – see Table 1

| Source of variance | All variants | | V-1 *versus* V-2 | | V-2 *versus* V-3 | |
|---|---|---|---|---|---|---|
| | $F$-test | $p$-level | $F$-test | $p$-level | $F$-test | $p$-level |
| Variant | 3.76 | 0.03 | 0.35 | 0.56 | 3.69 | 0.06 |
| Zone | 238.51 | <0.01 | 185.67 | <0.01 | 142.10 | <0.01 |
| Variant×Zone | 0.48 | 0.75 | 0.12 | 0.89 | 0.48 | 0.46 |

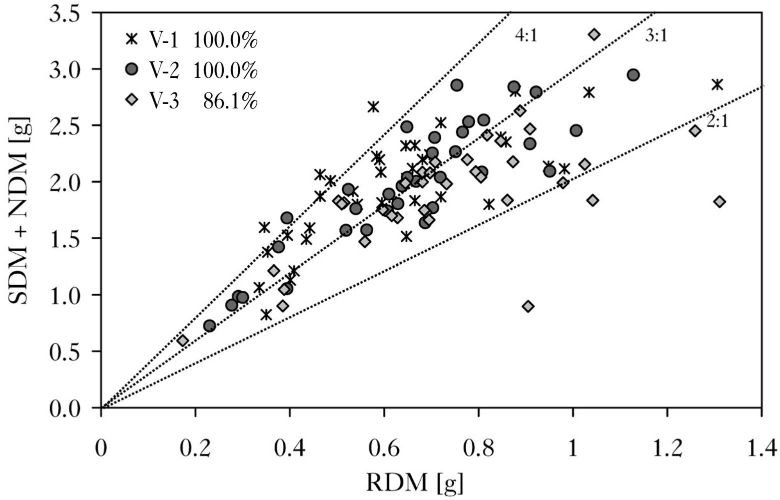


**Fig. 3.**

The relationship between the dry mass of the transpiration area – shoots and needles (SDM+NDM) and the water absorption area – roots (RDM) and share [%] of seedlings with S/R>2:1 of spruce seedlings grown in experimental variants; explanation of abbreviations – see Table 1

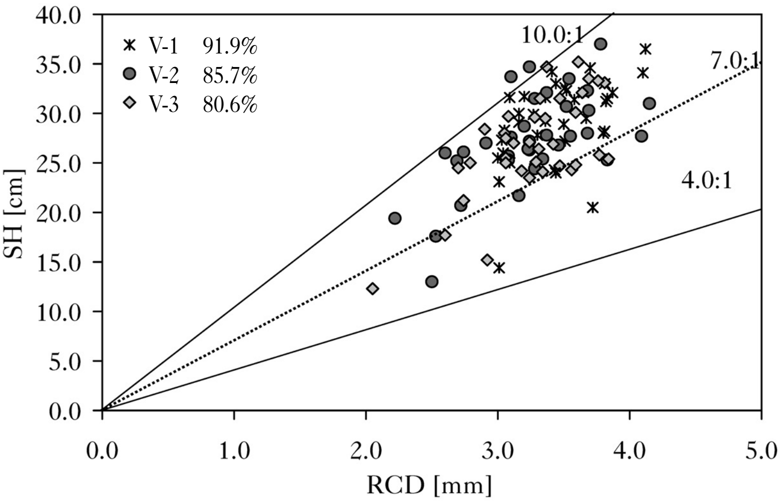


**Fig. 4.**

Relationship between seedling height (SH) and root collar diameter (RCD) and share [%] of Norway spruce seedlings with SQ>7.0 of three experimental variants; the dashed line determines the maximum value of SQ=7.0

Dickson quality index. The DQI ranged from 0.225 (V-1) to 0.244 (V-3), and the mean values did not differ significantly (Table 1). For individual seedlings, the range of DQI variability was 0.075-0.434. DQI increased with an increase in each of the analyzed parameters of spruce seedlings (Fig. 5). An analysis of regression equations showed a powerful linear relationship between DQI and dry mass (Fig. 5c-f), especially in the root system (Fig. 5d). DQI was also strongly correlated with the RCD (Fig. 5b) while weakly correlated with the SH (Fig. 5a), and an exponential equation described the observed relationship.

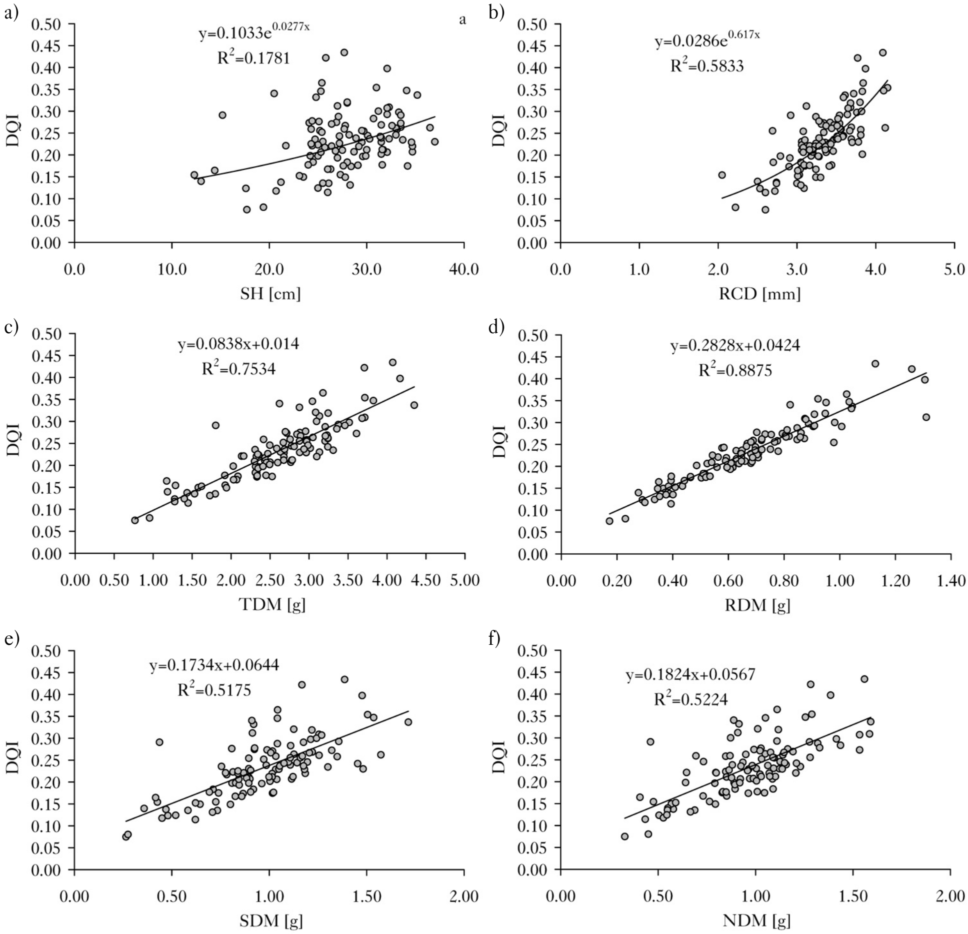


**Fig. 5.**

Comparison of the DQI and the values of analyzed characteristics of 1-year-old spruce seedlings grown in Hiko V-120SS containers; explanation of abbreviations – see Table 1

## Discussion

Seedlings grown in forest nurseries, regardless of whether they are seedlings with open or covered root systems, should be characterized by correct structure, *i.e.*, adequately developed, strong shoot, and rich assimilation apparatus. The root system of such a seedling should be proportional to the above-ground part and without any deformations (Szabla and Pabian, 2009). Comparative studies conducted in Estonia on more than a dozen forest plantations, during which the suitability of container-grown and bareroot spruce seedlings was evaluated, showed slightly better initial growth of bareroot seedlings. However, the survival rate did not depend on the planting material's production method. The lack of significant difference indicates better suitability of containerized seedlings, whose production is more accessible and the stress of transport and planting is significantly lower (Jäärats *et al.*, 2016).

An analysis of the effect of substrate compaction under precise irrigation control showed good growth of spruce seedlings. They were taller than the others and had a larger RCD. The spatial distribution of roots in the lump was similar, although individual variants differed in compaction and moisture content. The highest number of roots was found in the upper segment of the root lump, which may be explained by the morphology of the spruce root system, which is flat, with the majority of roots growing near the surface (Skrzyszewski, 1994; Paterson, 1996; Puhe, 2003). The presence of roots in the upper part of the lump in each experimental variant suggests the possibility of changing the Hiko V-120SS container (cavity depth 10.9 cm) used in the production of spruce in Poland to another type, *e.g.*, Hiko V-90AB (cavity depth 8.9 cm). A different result was obtained during laboratory tests, which showed statistically lower average root, shoot and needle weights in *P. abies* seedlings growing in soil with relative bulk densities (RBD) of 0.82 g·cm$^{-3}$, compared to those growing at RBD=0.67 g·cm$^{-3}$ (Labelle and Kammermeier, 2019).

The ratio of the mass of the above-ground part to the mass of the roots of the seedling (S/R) is one of the important parameters for assessing the quality of the seedlings and that which is already under cultivation (Kupka, 2007). The analysis of the dry mass of the spruce seedlings grown in Hiko V-120SS containers showed that most of the dry mass was located in the shoot and needles. Therefore, the ratio obtained for spruce seedlings, regardless of the experimental variant, was higher than the allowable limit, which, according to Haase (2007), should not exceed 2:1. In the experiment, only 4.6% of the seedlings had the correct value for this ratio. This aspect of seedling morphology is important since the mass of roots, in relation to the above-ground part, may directly affect the water balance of the seedling just after planting (Folk and Grossnickle, 1997; Grossnickle, 2012). A seedling with a larger root volume has a better water absorption capacity (Carlson, 1986), which helps it avoid moisture stress and, as a result, promotes better adaptation after planting (Rose *et al.*, 1991; Haase and Rose, 1993). The low S/R ratio of container-grown seedlings is generally associated with better survival during cultivation, especially under water stress (Zida *et al.*, 2008; del Campo *et al.*, 2010). With optimal soil moisture and, thus, without environmental stress during the growing season, the magnitude of the index based on the dry mass of shoots and roots is of little importance (Bernier *et al.*, 1995). Although the size of the root system, the fibrous structure, and numerous root endings are important immediately after planting (Hobbs, 1984), this is not the only factor allowing the seedlings to avoid post-planting stress. The survival and growth of seedlings in cultivation are the effects of the total impact of environmental factors, morphological and physiological features of the seedlings, and the manner of handling nursery material (South, 2000; Grossnickle, 2005; Ivetić and Škorić, 2013). Frequent irrigation but with low doses is one factor that allows nursery containers to grow more uniform *P. abies* seedlings with good growth characteristics. This nursery practice reduces the risk of consecutive short periods of drought and excess water, which negatively affects the condition of the seedlings (Langerud and Sandvik, 1991). In this aspect, a better solution would be the use of a controlled water dosing system for the production field with seedlings (Pat.232534) in combination with a containerized substrate moisture control system, which was used in our study (Kormanek *et al.*, 2018).

The obtained dry mass ratio (S/R) indicated that the above-ground part of the cultivated spruce seedlings was too large; this was also indicated by the high SQ, which, in each of the variants, exceeded the value of 7.0. This was most likely the result of applying too much-mixed fertilization, *i.e.* starter fertilization with Osmocote Bloom long-acting fertilizer combined with additional foliar fertilization with Floralesad fertilizer (Kormanek *et al.*, 2023). The magnitude of SQ determines the structure of the seedling (bulky or frail) and, at the same time, indicates its suitability for use under various forest conditions. It is a good index of abiotic damage tolerance for all types of seedlings, and its determination for seedlings grown in containers, where it can reach undesirable, very high values, is significant (Thompson, 1985; Haase, 2008). The cultivated spruce seedlings were characterized by an over-extended above-ground part, regardless of how they were produced. According to Banach *et al.* (2020), the optimal height of a spruce seedling grown in a Hiko 120SS container should be 12-25 cm. Such seedlings are characterized by a significant height increment in the first year after planting. Unfortunately, reduced irrigation and application of soil compaction resulted in weaker growth of the spruce root system, which was compensated by an increase in height and a proportionally smaller increase in thickness. As a result, a very unfavorable SQ ratio was observed, especially for compacted substrates, even though the thickest seedlings were grown in this variant. Ivetić *et al.* (2013), while analyzing the relationships between the characteristics of hop hornbeam seedlings, showed that their height is important since it affects survival during cultivation, especially in weedy habitats. However, according to Jurásek (2009), very short *P. abies* seedlings grown in a container nursery, which according to the quality classification should be rejected as out-of-class nursery material, showed very good growth and viability after nine years of growth on a forest plantation established under extreme mountain conditions compared to higher seedlings at the nursery production stage. This was also confirmed in other studies, in which it was shown that the height of *P. abies* seedlings produced in the nursery correlated negatively with the success rate on the forest plantation (Vaario *et al.*, 2009). Results obtained by Roller (1977) show that the suitability of seedlings should be assessed not only based on their height but also in combination with the diameter of the root collar. He showed the adverse effect of excessively high SQ value (above 6.0) on *Picea mariana* (Mill.) Britton, Sterns & Poggenb. seedlings, which, after planting, were severely damaged by wind, drought, and frost. Attempts should be made to reduce seedlings' height or increase the root collar's thickness by modifying the fertilizer to lower the SQ value. According to a study conducted on *Acer mono* Maxim. in the nursery, it was found that nitrogen and phosphorus in the ratio of 10:8 had a decisive effect on the growth of seedlings which reached their maximum height and diameter in the root collar (Razaq *et al.*, 2017). In the production of *P. abies* seedlings, photoperiod can also be controlled. According to Fløistad and Eldhuset (2017), the day-shortening treatment reduces the height of seedlings while it stimulates the growth of fine roots (<0.5 mm thick) and does not affect the root collar diameter, resulting in a better SQ value. Another option is to control the spectrum of light reaching the seedlings. A study by Riikonen *et al.* (2016) showed that removing far-red light (700-800 nm) from the spectrum and adding blue light (400-500 nm) reduces the height growth of spruce seedlings while increasing their SQ ratio. They also found that Norway spruce seedling's growth under treatment containing about 25% blue and 75% red light resulted in a low shoot-to-root ratio (S/R).

Determining the suitability of seedlings for planting by using the DQI gives the best results but is very laborious and requires the destruction of planting material (Ivetić *et al.*, 2013, 2016). For spruce, similar values of DQI were obtained in all experimental variants; therefore, no significant effect of irrigation and compaction reduction was found. This reduces the cost of seedling production due to a reduction in water quantity without the risk of reduction in their suitability for cultivation. A high value of this index correlates with some of the characteristics of the seedlings, *e.g.*, the thickness of the root collar, indicating the possibility of its determination using an indirect method without the need to destroy the seedling. In this case, a device for measuring the leaf area index (LAI) defined as the projected area of leaves over a unit of land, which shows a high correlation with the biomass of the above-ground part of trees, the area of the assimilation apparatus, as well as with the potential availability of water and nutrients in the soil (Fassnacht and Gower, 2007; Madugund *et al.*, 2008).

## Conclusions

- The results indicated that it is possible to control the RCD of seedlings during the production season by changing the density of the nursery substrate in combination with precise control of its moisture content.
- The precise water dosage to the production field with seedlings makes it possible to reduce the production costs of spruce seedlings by reducing water consumption during the growing season.
- The unfavorable value of the shoot-root coefficient of dry this indicates the need to change the technology of cultivation of Norway spruce seedlings to improve their suitability for planting in all soil moisture conditions.
- The main part of the root system of spruce seedlings (about 60%) was located in the upper part of the root lump, *i.e.*, to a depth of about 3.7 cm. It suggests changing the Hiko V-120SS container (cavity depth 11 cm) used in spruce production to Hiko V-90AB (9 cm). This container should not limit the development of the root system of spruce seedlings.

## Authors' contributions

The study's conception and design were performed by J.B., M.K., S.M. and G.D. Material preparation, data collection and analysis were performed by J.B., M.K., S.M., G.D. and B.M. The first draft of the manuscript was written by J.B. and B.M. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

## Conflicts of interest

The authors declare that they have no conflict of interest.

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## STRESZCZENIE

# Wpływ precyzyjnej kontroli nawadniania i zagęszczenia podłoża na wzrost sadzonek i rozmieszczenie korzeni u świerka pospolitego

Analizie poddano wzrost jednorocznych sadzonek świerka pospolitego hodowanych w szkółce kontenerowej. W badaniach zastosowano 3 warianty eksperymentalne, różniące się zagęszczeniem podłoża i ilością wody dostarczanej podczas nawadniania (kontrola poziomu wilgotności). Materiał szkółkarski został wyprodukowany w kontenerach Hiko V-120SS. Zmierzono wysokość i średnicę szyjki korzeniowej każdej sadzonki, dodatkowo określono suchą masę pędów i igieł. Suchą masę systemu korzeniowego określono oddzielnie dla 3 poziomów wysokości bryłki korze-

niowej, którą podzielono na 3 równe części: górną (A), środkową (B) i dolną (C). W każdym wariancie doświadczalnym zagęszczenie podłoża zwiększyło się w trakcie sezonu wegetacyjnego (ryc. 1). Sadzonki uprawiane w wariancie z zagęszczonym podłożem i precyzyjną kontrolą poziomu jego wilgotności osiągały maksymalną wysokość i największą średnicę w szyjce korzeniowej. Średni współczynnik wytrzymałości (SQ) sadzonek we wszystkich wariantach był bardzo wysoki, co wskazuje na ich niską odporność na czynniki abiotyczne po posadzeniu na uprawie. Podobnie stosunek suchej masy części nadziemnej do masy systemu korzeniowego był bardzo wysoki, co wskazuje na ograniczoną przydatność sadzonek do uprawy we wszystkich warunkach wilgotności gleby. Kontrolowane nawadnianie w celu precyzyjnej kontroli poziomu wilgotności nie miało znaczącego wpływu na wzrost sadzonek. Wartości indeksu jakości SQ i Dicksona również nie różniły się znacząco (tab. 1). Możliwe jest zatem obniżenie kosztów uprawy sadzonek przy użyciu systemu kontroli wilgotności gleby, który zmniejsza ilość wody dostarczanej na pole produkcyjne bez negatywnego wpływu na jakość sadzonek. Rozkład suchej masy w systemie korzeniowym był niemal identyczny we wszystkich wariantach doświadczalnych (ryc. 2). Większość korzeni znajdowała się w górnej części bryłki korzeniowej, tj. do głębokości około 3,7 cm. Średnio 60% masy całego systemu korzeniowego znajdowało się w tej strefie, a zatem pojemnik użyty do uprawy sadzonek świerka nie ograniczał wzrostu systemu korzeniowego. Niewielki udział korzeni w dolnej części bryłki sugeruje możliwość zmiany obecnie stosowanego kontenera o wysokości 11 cm na niższy, np. o wysokości 9 cm (V90AB). Udział korzeni w tej samej strefie bryłki korzeniowej nie różnił się istotnie między wariantami różniącymi się zagęszczeniem podłoża (V-1 i V-2) oraz poziomem wilgotności (V-2 i V-3), jednak istotna różnica ($p$<0,01) występowała między 3 strefami bryły korzeniowej (tab. 2). W każdym wariancie doświadczalnym większość sadzonek świerka charakteryzowała się niewłaściwą wartością współczynnika S/R, tj. proporcją suchej masy części nadziemnej do systemu korzeniowego (ryc. 3) oraz współczynnika wytrzymałości SQ, czyli ilorazu wysokości i średnicy w szyjce korzeniowej (ryc. 4). Wskazuje to na konieczność korekty technologii hodowli kontenerowych sadzonek świerka w celu poprawy obydwu parametrów (S/R≤2:1; SQ≤7,0), aby zwiększyć ich możliwości adaptacyjne przy pojawieniu się niekorzystnych warunków środowiskowych po założeniu uprawy. Analiza zależności indeksu jakości Dicksona, którego wyższa wartość wskazuje na dobry potencjał adaptacyjny sadzonki względem cech wzrostowych, wskazała na możliwość jego niedestrukcyjnego określania na podstawie średnicy w szyjce korzeniowej (ryc. 5).