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ORIGINAL RESEARCH ARTICLE

Influence of substrate compaction in nursery containers on the growth of Scots pine (*Pinus sylvestris* L.) seedlings

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Abstract. The paper presents research on influence of nursery soil compaction, composed of peat (90%) and perlite (10%), on the growth of seedlings of *Pinus sylvestris* grown in containers. Polyethylene nursery containers are used for the seedling production. These containers were filled with three different densities of the peat and perlite substrate (0.3, 0.5 and 0.7 g·cm^{-3}). During the experiment, nursery containers were initially placed in a plastic tent for a period of two months, and then for three further months in an open nursery field. Growth measurements for individual plants were the length of shoots and the root system, root collar diameter, root and shoot dry weight and photosynthetic rate. There was a relationship between the extent of compaction of the soil substrate and all analysed growth parameters of seedlings. A more compact substrate adversely affected on the number of grown seedlings and their length but positively influenced the dry mass of pine seedlings.

Key words: *Pinus sylvestris*, bulk density, container nursery, growth, root system

1. Introduction

The development of special nursery in Poland and particularly container nursery should be an impulse for more research for determining the optimal conditions for seedlings production. In specialised literature, however, there are very few publications on this subject. Therefore, resolving problems occurring during seedlings breeding in container nurseries has often an intuitive character, unsupported by research results based on field experiment analysis. One of the essential elements in this production is nursery substratum, which constitutes a habitat for seed germination and development of seedling's root system. It stores water and mineral substances which are being supplied with fertilisers that a growing plant uses. It may be also artificially enriched by mycorrhizal fungi, which improves the increase of seedlings in nursery containers and simplifies their adaption on the crop, especially on degraded areas (Szabla 2009; Buraczyk et al. 2012). An important issue in this context is defining optimal nursery substratum compaction, which influences air and water capacitance.

The majority of research and analysis associated with soil compaction influence on plant growth concern defining negative results of using forest machines working on cutting areas (Porter 1994; 1998; Więsik 1996, Ulrich et al. 2003) or on traditional filed nurseries inter alia connected with defining depth of pressure effect caused by their wheels (Etana, Håkansoon 1994; Ehlers et al. 2000; Arvidsson 2001; Boja N., Boja F. 2011), changes of characteristics and parameters of seedlings growing on compacted soil (Ozimek 1993; Kozlowski 1999; Kormanek, Banach 2012; Lipiec et al. 2013), and also changes of soil's water capacitance and absorption of mineral components supplied with fertilisers (Onweremadu et al. 2008; Lipiec, Rejman 2010).

There are few national research works concerning nursery substratum compaction and its influence on

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growth of forest tree species seedlings and so far they concern on pedunculate oak (Kormanek, Banach 2011). By contrast, foreign studies concentrate mainly on agricultural species (e.g. wheat, grass) (Bartholomew, Williams 2010; Alameda et al. 2012) and garden (Ferree et al. 2004; Onweremadu et al. 2008) or woods, but with no great importance to forest economy (Pan, Bassuk 1985; Gilman et al. 1987).

The research of nursery compaction influence, but concerning only forest trees species, was conducted by Maupin and Struve (1997) who stated that *Quercus rubra* seedling growth decreased only at substratum compaction over 1.75 $g \cdot cm^{-3}$. Similarly, container *Pinus contorta* seedlings limited their growth and dry mass at volume density over 1.7 $g \cdot cm^{-3}$ (Conlin, van den Driessche 1996). In some cases, it was necessary to increase nursery substratum compaction, as indicated by greater mass of root system and *Pinus nigra* seedling sprouts growing on substratum composed of vermiculate, peat and perlite (in proportion 1:1:1), compacted in the range from 0.71 to 1.01 $g \cdot cm^{-3}$, in comparison with non-compacted substratum (Zahreddine et al. 2004). The results mentioned obtained for some forest trees species indicate that the level of nursery substratum compaction has a significant meaning for regular seedlings growth and should be shaped depending on species and substratum type.

In this research, the aim was to define the influence of three different levels of peat substratum compaction in polyethylene container on the growth of Scots pine seedlings. The influence of compaction on plants growth was characterised by analysis of growth parameter variability and dry mass of bred planting material, combined with physical parameters of substratum.

2. Material and methods

Nursery substratum

Substratum used in production of seeds with covered root system according to the recommendation for the State Forests National Forest Holding should have air capacitance on the level of 20%–25% of volume, water capacitance in the range 800%–1000% of weight, general porosity at least of 70% and permanent pH in the range of 4.5–5.5 (Szabla, Pabian 2003).

A mixed substratum was used for research consisting of peat (90%) and perlite (10%) of pH 5.3, which was prepared in Javo mixer. Substratum after mixing was characterised by weight moisture 67.5±2.5%, which was consistent with the one used during filling the containers with seedlings production with covered root system. Then, prepared substratum was poured into containers, using three variants of compaction. First variant, without compaction (Z-1), was received after filling with substratum individual cells in nursery cassette, while the third, strong compaction (Z-3), was obtained by gradual adding substratum and its separate tamping with wooden stamp in all container's cells. After filling trial cells (without compaction and with strong compaction), the substratum was poured out, weighed and other following doses of substratum for both variants belonging to individual container was measured. Second variant, medium compaction (Z-2), was also defined with weight method as the average value of substratum mass needed for filling containers without compaction and substratum mass for variant with strong compaction. Substratum characteristics and its parameters after compaction in individual variants are shown in Table 1.

Nursery containers

For the research, a polyethylene container Hiko HV50 of 35×21 cm, consisting of 67 cells, was used. A single cell shaped like truncated cone has a full partition and a hole in lower part and vertical ribs preventing the curling up of the root system. In the case of this species breeding, nine nursery containers and three containers with different compaction of peat substratum in three repetitions were used. On roost situated on nursery bed in nursery tunnel from containers formed was tetragon (3×3 m), within which randomly individual variants of compaction were placed.

Seed sowing

Pine seeds used in the experiment originated from the collection in 2011 from selected seed stand in Niepołomice Forest District (subdivision 159c). Seeds were characterised with purity 99% and germination capacity 96%, and the mass of thousand seeds equalled 5.4 g. Nursery containers after filling with substratum were sown on 8th of May 2012, sowing one seed to each cell, and then were covered with thin layer of sand. Containers were transferred to plastic tunnel where they stayed for a 5-month period until the end of the experiment, wherein foil from tent was removed in mid-July, which is after nine weeks. Watering and fertilisation took place with the use of suspended, stationary micro-spraying system.

Table 1. Characteristics of substratum in the individual compaction variants

Variant of substratum compaction	Symbol of variant	Temporary bulk density	Dry mass bulk density	Porosity	Capillary water capacity	Air capacity
		g·cm^{-3}	g·cm^{-3}	%	%	%
Without compaction	Z-1	0.3	0.11± 0.00	90.6 ± 0.3	453.7 ± 13.2	41.0 ± 1.0
Medium compaction	Z-2	0.5	0.22 ± 0.01	81.3 ± 0.9	298.0 ± 31.9	17.0 ± 2.9
Strong compaction	Z-3	0.7	0.35 ± 0.01	69.6 ± 0.9	167.7 ± 2.3	10.3 ± 1.8

Laboratory work

After a 5-month period from the experiment beginning, grown seedlings were transferred to laboratory, where they were taken out from containers, and the substratum was removed from the root system. For this purpose, the seedlings were first soaked in water for 24 hours, and then the substratum was removed under running water. After surface drainage, separately for each seedling, the length of seedling's sprout and length of backbone root (accuracy up to 0.1 cm), and also diameter in root collar (to 0.1 mm), were measured. Then seedlings were dried in a temperature of 70°C (48 hours), and the dry mass was defined separately for root system, sprout and assimilation apparatus (up to 0.001 g).

Statistical analysis

In order to determine the influence of constant factor (variant of substratum compaction) on growth and weight parameters of seedlings, two-stage analysis of measurement data, with the use of program Statistica® 9.0 (polish version, StatSoft Inc, Tulsa, USA), were conducted. In the first stage, one-factor analysis model of variance for data from one-factor experiment was used, set up in totally random system with constant factor in the formula $y_{ik}=m+a_i+\varepsilon_{ik}$, where: y_{ik} is an observation of quantitative feature for *i*-th factor level in *k*-th repetition, m is an overall mean, a_i is an effect of *i*-th factor level, while ε_{ik} is a random component. In the second stage, after stating the relevant influence of soil compaction variant on examined seedlings feature, a graphic presentation of observed feature value for individual levels of examined factor was first performed, and then linear dependence function of measured parameters on instantaneous volume density (Mądry et al. 2010) was matched. These analyses were performed jointly for 557 seedlings obtained from three variants of nursery substratum compaction.

3. Results

The efficiency of the seedlings was very high, but depended on substratum compaction variant (Table 2) and was definitely higher from that given for this species in "Rules of silviculture" (2003) (0.7–0.8). Fewest seedlings were bred on substratum with highest compaction degree where for 201 sown seeds only 170 seedlings were obtained, whereas the highest number of seedlings (194) were obtained with the smallest substratum compaction.

The highest value of whole seedlings average length, which is a total length of backbone root and sprout, was obtained for uncondensed peat substratum (variant Z-1). Smaller seedlings observed were in the variant in which soil substratum was highly condensed (Z-3). The average reduction of seedling's length between variant Z-3 and Z-1 was close to 8.6%. This difference resulted from visibly shorter root system in variant Z-3 (by 14%). However, plants tried to compensate reduction of root length at high substratum compaction with increased growth of above-ground part (by 9.5%) and thickness in root collar (by 15.7%). Average parameters value of seedling's length in compaction variant Z-2 were very close to variant Z-1 without compaction, and only a small reduction of root system and small increase of over-ground part was noted, whereas average seedling length was equal to seedling length in variant Z-1 (Table 2, Fig. 1).

The dry mass of whole seedling increased by 26 mg (20.8%) with soil compaction increase to level Z-2 and by 40.6 mg (32.6%) for level Z-3 in comparison with

Table 2. Efficiency of Scots pine seedlings and average values of the growth characteristics with standard deviations

Variant of substratum compaction	Seedlings efficiency	Length of seedling	Length of sprout	Length of root system	Root collar diameter
	%	cm	cm	cm	mm
Z-1	96.5	18.5 ± 3.1	4.2 ± 0.9	14.3 ± 2.8	0.83 ± 0.12
Z-2	96.0	18.5 ± 3.1	4.3 ± 0.8	14.2 ± 2.7	0.90 ± 0.14
Z-3	84.6	16.9 ± 3.5	4.6 ± 1.1	12.3 ± 2.9	0.96 ± 0.18

Table 3. Average dry mass of the analysed part of Scots pine seedlings with standard deviations

Variant of substratum compaction	Average dry mass of:			
	total seedling	sprout without needles	root system	assimilative apparatus
	mg	mg	mg	mg
Z-1	124.5 ± 49.2	58.7 ± 22.8	25.1 ± 11.7	40.7 ± 17.4
Z-2	150.7 ± 56.8	70.6 ± 26.1	30.2 ± 13.1	49.9 ± 20.0
Z-3	165.3 ± 79.6	78.2 ± 37.1	31.2 ± 9.3	55.9 ± 28.1

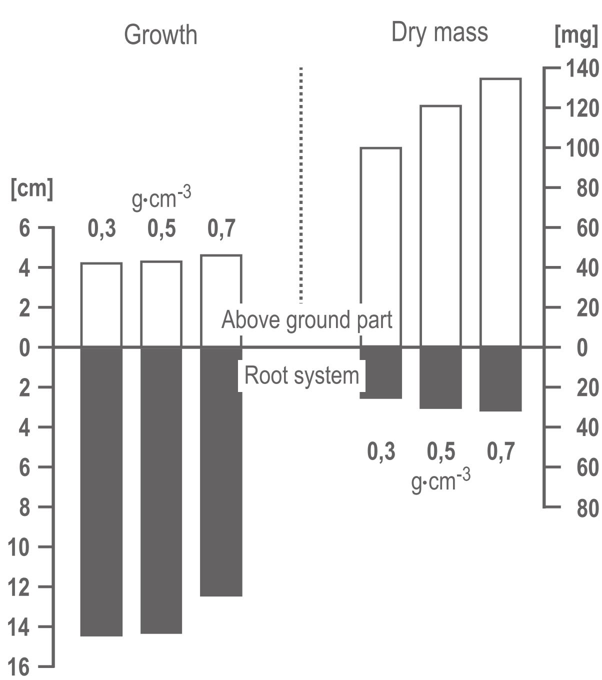

Figure 1. Proportion of length and dry mass between above-ground part and root system of Scots pine seedlings in the individual variants of substratum compaction

Z-1. The dry mass of each analysed part of seedling also increased with increase of substratum compaction (Table 3, Fig. 1).

With increase of substratum compaction the root system was reduced, whereas its mass was slightly bigger, which would indicate its stronger development. Meanwhile, the length of over-ground part was much smaller in comparison with root system (about three times), but in contrast to roots, slightly increased with stronger substratum compaction. Clearly, mass distribution of over- and under-ground part of pine seedling was differently developed, which generally increased with substratum compaction degree. Proportion between dry sprout mass with needles to mass of root system shaped was on level 3:1 for weakest compaction (0.3 $g \cdot cm^{-3}$) to 4:1 for strongest (0.7 $g \cdot cm^{-3}$). Generally, seedlings with compaction increase did have smaller length, but their dry mass was bigger (Fig. 1).

For all analysed Scots pine seedlings, the features stated a relevant statistical influence of substratum compaction degree (Table 4).

Generally, almost all analysed pine seedlings features, except for their total length and root system

Table 4. Effect of substratum compaction on the analysed parameters of Scots pine seedlings (bolded the significant)

Variable	Sum of square	Degrees of freedom	Mean square	*F*-test	Significance level (*p*)
Length of seedling	302.11	2	151.06	14.74	<0.001
Length of root system	455.42	2	227.71	28.80	<0.001
Length of above-ground part	16.05	2	8.03	9.58	<0.001
Root collar diameter	1.61	2	0.81	36.70	<0.001
Dry mass of whole seedlings	156565.89	2	78282.94	20.10	<0.001
Dry mass of above-ground part	35242.07	2	17621.04	21.01	<0.001
Dry mass of root system	4040.52	2	2020.26	9.12	<0.001
Dry mass of assimilative apparatus	21342.40	2	10671.20	22.02	<0.001

length, increased with the increase of substratum compaction in nursery containers (Fig. 2).

Correlation and determination factors between substratum compaction and parameters measured for single seedlings turned out to be relevant on established significance level at p=0.05. The highest correlation factor noted for root collar diameter was R=0.34 and for remaining value features was also positive, but slightly smaller. The exception was the length of underground part and length of whole seedling for which correlation dependence was negative (–0.23 and –0.16, respectively). The determination factor R^2 of direct trends for individual parameters was very low, which results from a high variability of parameters measured for single seedlings (Tables 2 and 3).

4. Discussion

Nursery substratum compaction leads to growth of its volume density, which consequently can significantly influence the deterioration of a plant's growth. In the majority of cases, it leads to limiting the growth of root system and reduction of whole seedling's size (Brais 2001; Ferree et al. 2004; Lipiec et al. 2013). With increment of covered root system nursery production, defining optimal factors related to used substratum is therefore an important issue.

The results obtained in the presented research indicate a visible relation between seedlings parameters and the level of nursery substratum compaction, composed of peat with perlite as an addition, as a component improving air capacitance. Generally with compaction, the seedling's dimensions decreased, but increased its thickness and dry mass. The increment of root system mass and sprout with increment of substratum compaction obtained for Scots pine is convergent with research results performed for other pine species. Seedlings of *Pinus nigra* grown on substratum composed of vermiculite, peat and perlite, condensed in the range from 0.71 to 1.01 g·cm^{-3}, were characterised by better parameters in comparison with seedlings from non-composed substratum (Zahreddine et al. 2004). Similarly, *Pinus contorta* seedlings produced in containers decreased in growth and dry mass with capacitance density over 1.7 g·cm^{-3} (Conlin, van den Driessche 1996). With comparable value of nursery substratum compaction (1.75 g·cm^{-3}) also began the limiting of *Quercus rubra* seedling growth (Maupin, Struve 1997). It indicates a need of conducting additional research for Scots pine with the use of higher volume condensation, although with used perlite–peat substratum, it is not possible due to its strongly porous structure. Perhaps such a substratum additional component should be recommended to be added to obtain higher compaction or to use containers of slightly bigger capacitance e.g. 120 cm^3, which are recommended by Szabla and Pabian (2003) for pine seedling breeding.

A significant meaning of nursery substratum compaction level indicators was also provided by Ferree et al. (2004) who by analysing *Malus domestica* seedlings grown in containers filled with soil composed of sand (20%), loam (62%) and clay (18%) stated an optimal capacitance density for their growth amounting

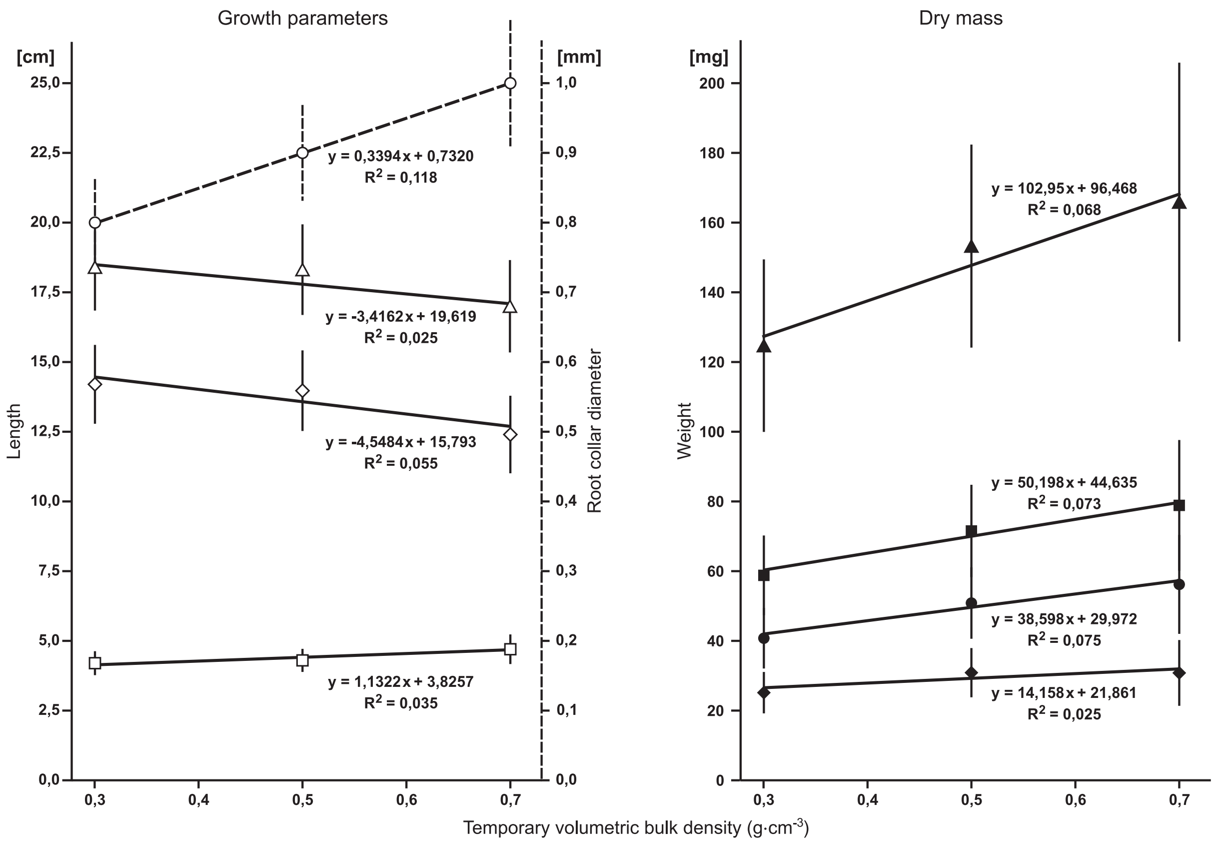

Figure 2. Change in mean value of growth parameters and mean value of dry mass of individual parts of Scots pine seedlings depending on the level of the soil substrate compaction. Length of: total seedling (Δ), above-ground part (□), root system (◊); root collar diameter (○); dry mass of: total seedling (▲), above-ground part (■), root system (♦), assimilative apparatus (●); vertical lines defined values ±1 standard deviation

to 1.2 g·cm^{-3}. Used substratum characterised with capacitance density over 1.5 g·cm^{-3} influenced negatively on seedlings, causing the decrease of their dimensions and dry mass. Slightly different results were obtained by Heilman (1981) analysing *Pseudotsuga menziesi* seedlings growing up on sandy clay and loam who stated a lack of relevant soil compaction effect on seedlings growth. Substratum penetration by roots decreased linearly with the increase of compaction and, then, its value in the range 1.74–1.83 g·cm^{-3} blocked the increment of root system. A significant influence of soil compaction on *Ailanthus altissima* seedlings was also pointed out in the research conducted by Pan and Bassuk (1985). The authors analysed the growth of seedlings in containers of diameter 20 cm filled with sandy clay and fine-grained sand and showed worse growth parameters and seedlings dry mass of this species on condensed soil. Similar results were obtained by Onweremadu et al. (2008) analysing *Citrus sinesis* seedlings growing in green-house conditions in containers filled with soil condensed to seven levels. In their research, the length of roots decreased with the increase of volume density and decreasing soil humidity. Similar result was obtained in the presented research for Scots pine, whose root system was shortened with increase of perlite–peat substratum compaction; however, its dry mass increased. Weaker increase of root system in soil of higher volume density, which is characterised by shortening of main and lateral roots, was also indicated in the analysis conducted for *Eucalyptus nitens* (Misra, Gibbons 1996). Negative influence of soil compaction was shown also in research concerning the architecture of *Gleditsia triacathos* seedlings root system. It was shown that in soil condensed by additionally reduced oxygen content, the seedlings roots grew up mainly to the top or horizontally (Gilman et al. 1987).

One of the most important parameters characterising nursery substratum is its water and air capacitance. For perlite-peat substratum, both characteristics depended on its compaction. The highest air capacitance was obtained in variants without soil compaction and research results indicate how those conditions were not optimal for pine seedlings growth. With soil compaction increase, there is decreased air capacitance and capillary water capacity, due to reduction of capillaries in soil, caused by approaching particles of permanent phase. This is confirmed by research conducted by Onweremadu et al. (2008) who stated a negative relation between soil volume compaction and its humidity. In spite of this, pine's seedlings growing up on the most condensed substratum were characterised with the highest mass, although they were slightly smaller dimensions in comparison with uncondensed substratum. Probably too loose a substratum caused quicker water float in the lower part of container, which stimulated elongation of root system. That is why stronger substratum compaction, despite lesser water and air capacitance, created better conditions for the growth of Scots pine seedlings.

5. Conclusions

1. Change of soil substratum compaction had a significant influence on all parameters established for Scots pine seedlings and the calculated determination factors for linear trend relation, despite relatively low values, were statistically significant.

2. With increase of nursery substratum compaction, the number and length of Scots pine seedlings decreased, while root system clearly shortened, whereas the length of seedlings over-ground part slightly increased. The seedlings compensated with increased root collar diameter and with increased assimilative apparatus mass for the harder growth conditions.

3. A relation between total seedling's length and their dry mass was observed. With increase of substratum compaction, the seedlings were smaller, whereas their dry mass increased.

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