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ORIGINAL PAPER

Effects of soil bulk density on sessile oak *Quercus petraea* Liebl. seedlings

Mariusz Kormanek[1] · **Tomasz Głąb**[2] · **Jacek Banach**[3] · **Grzegorz Szewczyk**[4]

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Abstract This article presents the results of laboratory examinations concerning the effects of soil bulk density on the growth of sessile oak *Quercus petraea* Liebl. seedlings. The soil for the study was collected from a nursery plot and then compacted into PCV pots in eight different bulk density levels ranging from 0.81 to 1.32 g cm^{-3}. Oak seedlings were cultivated in controlled conditions for 76 days after sowing. The growth and mass parameters of particular seedlings together with the parameters of the assimilation apparatus and roots were measured, taking into account the share of various diameter roots in the root system. For the purpose of the experiment, 120 acorns were sowed, of which 73 seedlings were cultured. An analysis of the growth of the sessile oak seedlings revealed that a change in soil density significantly affected root system development, total height of seedlings and dry mass. It was observed that the dry mass of the root system as well as the area and length of the roots decreased with an increase in soil density. Root system reduction was noted, the size of which determines the proper development of the tree and ensures its stability. Besides a decrease in the root system, an increase in soil compaction also resulted in a reduction in the number of roots of a specified diameter. The first to be affected were the smallest roots, i.e., those with diameters up to 0.2 mm, which are responsible for the uptake of mineral components. It was confirmed that even a slight increase in soil compaction might negatively result in the growth of young seedlings, impeding root system development.

Keywords Growth parameters · Roots growth strategy · Fine roots · Soil in nursery

Introduction

The growth of forest tree seedlings is conditioned by numerous abiotic factors, especially light, fertilization and water access (Sack 2004). Additionally, it may depend on numerous factors related to soil physics, including its compaction, i.e., an excessive density (Perez-Ramos et al. 2010; Alameda et al. 2012). Compaction increases bulk density and resistance during soil penetration by plant roots and decreases the diameter of soil pores, which in turn reduces permeability and water flow, as well as air capacity (Blouin et al. 2008; Bejarano et al. 2010; Boja and Boja 2011; Lipiec et al. 2012a). Such soil requires higher energy for the plant, which is essential for its root system development. This may affect the length and anatomical structure of the roots, as well as cause sprout shortening, which affects the total length of the plant (Passioura 2002; Ferree et al. 2004; Lipiec et al. 2012b). Compaction may negatively affect the growth and the quality of trees; however, these effects are not always the same and depend on the type and the level of

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✉ Mariusz Kormanek
rlkorma@cyf-kr.edu.pl

[1] Department of Forest Work Mechanization, University of Agriculture in Krakow, Al. 29 Listopada 46, 31-425 Kraków, Poland

[2] Institute of Machinery Exploitation, Ergonomics and Production Processes, University of Agriculture in Krakow, ul. Balicka 116B, 31-149 Kraków, Poland

[3] Department of Genetics and Forest Tree Breeding, Institute of Forest Ecology and Silviculture, University of Agriculture in Krakow, Al. 29 Listopada 46, 31-425 Kraków, Poland

[4] Department of Forest and Wood Utilization, University of Agriculture in Krakow, Al. 29 Listopada 46, 31-425 Kraków, Poland

soil density as well as on climatic factors (Blouin et al. 2008). In some cases, especially on skeletal soils, the high density may positively affect plant growth (Brais 2001; Fleming et al. 2006; Miransari et al. 2009). This is an effect of better contact between the roots and the soil, which improves nutrient and water uptake (Arvidsson 1999). Soil compaction can occur as a natural process as well as due to the impact of human activity and of animals treading over it (Kozłowski 1999). Anthropogenic compaction during the process of soil cultivation can be both direct and indirect, as in machines passing over a field (Picchio et al. 2012). This can be observed in both tree stands (Ampoorter et al. 2007; Zhao et al. 2010) and in forest nurseries, which are nothing other than sites where seedlings of trees and bushes are cultivated (Boja and Boja 2010, 2011).

The technology of seedling production with an uncovered root system practiced in traditional field nurseries is similar to that of agricultural production. Usually, soil preparation in forest nursery begins with tillage of the nursery area and then building beds with permanent tractor paths. Paths location should be carefully considered and very often changed; however, such approach is not always deployed. Paths usage reduces local excessive soil compaction; however, it does not fully eliminate it (Allmaras et al. 1993; Boja and Boja 2011; Lowerts and Stone 1982). The determination of the density, resulting in worsened plant seedlings' growth, holds a great deal of significance and affects the work results obtained (Mason 2004; Wesoły and Hauke 2009; Boja and Boja 2010, 2011).

Just like in agriculture, taking proper care of the soil in the nursery allows one to maximize its productivity potential. Excessive soil density is caused by a wrong selection of cultivation technology, mainly the use of heavy machines, their repeated passing along the same tracks, and improperly performed or timed cultivation practices (Hamza and Anderson 2005; Ampoorter et al. 2010; Boja and Boja 2010, 2011).

Our study concerning the effects of soil density on various species of forest trees has been conducted in tree stands (Williamson and Neilsen 2000; Mariani et al. 2006; Ampoorter et al. 2007; Neruda 2008; Boateng et al. 2011; Kormanek and Banach 2012; Picchio et al. 2012), in forest nursery conditions (Day and Bassuk 1994; Boja and Boja 2010, 2011; Kormanek et al. 2015) as well as by experiments performed in laboratory conditions (Blouin et al. 2008; Bejarano et al. 2010; Kormanek 2013).

A study on the effects of soil compaction on forest tree species under controlled conditions deals with various issues. Jordan et al. (2003) performed an analysis of seedling growth and nitrogen uptake by *Quercus rubra* and *Q. coccinea*. Soil compaction resulted in poorer seedling growth, which was reflected in their lower height and dry mass, as well as a lower nitrogen accumulation. Lower microbiological activity in the soil was also observed 6 months after the seeds were sown. Siegel-Issem et al. (2005) observed an effect of soil compaction and available water level on the growth of *Pinus ponderosa*, *P. echinata* and *P. taeda* seedlings cultured in PCV cylinders. Generally, these seedlings grow better in lower soil density with a wide range of humidity fluctuations. Soil compaction and soil air content limited plant growth, though the results varied depending on the tree species. *P. taeda* appeared to be the most resistant to air deficiency in the soil compared to the other examined species. The study conducted by Conlin (1996) on *Pseudotsuga menziessi* and *Pinus contorta* demonstrated a reduction in root growth as well as a decreased ratio of root length to root collar diameter with an increased density of clay soil. Additionally higher compaction level caused an increase in the root collar diameter of *P. contorta*, regardless of humidity level. A similar research on the growth of *P. contorta* on sandy clay soil of varying density and different humidity levels was conducted by Blouin et al. (2008). In this case, a higher water content in the soil affected seedling growth more than the level of soil compaction. Increase in soil density affected root system growth, and the critical value of soil compaction was 2500 kPa. Bejarano et al. (2010) conducted research on *Quercus pyreneica*, taking into account soil density and light access in controlled conditions. The total biomass of the seedlings was affected by both these factors; however, compaction demonstrated a higher negative impact on main root length, which was only half as long as those of the seedlings growing in low-density soil. Furthermore, the ratio of main root length to total mass was reduced by half in the case of higher compaction levels.

So far, there has been no information available in the literature concerning the effect of soil density on the growth of sessile oak (*Quercus petraea* Liebl.), which together with pedunculate oak (*Quercus robur* L.) are the most important among the 13 European oak species (Ducousso and Bordacs 2004). Both oak species are the most common and valuable in Europe, covering approximately 49,000 and 38,000 km^2, respectively (Hemery 2008), while forest stand in Poland with dominating oak covers more than 1090 km^2 (Rozwałka 2010).

Q. petraea and *Q. robur* seedling production grown in the ground nurseries in Poland stands at 7–8 million per year (Rozwałka 2010) and will increase because of the increased deciduous species participation in artificial forest cultivation. Thus, characterization of the soil mechanical parameters resulting in positive or negative impact on sessile oak seedling growth can be useful for the seedling production in nurseries and for forest cultivation.

This study examines the reactions of young seedlings (76 days after sowing) of *Q. petraea*, growing from seed, to changes in soil bulk density level. The reactions were determined based on biomass allocation and variability in the features of sprouts, leaves and roots, with special attention paid to the share of various diameter roots in the seedling's root system.

Materials and methods

Pot experiment

The pot experiment was conducted under controlled conditions in 2013. The soil for the pot experiment was collected in the spring of 2013 from the nursery plot in the "Kłaj" forest nursery (Niepołomice Forest District, southern Poland).

The pots used in the experiment were PCV cylinders of length 250 mm and diameter 150 mm. A plastic net was fixed at the bottom of each pot using a clamp, and a filter paper disk was placed inside each pot to prevent soil washout. Calculations were made to determine the mass of soil needed to fill each pot, keeping in mind the specific density needed for that pot. After the required soil mass was weighed and gradually poured into the pot, pressure was applied by a hydraulic press using a compaction stamp with a diameter of 140. In total, 32 pots with the soil compacted to eight levels of wet bulk density—1.1 (P1); 1.2 (P2); 1.3 (P3); 1.4 (P4); 1.5 (P5); 1.6 (P6); 1.7 (P7) and 1.8 g cm^{-3} (P8)—were prepared in the experiment. Each density level was prepared with four replications. The seedlings were cultivated in 24 pots, while soil samples were collected from the other ones.

Five seeds were sowed into each of the 24 pots, and they were covered with a soil layer 3–5 cm thick (Wesoły and Hauke 2009). The seeds used in the experiment were of the best quality (germination ability of 76 %) and were collected in October 2012 from the seed tree stand in Oleszyce Forest District. The pots with the sowed seeds were placed under controlled thermal (21 °C), light and humidity conditions. Irrigation was performed using micro-drenchers fixed above the cylinders.

Measurements

The soil texture, water content and the nitrogen and carbon content were determined using the sedimentation method, gravimetric method and the TruMac CNS 2000 analyzer (LECO Corporation), respectively. The soil water content during collection was 0.230 ± 0.012 cm^3 cm^{-3}. The soil texture was sandy loam (75 % sand, 14 % clay, 11 % dust). Compost was introduced into the soil more than a year earlier, which explains the increased organic carbon level (48.56 g kg^{-1}) and the low nitrogen level (3.44 g kg^{-1}) in the examined soil samples. Density of the solid phase of soil (2.34 ± 0.021 g cm^{-3}) was obtained using the pycnometric method, and the drier method was used to measure the dry bulk density and the total porosity (Terzaghi 1996). Maximum bulk density (MBD) of soil was determined using Proctor's method (ASTM 2000), and it was 1.55 g cm^{-3}. The assumed range of soil bulk density (BD) changes in the cylinder divided by the maximum bulk density (MBD) of the soil provided a relative bulk density (RBD) (Zhao et al. 2010) ranging from 0.52 to 0.85.

It was reached with optimum water content at a level of 0.282 cm^3 cm^{-3}. Soil water content during the experiment was established at the level of 0.230 cm^3 cm^{-3}.

After the appearance of leaves, the seedlings were fertilized using a foliar fertilizer. The experiment lasted 76 days, after which the soil was removed from the pot and the root system was washed under running water. The height of the seedling, its main root length (with an accuracy of ±1 mm) as well as its root collar diameter (with an accuracy of ±0.01 mm) were measured. The number and the area of the leaves were determined using Winseedle software, while the root length and diameter were determined using WinRhizo software (Regent Instruments Inc., Quebec, Canada). Seven root diameter classes were determined: <0.1; 0.1–0.2; 0.2–0.5; 0.5–1; 1–2; 2–5 and >5 mm. Dry mass of the root system, sprouts and leaves from each seedling were evaluated after drying for 48 h at a temperature of 70 °C (with an accuracy of ±0.001 g).

Statistics

The significance of the effects of soil compaction level on seedlings and on uniform groups was determined using analysis of variance (one-factor, constant model) and Tukey's test of multiple comparisons (Statistica 10.0 software; StatSoft Inc, Tulsa, OK, USA), respectively. In cases where the analysis of variance demonstrated statistically significant differences, analysis of correlation and analysis of regression were made.

Results

In total, 73 seedlings were cultivated from 120 acorns, thus sowing efficiency was 60.8 %. Analysis of the physical properties of the soil in the cylinders after various compaction treatments demonstrated an increase in bulk density and a decrease in total porosity and air capacity. In the variant with the highest soil density (P8), total porosity decreased up to the value of 0.435 cm^3 cm^{-3} (Table 1).

An increase in soil density caused a considerable reduction in the main root length, which together with a lack of change in the sprout length caused a decrease in the total length of the seedlings. The lowest value of main root length was noted in the case of the highest soil bulk density

Table 1 Physical soil parameters for compaction treatments (mean ± SD)

Treatments	Bulk density (BD) (g cm^{-3})	Total porosity (TP) ($\mathrm{cm}^3\ \mathrm{cm}^{-3}$)
P1	0.808 ± 0.006	0.654 ± 0.001
P2	0.888 ± 0.001	0.621 ± 0.001
P3	0.979 ± 0.012	0.581 ± 0.005
P4	1.050 ± 0.002	0.551 ± 0.001
P5	1.137 ± 0.011	0.514 ± 0.004
P6	1.205 ± 0.004	0.485 ± 0.002
P7	1.276 ± 0.004	0.455 ± 0.002
P8	1.316 ± 0.009	0.437 ± 0.004

(P8), i.e., 1.316 g cm^{-3}, while the length of the whole seedling was the highest with the lowest soil bulk density of 0.808 g cm^{-3} (P1).

Significant differences between the average length of the main root and the total seedling length obtained in particular density variants were observed and further confirmed by the analysis of variance and post hoc Tukey's test. The differences were not significant for other growth features (Table 2).

The lowest value of root system and whole seedling dry mass (Table 3) was obtained for P7, which was characterized by bulk density of 1.276 g cm^{-3}, while the highest one was for P1, with a bulk density of 1.1 g cm^{-3}. Soil compaction affected only the root system and the whole seedling dry mass significantly.

The analysis conducted did not demonstrate any significant difference in the number of leaves, their total area as well as leaves area on the seedling for any of the soil density variants (Table 4), whereas a significant effect of soil density was observed in the case of total length, area of the roots, average diameters of the roots as well as in the root length to their dry mass ratio (Table 5).

Total length of the roots decreased with an increased soil density (Table 5), but the range of this change was related to their diameter (Table 6). The highest loss was noted for the thinnest roots with diameters <0.1 mm and in the range from 0.1 to 0.2 mm, i.e., the roots which are responsible for nutrient uptake.

An increase in soil bulk density was negatively correlated with the length of the main root and total length of the seedling, the root system and the whole seedling dry mass, the total length and area of the roots as well as root length to their mass ratio, while a positive correlation was observed in the case of average root diameter (Table 5). An especially strong negative correlation was observed in the case of main root length ($r = -0.784$; $p < 0.01$). In the case of other mentioned features, the value of correlation coefficient was in the range of 0.5 to −0.6. The values obtained from the main root length to total root system dry mass ratio suggested that in the case of higher soil density, the roots had a higher mass per cm of the length, which means that roots with a low diameter (capillary) formed a lower share of the total mass, while the thicker roots formed the bulk. The length of roots of a particular diameter decreased with an increase in bulk density, and an especially high negative correlation was noted in the case of the finest roots, i.e., with diameter lower than 0.1 mm ($r = -0.707$; $p < 0.01$) (Table 7).

Table 2 Average growth parameters of the analyzed seedlings corresponding to the bulk density (mean ± SD; letters show means in homogeneous subsets; $p < 0.05$, Tukey's HSD post hoc test)

Treatments	Growth parameter			
	Length of primary root (cm)	Length of sprout (cm)	Length of seedling (cm)	Root collar diameter (mm)
P1	20.0 ± 1.5^{e}	16.4 ± 3.5^{a}	36.4 ± 3.7^{c}	3.17 ± 0.65^{a}
P2	19.5 ± 1.6^{de}	16.1 ± 4.1^{a}	35.5 ± 4.5^{bc}	3.28 ± 0.63^{a}
P3	18.4 ± 0.7^{cde}	15.7 ± 1.5^{a}	34.1 ± 1.6^{abc}	2.76 ± 0.68^{a}
P4	17.6 ± 1.7^{bcd}	14.0 ± 1.2^{a}	31.6 ± 2.6^{abc}	2.81 ± 0.42^{a}
P5	16.6 ± 1.7^{abc}	16.4 ± 2.0^{a}	33.0 ± 2.2^{abc}	3.49 ± 0.34^{a}
P6	15.9 ± 0.8^{ab}	16.0 ± 0.5^{a}	31.9 ± 1.14^{ab}	3.37 ± 0.44^{a}
P7	16.0 ± 1.1^{ab}	15.2 ± 1.9^{a}	31.2 ± 2.4^{ab}	2.81 ± 0.42^{a}
P8	15.5 ± 0.7^{a}	15.7 ± 3.6^{a}	31.2 ± 3.8^{a}	2.86 ± 0.44^{a}
Mean	17.6 ± 2.0	15.7 ± 2.6	33.3 ± 3.4	3.07 ± 0.57
Significance level (p)	<0.0001	0.6701	0.0007	0.0137

Table 3 Average dry mass of seedling parts corresponding to the variant of the bulk density (mean ± SD; letters show means in homogeneous subsets; $p < 0.05$, Tukey's HSD post hoc test)

Treatments	Dry mass of (g)			
	Root system	Sprout	Leaves	Total seedling
P1	1.085 ± 0.351^{a}	0.350 ± 0.202^{a}	0.440 ± 0.292^{a}	1.876 ± 0.805^{a}
P2	0.885 ± 0.258^{a}	0.242 ± 0.106^{a}	0.257 ± 0.108^{a}	1.384 ± 0.408^{a}
P3	0.840 ± 0.230^{a}	0.236 ± 0.083^{a}	0.293 ± 0.183^{a}	1.369 ± 0.436^{ab}
P4	0.793 ± 0.197^{a}	0.244 ± 0.022^{a}	0.323 ± 0.181^{a}	1.361 ± 0.205^{ab}
P5	0.718 ± 0.099^{ab}	0.266 ± 0.069^{a}	0.345 ± 0.114^{a}	1.329 ± 0.117^{ab}
P6	0.707 ± 0.104^{ab}	0.261 ± 0.037^{a}	0.293 ± 0.073^{a}	1.260 ± 0.154^{ab}
P7	0.610 ± 0.122^{ab}	0.227 ± 0.105^{a}	0.348 ± 0.094^{a}	1.185 ± 0.116^{a}
P8	0.650 ± 0.120^{b}	0.226 ± 0.045^{a}	0.377 ± 0.122^{a}	1.254 ± 0.245^{a}
Mean	0.797 ± 0.247	0.258 ± 0.105	0.335 ± 0.167	1.390 ± 0.432
Significance level (p)	0.0002	0.1703	0.3277	0.0167

Table 4 Average values of area of leaves corresponding to the variant of the bulk density (mean ± SD; letters show means in homogeneous subsets; $p < 0.05$, Tukey's HSD post hoc test)

Treatments	Leaves		
	Number (pcs)	Total area (cm^{2})	Average area (cm^{2})
P1	6.5 ± 2.2^{a}	122.0 ± 58.1^{a}	18.8 ± 6.9^{a}
P2	5.2 ± 1.0^{a}	83.6 ± 21.1^{a}	16.5 ± 4.5^{a}
P3	4.8 ± 1.2^{a}	102.0 ± 43.3^{a}	21.0 ± 7.9^{a}
P4	6.4 ± 1.8^{a}	119.8 ± 37.0^{a}	20.0 ± 9.2^{a}
P5	5.1 ± 1.4^{a}	103.3 ± 27.9^{a}	21.7 ± 7.9^{a}
P6	5.6 ± 0.5^{a}	125.4 ± 23.7^{a}	22.4 ± 3.1^{a}
P7	5.6 ± 1.3^{a}	96.2 ± 25.0^{a}	17.9 ± 6.1^{a}
P8	5.3 ± 0.9^{a}	114.7 ± 41.6^{a}	22.0 ± 7.9^{a}
Mean	5.5 ± 1.4	107.8 ± 38.3	20.0 ± 7.0
Significance level (p)	0.1061	0.2528	0.5763

Table 5 Average values of root traits corresponding to the variant of the bulk density (mean ± SD; letters show means in homogeneous subsets; $p < 0.05$, Tukey's HSD post hoc test)

Treatments	Roots			
	Total length (cm)	Total area (cm^{2})	Length/dry mass (cm/g)	Average diameter (mm)
P1	344.0 ± 157.3^{c}	67.4 ± 24.9^{c}	329.7 ± 132.1^{a}	0.63 ± 0.08^{c}
P2	339.4 ± 148.9^{bc}	59.9 ± 20.6^{bc}	399.3 ± 145.9^{a}	0.59 ± 0.10^{ac}
P3	230.6 ± 111.2^{abc}	46.6 ± 18.3^{abc}	280.7 ± 122.4^{ab}	0.69 ± 0.13^{ac}
P4	181.4 ± 80.4^{abc}	37.3 ± 11.0^{ab}	226.7 ± 73.5^{ab}	0.79 ± 0.11^{ab}
P5	178.2 ± 71.0^{a}	37.4 ± 8.8^{a}	255.1 ± 106.6^{ab}	0.69 ± 0.11^{ab}
P6	174.2 ± 28.0^{abc}	37.7 ± 7.4^{ab}	249.3 ± 47.3^{ab}	0.67 ± 0.08^{abc}
P7	147.0 ± 65.9^{a}	33.8 ± 9.3^{ab}	256.5 ± 138.8^{ab}	0.81 ± 0.20^{ab}
P8	113.3 ± 49.8^{a}	29.5 ± 10.0^{a}	172.5 ± 63.6^{b}	0.86 ± 0.10^{b}
Mean	219.0 ± 128.1	44.6 ± 19.7	274.1 ± 124.9	0.71 ± 0.14
Significance level (p)	<0.0001	<0.0001	0.0020	<0.0001

Analysis of the regression of relationship of main root length and total seedling length (Fig. 1a), dry mass of root system and total seedling (Fig. 1b), total root length (Fig. 2a), root area (Fig. 2b) as well as the values of bulk density level demonstrated the best adjustment of trend lines, which is described by a quadratic equation. The highest coefficient of determination was obtained for the course of the changes in main root length on bulk density increase ($R^2 = 0.634$).

In the case of the ratio of root length to their mass in the root system (Fig. 2c), and root diameter (Fig. 2d), the

Table 6 Average length of roots with different diameter corresponding to the variant of the bulk density (mean ± SD; letters show means in homogeneous subsets; $p < 0.05$, Tukey's HSD post hoc test)

Treatments	Length of root with diameter (mm)						
	>5.0	2.0–5.0	1.0–2.0	0.5–1.0	0.2–0.5	0.1–0.2	<0.1
P1	0.1 ± 0.2^{a}	253.2 ± 90.8^{b}	131.4 ± 36.8^{a}	157.2 ± 75.0^{b}	377.7 ± 300.2^{a}	1284.6 ± 671.9^{bc}	1235.6 ± 519.9^{c}
P2	0.1 ± 0.1^{a}	192.6 ± 84.7^{ab}	131.6 ± 30.0^{a}	122.2 ± 43.6^{ab}	340.2 ± 215.4^{a}	1339.9 ± 740.3^{c}	1267.7 ± 538.3^{c}
P3	0.0 ± 0.0^{a}	164.9 ± 72.7^{a}	120.1 ± 10.2^{a}	101.1 ± 51.7^{ab}	238.1 ± 233.2^{a}	798.5 ± 448.7^{abc}	883.3 ± 383.0^{bc}
P4	0.0 ± 0.0^{a}	162.4 ± 42.3^{ab}	113.4 ± 23.4^{a}	84.2 ± 42.4^{a}	168.8 ± 120.4^{a}	687.6 ± 428.8^{abc}	597.5 ± 320.2^{ab}
P5	0.0 ± 0.0^{a}	126.7 ± 33.6^{a}	118.5 ± 19.0^{a}	89.8 ± 28.8^{ab}	185.0 ± 176.5^{a}	568.0 ± 326.5^{a}	$694.\ 5 \pm 224.5^{ab}$
P6	0.0 ± 0.0^{a}	135.6 ± 39.0^{a}	111.9 ± 20.6^{a}	91.9 ± 35.0^{ab}	247.7 ± 125.9^{a}	607.9 ± 113.1^{ab}	547.0 ± 101.3^{ab}
P7	0.0 ± 0.0^{a}	139.2 ± 40.5^{a}	102.7 ± 21.2^{a}	113.3 ± 65.9^{ab}	229.8 ± 146.8^{a}	548.5 ± 277.3^{a}	336.5 ± 150.5^{a}
P8	0.0 ± 0.0^{a}	134.5 ± 53.0^{a}	111.2 ± 10.8^{a}	86.9 ± 38.5^{a}	153.8 ± 127.9^{a}	390.7 ± 215.4^{a}	255.7 ± 95.1^{a}
Mean	0.0 ± 0.1	165.9 ± 72.5	118.6 ± 24.6	106.6 ± 52.2	244.9 ± 202.8	797.4 ± 558.9	756.3 ± 490.7
Significance level (p)	0.433	0.0006	0.1698	0.027	0.1518	<0.0001	<0.0001

Table 7 Pearson's correlation coefficients (r) between soil bulk density and seedling parameters

Seedling parameters	r
Length of main root	–0.784**
Length of sprout	–0.064
Length of seedling	–0.513**
Root collar diameter	–0.082
Dry mass of root system	–0.546**
Dry mass of sprout	–0.227
Dry mass of leaves	0.011
Dry mass of seedlings	–0.363*
Number of leaves	–0.109
Total area of leaves	0.055
Area of average leaf	0.152
Total length of roots	–0.613**
Total area of roots	–0.615**
Length/dry mass of roots ratio	–0.438**
Average root diameter	0.502**
Length of root with diameter (mm)	
2.0–5.0	–0.473**
0.5–1.0	–0.317*
0.1–0.2	–0.551**
<0.1	–0.707**

* Correlation coefficients significant at $p < 0.05$

** Correlation coefficients significant at $p < 0.01$

linear equations of regression have the opposite signs in the trend line slopes. The root length to their mass ratio decreases with an increase in soil density, and the average root diameter is subjected to an increase, which proves a decrease in the length of lower-diameter root length in favor of the roots with higher diameters. This is also confirmed by the changes in root length in particular diameter ranges (Fig. 3a–d).

Discussion

The study demonstrated the effects of soil compaction on the growth of *Quercus petraea* seedlings. Soil compaction caused an increase in bulk density and a reduction in total soil porosity, negatively affecting plant growth as a result of the constant increase in soil compaction and the subsequent reduction in air capacity. This is in agreement with the correlation observed on other species (Misra and Goibbons 1996; Montagu et al. 1998; Zou et al. 2001; Hamza and Anderson 2005; Watson and Kelsey 2006). In field conditions, similar changes in soil parameters may be effected as a result of heavy machine traffic or intense treading by animals (Reisinger et al. 1988; Jordan et al. 2003; Cubera et al. 2009; Sowa et al. 2011; Stańczykiewicz et al. 2012; Kulak et al. 2014).

In our research soil with unprofitable density parameters (in the range of 0.81–1.32 g cm^{-3}) inhibits the growth of seedling roots and may also limit the maximum depth of their penetration. Similar results were obtained by Tworkoski et al. (1983), who observed a growth reduction in *Q. alba* seedlings, cultivated in a growth chamber, which was a reaction to the changes in soil bulk density from 1.0 to 1.5 g cm^{-3}.

The range of bulk density changes obtained in the experiment was not wide. The highest bulk density, i.e., 1.32 g cm^{-3} (Table 1) obtained for (P8) variant had relatively low value. It was an effect of high content of organic matter (organic carbon = 48.56 g kg^{-1}, nitrogen = 3.44 g kg^{-1}) that resulted from compost applications for some years before the soil analysis was conducted.

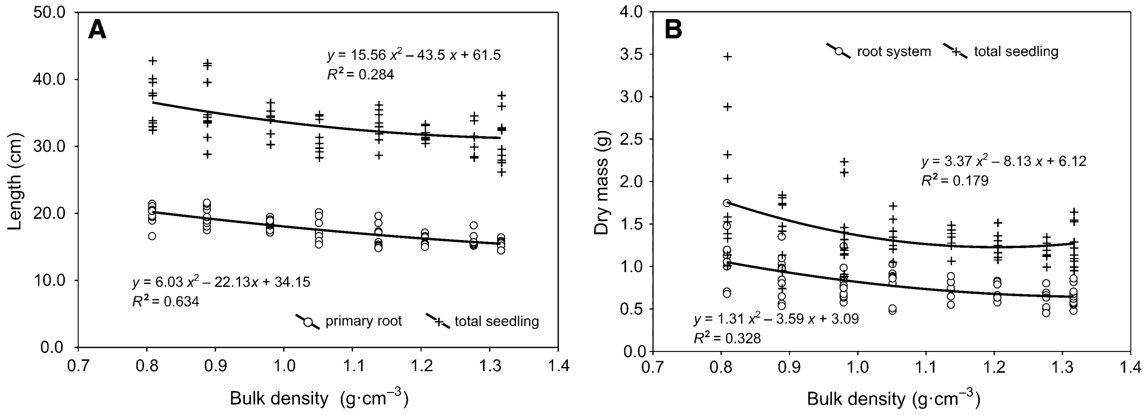

Fig. 1 Length and dry mass of particular parts of seedling depending on the variant of bulk density

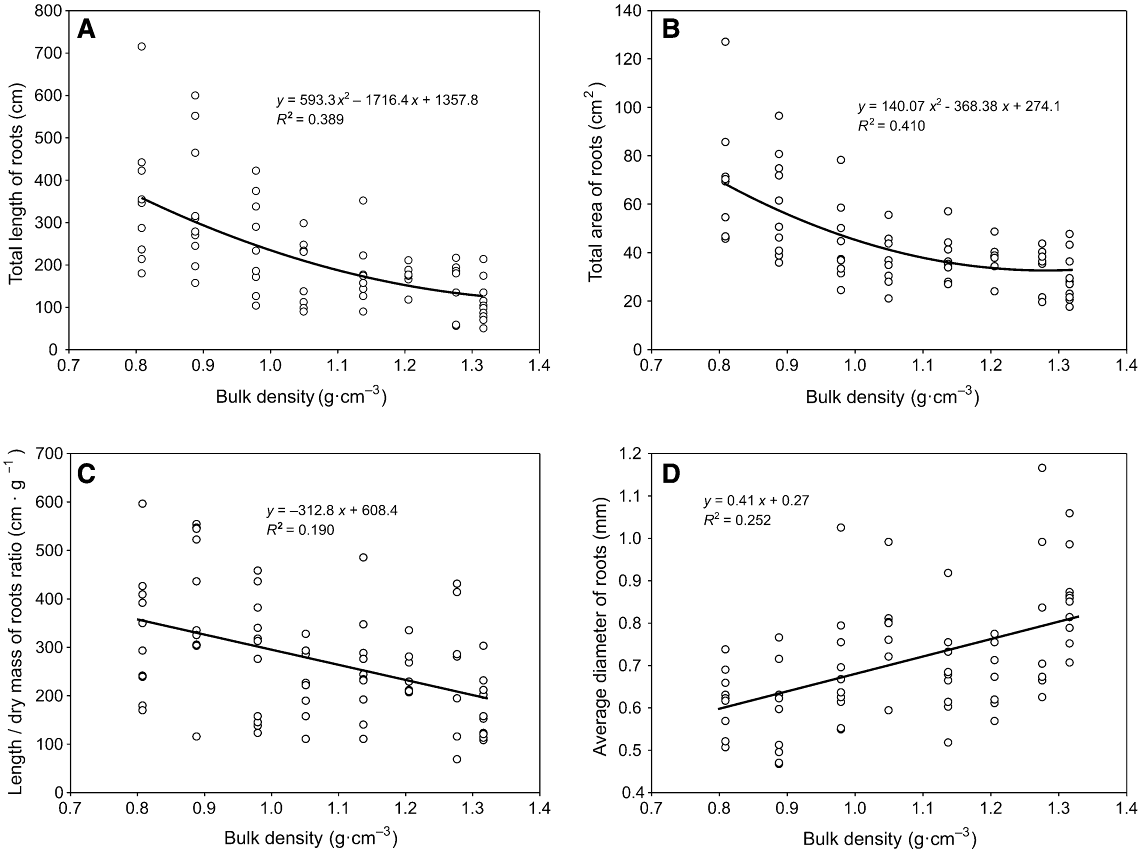

Fig. 2 Total length of roots (**a**), total area of roots (**b**), total length to dry mass of roots ratio (**c**) and average diameter of roots (**d**) depending on the variant of bulk density

However, even a slight increase in soil density caused negative effect on the plant growth.

Our research did not confirm the information regarding the range of RBD where maximum growth of seedlings is observed, or RBD value above which inhibition of seedlings is noted. According to Zhao et al. (2010), the maximum stem growth of *P. contorta, Picea glaca* and *Picea engelmannii* seedlings is for RBD range between 0.60 and 0.80. Moreover, RBD higher than 0.72 caused the growth inhibition for *Pseudotsuga menziesii* (Zhao et al. 2010), while soil RBD value higher than 0.80 should be considered as a marker of significant soil degradation. In our experiment, RBD range between 0.52 and 0.85 was established. Simultaneously, with increased RBD value, the root system of seedlings was decreased; however, it did not result in significant changes in stem parameters. Data

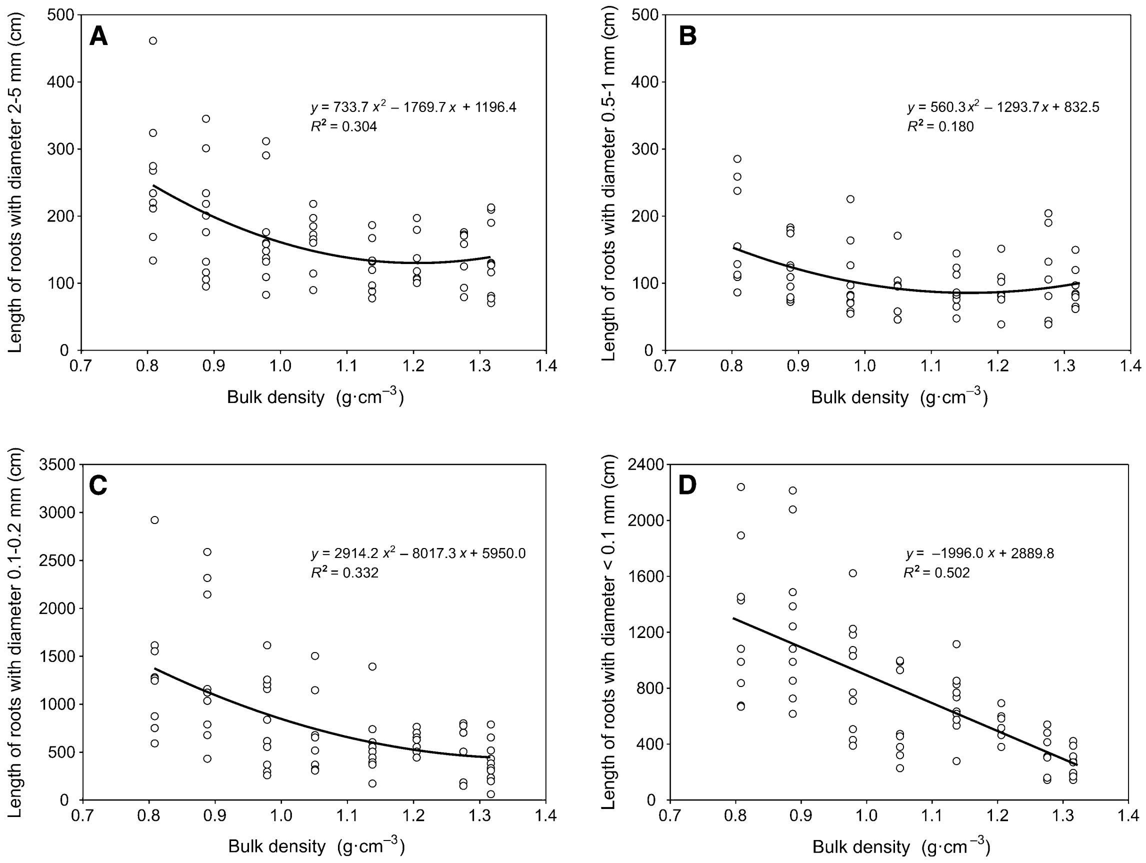

Fig. 3 Total length of seedling roots with different diameter classes depending on the variant of bulk density

discrepancy in comparison with Zhao et al. (2010) probably resulted from the very young age of oak seedlings (analysis after 76 days after sowing) which can respond negatively to even a slight increase in soil density. Germinating seeds, seedlings and young seedlings have sensitive root system, whereas stem might respond to higher density afterward (Kozlowski 1999). Another explanation of the data discrepancy might result from different growth conditions because Zhao et al. (2010) analyzed seedlings from cultivation, not from pot experiment.

According to Arvidsson (1999), slight compaction may have a positive effect on plant growth and could be due to a better root–soil contact allowing higher nutrient transport rates. This effect could be also ascribed to the fact that an increase in bulk density is related to an increase in the amount of nutrients per volume unit (Alameda et al. 2012). Alameda et al. (2012) stated that, in the absence of additional limiting stresses such as water and nutrient supplies, soil compaction enhanced growth at bulk densities up to 1.4 g cm^{-3} for a sandy soil. Tracy et al. (2013) observed that plants grown on clay loam exhibited greater growth at the higher bulk density (1.6 g cm^{-3}), whereas those grown on loamy sand showed optimum growth at 1.3 g cm^{-3}. Czyż (2004) found the optimum bulk density of sandy loam soil to be in the range from 1.51 to 1.63 g cm^{-3} in a trial with barley.

There are significant differences in bulk density range, which favor or limit the plant growth. Thus, every species should be examined separately, considering operational use of the given density range (nursery, cultivation, etc.), and for seedlings as well. RBD values range for seedlings can vary and may depend on the samplings growth stage.

The reduction in the average depth of root penetration in compact soil which was demonstrated for *Q. petraea* was similar to the reaction of the root system in *Q. pyreneica* observed in the study conducted by Bejarano et al. (2005). This is an important finding when we consider that root system development, especially the depth of soil penetration by the root, is of significant importance for the survival of seedlings. This was demonstrated by Moehring and Rowls (1970), who observed a reduction in the survival rate of trees in forests where of the value of soil density had increased up to 57 %. Additionally, young seedlings cultivated on strongly compacted soil are more susceptible to stress related to other factors, like water and nitrogen deficiency (Youngberg 1959; Reisinger et al. 1988; Jordan et al. 2003). Significant negative correlation between an increase in soil density and total seedling length was also obtained by Cubera et al. (2009) for *Q. ilex* seedlings, which is also consistent with the results obtained for *Q. petraea* in this experiment. A decrease in root numbers in *Q. palustris*, though the trees were of a higher size (DBH 30 cm), as an effect of soil compaction was also noted by Watson and Kelsey (2006), and the reason for this phenomenon was mainly the reduction in the spring oxygen diffusion rate resulting from the compaction of upper soil layers caused by moving machines. These results confirm the negative effect of excessive compaction on oak growth in natural restoration conditions, and they also prove the sustainability of a negative effect on the trees. On the other hand, none of the studies mention a reduction in tree diameter at breast height, leaves area, trunk growth or tree decline. As demonstrated by Moreno et al. (2005), a high density and a good penetration depth of a suitably developed root system minimizes the underground competition between the trees and herbal plants, like *Q. ilex* which in forest sites concentrate their roots at a depth of 30–50 cm. The studies conducted for various oak species also point to their different reactions to a stress condition such as soil compaction, which justifies the need for such kind of research to be performed separately for each species. The results obtained by Hicks (1998) point to a higher resistance of *Q. rubra* to stress conditions, such as compaction or shadowing, compared to *Q. coccinea*. The study of Yarham (1988) in turn, demonstrated a higher susceptibility of the roots to fungal infections, occurring in the presence of growth limiting factors. Brasier (1996) demonstrated that in the case of oaks, the root loss together with drought may favor the colonization and development of the *Phytophtora cinnamomi* pathogen.

The experiments conducted under controlled conditions are, however, of a different character compared to the field experiments conducted on mature trees, but the conclusions obtained point toward the unprofitable effect of soil compaction on oak, which could even lead to its decline. This was demonstrated in the research concerning the decline of other tree species as a result of soil compaction related to a decrease in NH_4–N content (Wilson and Skeffington 1994; Azlin and Philip 2004; Fonseca et al. 2004).

The present results are consistent with the results of greenhouse research on *Q. petrea* and those on various other species of forest trees cultivated on soil with artificially induced and controlled compaction levels (Sands and Bowen 1978; Corns 1988). The reduction in root growth and root system dry mass as a response to high soil density was noted in other seedlings and trees as well (Misra and Goibbons 1996; Mosena and Dillenburg 2004). Onweremadu et al. (2008) demonstrated a significant effect of soil bulk density and water content on *Citrus sinensis* seedlings, while Zhao et al. (2010) and Blouin et al. (2008) conducted research on *P. menziesii*, *P. contorta* and the crossbreed of *Picea glauca* and *P. engelmannii*, and on *P. contorta* seedlings, respectively. A reduction of the main root length with an increase in soil bulk density was also observed by Sands and Bowden (1978) in *Pinus radiata* seedlings, as well as by Corns (1988) for *P. contorta* and *P. glauca* seedlings. The effect of compaction level on the growth of *Pinus nigra* seedlings was evaluated by Zisa et al. (1980) in the experiment using silty clay and loamy sand compacted in the range of 1.2–1.8 g cm^{-3}. The author noted a reduction in the root system of seedlings cultivated on silty clay with a bulk density of 1.4 g cm^{-3}, while in these seedlings cultured on loamy sand in density of 1.6 g cm^{-3}. Hatchell et al. (1970) demonstrated that *Pinus taeda* seedlings cultivated in laboratory conditions showed definitely poorer growth when cultivated on strongly compacted soil as compared to those grown on non-compacted soil.

All cited authors thus point to a negative effect of soil compaction on root system growth in the seedlings of various forest tree species. It was also observed that in Mediterranean species, the depth of root penetration determines the plant's resistance to drought (Rambla 1993). The higher biomass allocation in the root system of these seedlings allows for an intense water uptake by the roots from the deeper, more humid soil layers, thus increasing their chance to survive. Thus, the reduction in the size of the root system as a result of an increased soil compaction may also be significant for the adaptation of the *Q. petraea* species.

Conclusions

An analysis of the growth of sessile oak seedlings cultivated in a laboratory pot experiment demonstrated that changes in soil bulk density in the range of 0.81–1.32 g cm^{-3} significantly affected root system development, total height and seedling dry mass.

Increased soil compaction had negative impact on seedling growth in the experiment, though there were relatively low RBD values compared to other studies. Even a slight increase in soil density had a negative impact on plant growth, limiting root system growth in case of young seedlings (76 days after sowing).

It was noted that the main root of *Q. petraea* seedlings decreased significantly with soil density increase, also in addition to the dry mass of the whole root system, the total area and the length of the roots also being reduced. This reduction in the size of the root system is cause for concern since it is this which determines the proper development of the tree and ensures its stability. In addition to a decrease in the root system, the numbers of roots of a specified diameter were also reduced with an increase in soil compaction. The first to be affected were the smallest roots, i.e., those with diameters up to 0.2 mm, which are responsible for the uptake of mineral components.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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