

Quality of Scots pine, European beech and pedunculate oak grown from sowing on soil with different compaction levels

Jacek Banach^{1*} , Mariusz Kormanek² , Jakub Jaźwiński³ 

University of Agriculture in Krakow, Faculty of Forestry, 46 29-Listopada 46 Ave., 31–425 Krakow, Poland; ¹Department of Forest Ecology and Silviculture; ²Department of Forest Work Mechanization; ³Department of Forest Management

*Tel. +48 12 6625125, e-mail: rlbanach@cyf-kr.edu.pl

Abstract: In this study, we explore the effect of soil compaction on the growth of seedlings of Scots pine *Pinus sylvestris* L., European beech *Fagus sylvatica* L. and pedunculate oak *Quercus robur* L. On the experimental plots, ground contact pressures ranging from 0 to 250 kPa was applied on the soil. The applied pressure resulted in an increase in soil compaction between 1.02 to 1.19 g cm⁻³, which reflected pressures exerted by the undercarriage of vehicles used in logging. We then measured the seedlings as well as the dry weight of the roots and the above-ground parts. Using this data, we calculated the following quality indicators for each seedling: *SQ* – sturdiness quotient, *S/R* – shoot to root dry mass, *DQI* – Dickson quality index. For pedunculate oak, the *SQ* value significantly improved with increasing soil compaction, whereas no differences in the other two indicators were observed. In case of the European beech, the best value of *SQ* and *DQI* were observed at a soil density of 1.11 g cm⁻³, whilst no significant difference for the *S/R* coefficient could be found. Completely different results were obtained for Scots pine. The most favorable growth was observed when no pressure was applied. However, the *SQ* and *S/R* ratios even exceeded the values commonly considered acceptable. Our results therefore indicate that the values of seedling quality indicators are indeed influenced by soil compaction. At a soil compaction of 1.11 g cm⁻³, the share of seedlings with the *SQ* value below the critical level was the highest, but a similar relationship could not be confirmed for the other indicators. The response of the seedlings to compaction is likely to be species specific.

Keywords: ground contact pressure, seedling quality, sturdiness quotient, *S/R*, *DQI*

1. Introduction

Excessive soil compaction as a result of logging is considered to be an important factor that can affect the natural regeneration of the forest (Ulrich et al. 2003). Alexander's research (2012) showed that even 40 years after harvesting, soil compaction in areas where the machines moved was significantly higher compared to areas where they were absent. According to Basset et al. (2005), excessive soil compaction can cause weaker development of seedling roots by limiting the availability of oxygen as a result of decreased porosity and the lack of connections between pores, hindering the process of gas, water and heat exchange and also inhibits the growth of horizontal roots. Such changes were observed both within the skid trail and in its immediate vi-

city (Whalley et al. 1996; von Wilpert, Schäffer 2006). The natural regeneration of the forest under such conditions can be limited, with the additional negative aspects of erosion and the runoff of the most fertile soil layer (Cambi et al. 2015). The research conducted by Sohrabi et al. (2019) showed that the negative effects of soil compaction are still visible 20 years after skidding, as shown by lower porosity and higher compaction, which hinder the penetration of roots into the deeper layers of the soil profile.

There is little information on the tolerance of the natural regeneration of forest trees to soil or substrate compaction. National studies have shown that an increase in ground contact pressure on the soil in the range of 50 to 250 kPa has a negative impact on the growth parameters of pine, beech and oak (Kormanek, Banach 2012; Kormanek et al. 2015a).

Received: 28.08.2020 r., accepted after revision: 23.10.2020 r.

A similar dependence was shown in studies of other forest species (Brais 2001; Fleming et al. 2006). A smaller number of emerging regeneration in the area of skidding trails was also observed compared to the area outside these trails (De Armond et al. 2019; Sohrabi et al. 2019).

Research has mainly focused on changes in the growth parameters of natural renewals or nursery-produced seedlings due to a change in soil compaction (Jordan et al. 2003; Alameda, Villar 2009; Kormanek et al. 2015a,b; Jourgholami et al. 2016), but there is no information on the quality of the renewals. In this study, three coefficients were used to assess the quality of pine, beech and oak renewals growing in soil with different levels of compaction, which are usually used to assess seedlings grown in forest nurseries (Thompson 1985; Olivo Buduba 2006; Hasse 2007; Ivetić et al. 2016; Skrzyszewska et al. 2019). The performed analyses investigate hypothesis about the lack of influence of compaction on the size of the quality indicators of the grown experimental material.

2. Material and methods

The experiment was located in the back areas surrounding the Kłaj nursery in the Niepołomice Forest District in Section 296a (49°59'41"N, 20°20'16"E). The study site was set up under a forest canopy consisting of 80–100-year-old pedunculate oak growing in a fresh mixed forest habitat (LMśw) and on rusty soils (RDw). Experimental plots were prepared for the three analysed species on which ground contact pressure of the following values was exerted: 50 (variant ZG_{50}), 100 (ZG_{100}), 150 (ZG_{150}), 200 (ZG_{200}) and 250 kPa (ZG_{250}), using a CUWKN-1 device for the static compaction of the soil (Kormanek 2011, 2015). For each pressure variant, 6 experimental plots of 25 × 25 cm and 6 control plots were prepared, i.e. without pressure-variant ZG_0 (0 kPa). A total of 36 plots were tested. Depending on the ground contact pressure level, soil compaction in the upper soil layer changed up to 10 cm deep (compaction was determined with graduated cylinders of 250 cm³ volume), amounting to 1.03 g·cm⁻³ for variant ZG_{50} , 1.11 for ZG_{100} , 1.14 – ZG_{150} , 1.15 – ZG_{200} , 1.19 – ZG_{250} and 1.02 g·cm⁻³ for the variant without compaction – ZG_0 . The same number of seeds of a given species was sown in each experimental plot, i.e. 150 pine seeds, 100 beech and 50 oak, which amounted to 2,400 pine, 1,600 beech and 800 oak seeds per 1 m². The applied sowing standard took into account the low sowing value of the seeds used. The number of seeds sown in the experimental plots, although not occurring under conditions of natural regeneration, is used for full sowing (pine) or partial sowing (beech, oak) for cultivating nursery seedlings. After sowing, the seeds were covered with soil and the germination and

growth of the seedlings was controlled. The plots were watered by sprinkler irrigation during longer periods without natural rainfall. After six months, the grown seedlings were obtained by digging out the whole experimental plot, softening the soil lumps and separating out individual seedlings. Their growth characteristics were measured to determine: height, root collar thickness, length of the root system and dry mass. A more detailed description of the methodology of establishing and conducting the experiment is presented in the study by Kormanek and Banach (2012), and the methodology of determining compaction – in the study by Kormanek et al. (2015a). The results of the analysis of the growth characteristics of one-year regeneration of pine, beech and pedunculate oak depending on the applied unit pressure are presented in the study by Kormanek and Banach (2012). Using the results of measurements from those studies, we performed additional analyses of the quality of the regeneration grown in conditions of variable soil compaction, calculating and analysing three indicators used to assess the breeding suitability of seedlings grown in nurseries. For each cultivated specimen, the following attributes were calculated: sturdiness quotient (SQ), shoot to root dry mass (S/R) and the Dickson quality index (DQI).

The SQ of seedlings is calculated analogously to the slenderness coefficient of trees, with the difference that root collar thickness is used instead of diameter at breast height (1). A high SQ indicates that the seedlings are flaccid, and a low SQ indicates that the seedlings are sturdy. At a low SQ , the seedlings have a higher resistance to adverse abiotic factors and, as a result, a better survival rate. The maximum SQ value is 70 for pine and 65 for beech and oak, which are the result of converting the limits of quality Classes I and II seedlings contained in the PN-R-67025 (1999) standard.

$$SQ = \frac{SH}{RCD} \times 10 \quad (1)$$

where:

SH – seedling height [cm],

RCD – root collar diameter [mm].

Using dry mass (d.m.), the S/R was calculated as the ratio of the d.m. of the above-ground part to the d.m. of the root system (2). This ratio determines the balance between the transpiration area (shoot + needles) and the water absorption area (roots). Its size for seedlings grown in the ground should not exceed a value of 3:1 (Iverson 1984; Thompson 1985; Haase 2007):

$$S/R = \frac{SNDM}{RDM} \quad (2)$$

where:

$SNDM$ – dry mass of the shoot with assimilation apparatus [g],

RDM – dry mass of the root system [g].

The last index used, the *DQI*, determines the plant's potential for survival and growth (3). Higher *DQI* values indicate a potentially better adaptation of the seedlings after planting in the field (Dickson et al. 1960; Olivo, Buduba 2006):

$$DQI = \frac{TDM}{\frac{SH}{RCD} + \frac{SNDM}{RDM}} \quad (3)$$

where:

TDM – total dry mass of the seedling [g],

SH – seedling height [cm],

RCD – root collar diameter [mm],

SNDM – dry mass of the shoot with assimilation apparatus [g],

RDM – dry mass of the root system [g].

The statistical significance of differences between average quality indicator values was determined with the single-factor variance analysis (fixed model) using Statistica 13.3 (TIBCO Software Inc. 2017). For the *SQ* and *S/R* coefficients, the number of seedlings below and above the maximum allowable value was calculated, and the results are shown in the figures.

3. Results

For all analysed species, the difference between average *SQ* values for individual variants of ground contact pressure was statistically significant at the level of $p < 0.05$. The average *SQ* of pine specimens was very high, significantly exceeding the value assumed as the maximum ($SQ=70$) and ranged from about 141.8 for variant ZG_{150} to 197.8 for ZG_{50} . This feature differed for both analysed deciduous species. For beech and oak, the average *SQ* was below the maximum value ($SQ=65$) in each of the variants of ground contact pressure. For beech, *SQ* reached a value of 50.2 for variant ZG_{100} to 60.9 for ZG_{250} , while in the case of oak, a gradual decrease of this indicator was observed, from a value of 42.4 for variant ZG_0 , i.e. with no pressure applied, to 28.4 for variant ZG_{250} (Table 1).

The share of seedlings meeting the sturdiness criterion, i.e. with *SQ* below the maximum value for the species, was highest at ZG_{100} ground contact pressure and amounted to 13% for pine, 84% for beech and 100% for oak. Regardless of the pressure variant, the highest number of individuals with $SQ < \text{maximum}$ occurred for oak – 96% in total, and the lowest for pine – 4% (Fig. 1).

The analysis of the *S/R* emphasised large differences between pine and both deciduous species. In all experimental variants, the average *S/R* ratio of pine trees significantly exceeded the critical level of 3:1, and particularly high values were obtained for specimen sin ZG_{100} (12.2:1) and ZG_{50}

(10.6:1) ground contact pressure plots. In the case of beech and oak, the mean *S/R* values in each experimental variant did not exceed the limit value, and the differences between the variants proved not to be statistically significant. For beech, the index value ranged from 1.8:1 (ZG_0 , ZG_{100} and ZG_{200}) to 2.3:1 for ZG_{50} . The *S/R* ratio for oak in almost all variants was 0.6:1, except for variant ZG_{200} – 0.7:1 (Table 1).

The share of seedlings meeting the *S/R* criterion, i.e. with *S/R* below the maximum value of 3:1, was 100% for oak and 88% for beech, while for pine, it was 16% on average, ranging from 4% for variant ZG_{250} to 30% for variant ZG_{150} ground contact pressure (Fig. 2).

The *DQI* values varied and depended on the analysed species. On average, the lowest *DQI* values were obtained for pine, ranging from 0.002 to 0.004 for ZG_0 . In the case of beech, this index varied from 0.068 (variant ZG_{50}) to 0.99 (ZG_{100}). The highest *DQI* was characteristic of pedunculate oak, ranging from 0.115 (ZG_{250}) to 0.141 (ZG_{100}). The obtained differences between the average *DQI* values for individual ground contact pressure variants were statistically significant at $p < 0.05$ (Table 1) for only pine and beech trees.

4. Discussion

Many scientific studies have shown a relationship between soil or nursery substrate compaction and the parameters of seedlings of different forest tree species (Jordan et al. 2003; Alameda, Villar 2009; Kormanek et al. 2015b; Jourgholami et al. 2016). Increased compaction affects the properties of the soil (nursery substrate), reducing porosity (Kormanek et al. 2015b; Sohrabi et al. 2019), hindering the growth of the root system (Kozlovsky 1999; von Wilpert, Schäffer 2006; Cambi et al. 2017) and mineral uptake (Jordan et al. 2003; Cambi et al. 2017), resulting in worse plant growth. Considered separately, growth parameters (height, root collar thickness, dry mass, etc.) do not always reflect the actual value and adaptability of seedlings – a better solution is to combine them into a single index (Thompson 1985; Haase 2007). In other words, a tall seedling planted in a crop field or grown from natural renewal will not always grow well or even survive if other parameters are low.

In the presented study results, applying values of ground contact pressure in the range of 50 to 250 kPa was aimed at mapping the actual value of the pressure exerted by the undercarriage of the machines used in logging operations and its relation to seed germination and plant growth. An earlier analysis of growth and dry mass (Kormanek, Banach 2012) showed the highest values of these parameters for seedlings grown on uncompacted soil, which rapidly deteriorated at the lowest level of applied pressure (50 kPa). For oak seedlings, all analysed parameters decreased in their

Table 1. Average values of quality indicators of seedlings of analyzed species in different variants of ground contact pressure (homogeneous groups determined by Tukey's test, $p=0.05$)

Species	Variant of ground contact pressure	Soil compaction [g·cm ⁻³]	Mean value of quality index (\pm SE)		
			<i>SQ</i>	<i>S/R</i>	<i>DQI</i>
<i>Pinus sylvestris</i>	ZG ₀	1.02	170.2 \pm 6.8 ^{ab}	6.2 : 1 ^a	0.004 \pm 0.000 ^a
	ZG ₅₀	1.03	197.8 \pm 11.5 ^b	10.6 : 1 ^{bc}	0.002 \pm 0.000 ^b
	ZG ₁₀₀	1.11	173.6 \pm 11.4 ^{ab}	12.2 : 1 ^c	0.002 \pm 0.000 ^b
	ZG ₁₅₀	1.14	141.8 \pm 6.1 ^a	6.9 : 1 ^{ab}	0.003 \pm 0.000 ^b
	ZG ₂₀₀	1.15	277.9 \pm 21.7 ^c	7.0 : 1 ^{abc}	0.002 \pm 0.000 ^b
	ZG ₂₅₀	1.19	197.5 \pm 6.3 ^b	6.8 : 1 ^{ab}	0.002 \pm 0.000 ^b
<i>F</i> -test (p – significance level)			17.25 ($p<0.001$)	5.06 ($p<0.001$)	10.91 ($p<0.001$)
<i>Fagus sylvatica</i>	ZG ₀	1.02	53.5 \pm 2.4 ^{ab}	1.8 : 1 ^a	0.078 \pm 0.011 ^{ab}
	ZG ₅₀	1.03	60.0 \pm 1.8 ^{ab}	2.3 : 1 ^a	0.068 \pm 0.011 ^b
	ZG ₁₀₀	1.11	50.2 \pm 2.5 ^a	1.8 : 1 ^a	0.099 \pm 0.010 ^a
	ZG ₁₅₀	1.14	54.8 \pm 2.7 ^{ab}	2.0 : 1 ^a	0.098 \pm 0.009 ^a
	ZG ₂₀₀	1.15	55.9 \pm 1.9 ^{ab}	1.8 : 1 ^a	0.093 \pm 0.006 ^a
	ZG ₂₅₀	1.19	60.9 \pm 2.7 ^b	1.9 : 1 ^a	0.086 \pm 0.007 ^{ab}
<i>F</i> -test (p – significance level)			2.53 ($p=0.029$)	2.01 ($p=0.076$)	2.97 ($p=0.012$)
<i>Quercus robur</i>	ZG ₀	1.02	42.4 \pm 2.6 ^b	0.6 : 1 ^a	0.134 \pm 0.011 ^a
	ZG ₅₀	1.03	38.6 \pm 2.4 ^{ab}	0.6 : 1 ^a	0.121 \pm 0.020 ^a
	ZG ₁₀₀	1.11	40.2 \pm 3.4 ^{ab}	0.6 : 1 ^a	0.141 \pm 0.030 ^a
	ZG ₁₅₀	1.14	37.4 \pm 5.0 ^{ab}	0.6 : 1 ^a	0.137 \pm 0.016 ^a
	ZG ₂₀₀	1.15	39.3 \pm 2.9 ^{ab}	0.7 : 1 ^a	0.116 \pm 0.014 ^a
	ZG ₂₅₀	1.19	28.4 \pm 2.5 ^a	0.6 : 1 ^a	0.115 \pm 0.023 ^a
<i>F</i> -test (p – significance level)			2.59 ($p=0.030$)	0.75 ($p=0.585$)	0.31 ($p=0.904$)

values except for root collar thickness. The highest value of thickness at the maximum applied pressure can be interpreted as compensation for weaker growth in height (Kormanek, Banach 2012). This resulted in a clear improvement of the sturdiness factor (*SQ*) as soil compaction increased, thus increasing resistance to unfavourable abiotic conditions that may occur during the initial years of renewal growth. The factor whose influence was not determined in that experiment, and which could probably be significant in the context of the obtained seedling parameters, was their

compaction in the experimental plots. However, despite the large number of seeds sown, the number of seedlings obtained was much lower, with the yield ranging from 7% for oak to 20% for pine (Kormanek, Banach 2012), which does not deviate from the yield obtained in seedling production using the uncovered root system in outdoor nurseries. However, no significant differences were obtained between the applied ground contact pressure variants for the other two indicators (*S/R* and *DQI*). This confirmed a similar lack of correlation between the *S/R* indicator and soil compaction,

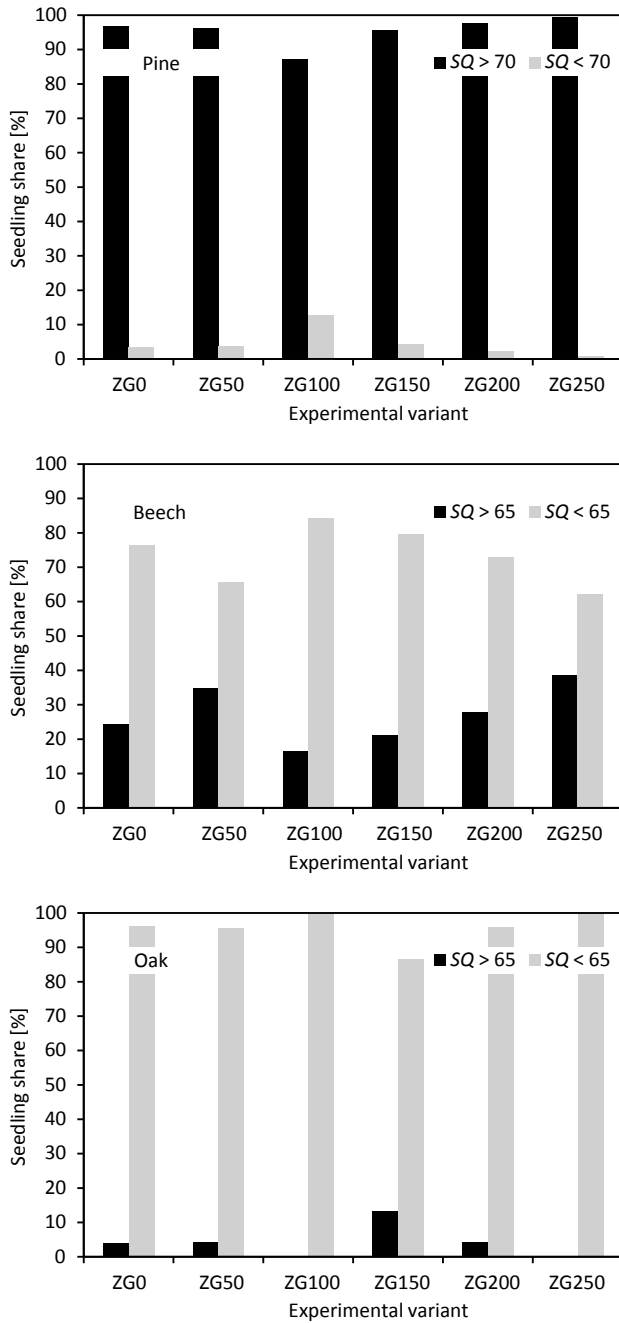


Figure 1. The share of seedlings of the analyzed species below and above the limit value of the sturdiness quotient (SQ)

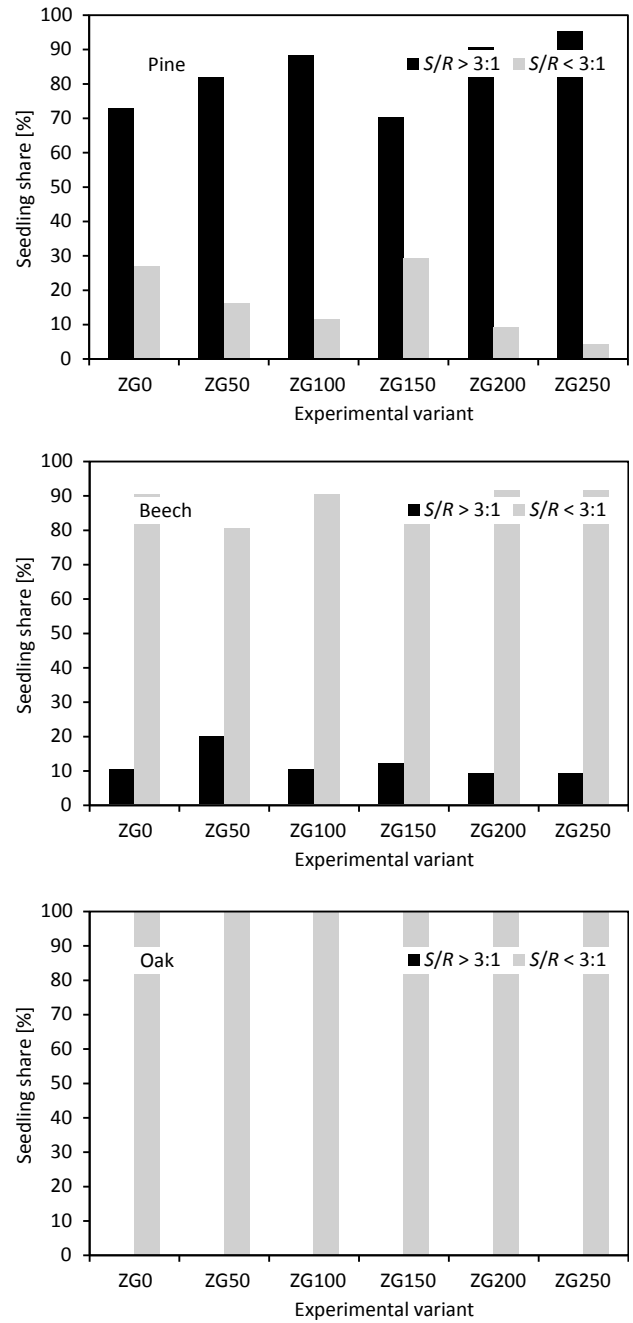


Figure 2. The share of seedlings of the analyzed species below and above the limit value shoot-root index (S/R)

which was found for other oak species, i.e. *Quercus castaneifolia* C.A.Mey. (Jourgholami et al. 2016) and *Q. ilex* L., *Q. canariensis* Willd. and *Q. pyrenaica* Willd., whereas for *Q. coccifera* L. and *Q. faginea* Lam., this indicator changed with the change in compaction (Alameda, Villar 2009). The SQ value of almost all analysed stems of the oak seedlings

was below the maximum level, except for a slightly lower value for the 150 kPa pressure variant. For beech, a slightly different picture of variability was obtained. The best average value of the SQ indicator, as well as for the DQI, was obtained in the 100 kPa pressure variant. A similar result, i.e. a significant effect of compaction on the growth characteri-

stics of European beech, was obtained by Kormanek (2013), who analysed the growth of this species under laboratory conditions. For the S/R indicator, no significant differences between the pressure variants were observed for the analysed beeches, which is consistent with the results for *Fagus orientalis* Lipsky grown from natural regeneration in felled areas after skidding machines had exerted different pressures on the soil. The *SQ* sturdiness coefficient calculated for this species in variants with different compaction significantly differed from the soil control variant (Picchio et al. 2019). At a pressure of 100 kPa, the highest share of beech (>80%) was obtained below the allowable *SQ* coefficient value, which suggests that compaction of about $1.11 \text{ g}\cdot\text{cm}^{-3}$ is optimal for the natural regeneration of this species.

Decidedly different results were obtained for Scots pine. Although the differences between the averages of the indicators in the individual variants turned out to be statistically significant, the values of the *SQ* and *S/R* coefficients considerably exceeded permissible values. Similarly, the *DQI* reached very low values, much lower than those usually obtained from nursery-grown seedlings (Memisoglu, Tilki 2014; Ivetić et al. 2017; Kolevska et al. 2020). The best indicator values were obtained for the variant with no ground contact pressure, which is consistent with Wåsterlund's earlier research (1985), in which the length of the coarse roots of common pine was inversely proportional to soil compaction. This factor also influenced the much weaker growth of the fine roots. A concurrent result for this species was obtained by Mickovski (2018), who noted that the rate of the root system's development decreased with increasing soil compaction. In addition, it turned out that the greatest increase in axial root length occurred at 15°C. In this case, the low quality indicator values of the pine seedlings could have been affected by its high density per unit area. However, this is contradicted by the best values of the indicators obtained in the control variant, i.e. with no applied compaction, as well as by the large number of germinated seeds and the obtained regeneration reported by Kormanek and Banach (2012), which could also have been affected by the fresh mixed forest habitat that is not optimal for pine. On poorer (coniferous) habitats, a lower productivity and seedlings with worse growth parameters would probably be obtained, as indicated by the results of the Dobrowolska study (2010). A significant number of renewals on intact soil compared to an area strongly affected by skidding machines was found by Lucas-Borja et al. (2020) for black pine, which, however, did not negatively affect its growth. The same trend was noted by Sohrabi et al. (2019), who analysed the regeneration in intact stands and after cutting and skidding. The difference in the number of renewals was visible 20 years after harvesting.

Generally speaking, soil compaction affects the value of the qualitative indicators, but an unequivocal answer cannot be made about the direction of the change taking place. The reaction is species-specific, which may result from the influence of various environmental factors (Blouin et al. 2008; Bejarano et al. 2010) not analysed in this experiment.

5. Conclusions

The application of different ground contact pressures on the soil influenced the size of all the indicators characterising the quality of pine seedlings. European beech seedlings were found to be significantly influenced by pressure in the *SQ* and *DQI*, while pedunculate oaks, only in the *SQ* indicator.

For each of the analysed species, the ZG_{100} ground contact pressure variant, corresponding to a soil compaction of $1.11 \text{ g}\cdot\text{cm}^{-3}$, turned out to be the variant in which the share of seedlings with *SQ* and *S/R* values below the critical level was the highest, and the *DQI* value was at its maximum. This may indicate a better increase in the renewal of the analysed species on soil with a bulk density close to this level.

Conflict of interest

The authors declare the lack of potential conflicts of interest.

Acknowledgements and funding sources

The authors would like to thank the Niepołomice Forest District for making the Klaj nursery facility available for the experiment. The research was financed from a grant of the Ministry of Science and Higher Education for the University of Agriculture in Kraków.

References

- Alameda D., Villar R. 2009. Moderate soil compaction: Implications on growth and architecture in seedlings of 17 woody plant species. *Soil and Tillage Research* 103: 325–331. DOI 10.1016/j.still.2008.10.029.
- Alexander A.B. 2012. Soil compaction on skid trails after selective logging in moist evergreen forest of Ghana. *Agriculture And Biology Journal of North America* 3(6): 262–264. DOI 10.5251/abjna.2012.3.6.262.264.
- Bassett I., Simcock R., Mitchell N. 2005. Consequences of soil compaction for seedling establishment: Implications for natural regeneration and restoration. *Austral Ecology* 30: 827–833. DOI 10.1111/j.1442-9993.2005.01525.x.
- Bejarano M.D., Villar R., Murillo A.M., Quero J.L. 2010. Effects of soil compaction and light on growth of *Quercus py-*

- renaica* Willd.(Fagaceae) seedlings. *Soil and Tillage Research* 110:108–114. DOI 10.1016/j.still.2010.07.008.
- Blouin V.M., Schmidt M.G., Bulmer C.E., Krzic M. 2008. Effects of compaction and water content on lodge pole pine seedling growth. *Forest Ecology and Management* 255: 2444–2452. DOI 10.1016/j.foreco.2008.01.008.
- Brais S. 2001. Persistence of soil compaction and effects on seedling growth in northwestern Quebec. *Soil Science Society American Journal* 65(4): 1263–1271. DOI 10.2136/sssaj2001.6541263x.
- Cambi M., Certini G., Neri F., Marchi E. 2015. The impact of heavy traffic on forest soils: A review. *Forest Ecology and Management* 338: 124–138. DOI 10.1016/j.foreco.2014.11.022.
- Cambi M., Hoshika Y., Mariotti B., Paoletti E., Picchio R., Venanzi R., Marchi E. 2017. Compaction by a forest machine affects soil quality and *Quercus robur* L. seedling performance in an experimental field. *Forest Ecology and Management* 384: 406–414. DOI 10.1016/j.foreco.2016.10.045.
- DeArmond D., Emmert F., Lima A.J.N., Higuchi N. 2019. Impacts of soil compaction persist 30 years after logging operations in the Amazon Basin. *Soil and Tillage Research* 189: 207–216. DOI 10.1016/j.still.2019.01.010.
- Długosiewicz J., Zając S., Wysocka-Fijorek E. 2019. Ocena naturalnego i sztucznego odnowienia drzewostanów sosnowych *Pinus sylvestris* L. w Nadleśnictwie Nowa Dęba. *Leśne Prace Badawcze* 80(2): 105–116. DOI 10.2478/frp-2019-0009.
- Dobrowolska D. 2010. Warunki powstawania odnowień naturalnych sosny zwyczajnej (*Pinus sylvestris* L.) na terenie Nadleśnictwa Tuszyn. *Leśne Prace Badawcze* 71(3): 217–224. DOI 10.2478/v10111-010-0017-y.
- Fleming R.L., Powers R.F., Foster N.W., Kranabetter J.M., Scott D.A., Ponder F. Jr., Berch S., Chapman W.K., Kabzems R.D., Ludovici K.H., Morris D.M., Page-Dumroese D.S., Sanborn P.T., Sanchez F.G., Stone D.M., Tiarks A.E. 2006. Effects of organic matter removal, soil compaction, and vegetation control on 5-year seedling performance: a regional comparison of long-term soil productivity sites. *Canadian Journal of Forest Research* 36(3): 529–550. DOI 10.1139/x05-271.
- Haase D.L. 2007. Morphological and physiological evaluations of seedling quality. USDA Forest Service Proceedings RMRS-P-50, 3–8.
- Iverson R.D. 1984. Planting stock selection: Meeting biological needs and operational realities, w: Duryea M.L., Landis T.D.(red.) Forest nursery manual. Oregon State University. Corvallis, USA, 261–266.
- Ivetić V., Grossnickle S., Škorić M. 2016. Forecasting the field performance of Austrian pine seedlings using morphological attributes. *iForest* 10: 99–107. DOI 10.3832/ifer1722-009.
- Ivetić V., Maksimović Z., Kerkez I., Devetaković J. 2017. Seedling quality in Serbia –Results from a three-year survey. *Reforesta* 4:27–53. DOI 10.21750/REFOR.4.04.43.
- Johnson J.D., Cline M.L. 1991. Seedling quality of southern pines, w: Duryea M.L., Dougherty P.M. (red.) Forest Regeneration Manual. Kluwer Academic Publishers, 143–159. DOI 10.1007/978-94-011-3800-0.
- Jordan D., Ponder F. Jr., Hubbard V.C. 2003. Effects of soil compaction, forest leaf litter and nitro genfertilizer on two oak species and microbial activity. *Applied Soil Ecology* 23: 33–41. DOI 10.1016/S0929-1393(03)00003-9.
- Jourgholami M., Khoramizadeh A., Zenner E.K. 2016. Effects of soil compaction on seedling morphology, growth, and architecture of chestnut-leaved oak (*Quercus castaneifolia*). *iForest* 10: 145–153. DOI 10.3832/ifer1724-009.
- Kolevska D.D., Dimitrova A., Cokoski K., Basova M. 2020. Growth and quality of *Pinus nigra* (Arn.), *Pinus sylvestris* (L.) and *Pinus pinaster* (Aiton) seedlings in two container types. *Reforesta* 9: 21–36. DOI 10.21750/REFOR.9.04.78.
- Kormanek M. 2011. Urządzenie ciągnikowe do wywierania kontrolowanego nacisku na grunt. Prawo ochronne na wzór użytkowy W – 120048.
- Kormanek M. 2013. Determination of the impact of soil compaction on germination and seedling growth parameters of common beech in the laboratory conditions. *Acta Scientiarum Polonorum Silvarum Colendarum Ratio et Industria Lignaria* 12(1): 15–27.
- Kormanek M. 2015. Relacja między mechanicznie zagęszczoną glebą a cechami biometrycznymi i jakością hodowlaną jednorocznych siewek sosny zwyczajnej *Pinus sylvestris* L. oraz buka zwyczajnego *Fagus sylvatica* L. *Zeszyty Naukowe Uniwersytetu Rolniczego im. Hugona Kollątaja w Krakowie* 530(407): 1–165.
- Kormanek M., Banach J. 2012. Wpływ nacisku jednostkowego wywieranego na glebę na jakość odnowienia wybranych gatunków drzew leśnych. *Acta Agrophysica* 19(1): 51–63.
- Kormanek M., Banach J., Sowa P. 2015a. Effect of soil bulk density on forest tree seedlings. *International Agrophysics* 29: 67–74. DOI 10.1515/intag-2015-0003.
- Kormanek M., Głąb T., Banach J., Szweczyk G. 2015b. Effects of soil bulk density on pedunculate oak *Quercus petraea* Liebl. seedlings. *European Journal of Forest Research* 134: 969–979. DOI 10.1007/s10342-015-0902-2.
- Kozłowski T.T. 1999. Soil compaction and growth of woody plants. *Scandinavian Journal of Forest Research* 14(6): 596–619. DOI 10.1080/02827589908540825.
- Lucas-Borja M.E., Heydari M., Miralles I., Zema D.A., Manso R. 2020. Effects of skidding operations after tree harvesting and soil scarification by felled trees on initial seedling emergence of Spanish black pine (*Pinus nigra* Arn. ssp. *salzmannii*). *Forests* 11(7): 767. DOI 10.3390/f11070767.
- Memisoglu T., Tilki F. 2014. Growth of Scots pine and silver birch seedlings on different nursery container media. *Notulae Botanicae Horti Agrobotanici* 42(2): 565–572. DOI 10.15835/nbha4229551.
- Mickovski S.B. 2018. The effect of environmental factors on the development of pine root systems, w: Kallel A., Ksibi M., Ben Dhia H., Khélifi N. (red.) Recent advances in environmental science from the euro-Mediterranean and surrounding regions. EMCEI 2017. Advances in Science, Technology & Innovation (IEREK Interdisciplinary Series for Sustainable Development). Springer, Cham. DOI 10.1007/978-3-319-70548-4_346.
- Olivo V.B., Buduba C.G. 2006. Influence of six substrates in *Pinus ponderosa* grown in containers under greenhouse conditions. *Bosque* 27(3): 267–271. DOI 10.4067/S0717-92002006000300007.

- Picchio R., Tavankar F., Nikooy M., Pignatti G., Venanzi R., Lo Monaco A. 2019. Morphology, growth and architecture response of beech (*Fagus orientalis* Lipsky) and maple tree (*Acer velutinum* Boiss.) seedlings to soil compaction stress caused by mechanized logging operations. *Forests* 10: 771. DOI 10.3390/f10090771.
- Skrzyszevska K., Banach J., Bownik G. 2019. Wpływ sposobu przedsięwzięcia przygotowania żołądki i terminu siewu na kiełkowanie nasion i wzrost sadzonek dębu szypułkowego. *Sylwan* 163(9): 716–725. DOI 10.26202/sylwan.2019043.
- Sohrabi H., Jourgholami M., Tavankar F., Venanzi R., Picchio R. 2019. Post-harvest evaluation of soil physical properties and natural regeneration growth in steep-slope terrains. *Forests* 10: 1034. DOI 10.3390/f10111034.
- Thompson B.E. 1985. Seedling morphological evaluation – what you can tell by looking, w: Durvea M.L. (red.). Proceedings: Evaluating seedling quality: principles, procedures, and predictive abilities of major tests. Workshop held October 16–18, 1984. Forest Research Laboratory, Oregon State University, Corvallis, 59–71.
- TIBCO Software Inc. 2017. Statistica (data analysis software system), version 13. <http://statistica.io>.
- Ulrich R., Neruda J., Valenta J., 2003. Wpływ układów jezdnych wybranych maszyn na glebę. *Inżynieria Rolnicza* 11(53): 229–235.
- von Wilpert K., Schäffer J. 2006. Ecological effects of soil compaction and initial recovery dynamics: a preliminary study. *European Journal of Forest Research* 125(2): 129–138. DOI 10.1007/s10342-005-0108-0.
- Wästerlund I. 1985. Compaction of till soils and growth tests with Norway spruce and Scots pine. *Forest Ecology and Management* 11(3): 171–189. DOI 10.1016/0378-1127(85)90025-8.
- Whalley W., Dumitru E., Dexter A.R. 1995. Biological effects of soil compaction. *Soil and Tillage Research* 35: 53–68. DOI 10.1016/0167-1987(95)00473-6.

Authors' contributions

J.B. – study concept, field work, coefficient calculations and statistical analysis, graphics preparation, literature review, manuscript writing; M.K. – study concept, field work, literature review, manuscript writing; J.J. – field work, manuscript writing.