CUTTINGS GROWTH RESPONSE OF *DALBERGIA SISSOO* (SHISHAM) TO SOIL COMPACTION STRESS

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Abstract. Because of the intensive use of machinery, soil compaction is a serious concern for soil management authorities worldwide. The use of heavy machinery to perform forestry activities such as logging has increased during the last few decades, which influences the soil ecosystem by inducing soil compaction. The main objective of this study was to observe the morphological growth response of *Dalbergia sissoo* at different compaction levels. Different morphological parameters were recorded including girth/diameter, shoot length, root length, shoot weight, root weight, shoot dry weight, root dry weight, root-shoot ratio, moisture content availability, and biomass production to analyze the effect of soil compaction. As the compaction level increased, the shoot length, root length, root weight to shoot weight ratio, and biomass production decreased. Simultaneously, the bulk density of soil increased as the compaction level increased. Soil compaction produced an overall negative effect on the growth of *D. sissoo*. Different levels of soil compaction significantly affected the physical growth parameters of the plant and reduced growth as soil compaction increased. Based on the results, the plantation of *D. sissoo* without compaction can be a viable option to obtain good quality timber.
Keywords: *biomass production, heavy machinery, morphological growth, soil bulk density, timber*

Introduction

Soil compaction is a significant factor of despoiled land and an important concern for soil management authorities all over the world. It is a serious issue associated with agriculture, forest cropping, wildlife trampling, and land restoration (Arbuckle and Lasley, 2013; Ferrara et al., 2015). The use of heavy equipment in forest management often leads to soil disturbance and compaction, which in turn affects ecosystem resilience and site efficiency (Cambi et al., 2015). This machinery seriously influences the soil ecosystem by rutting the soil, churning the upper soil layer, and soil compaction. Soil compaction can be caused by different harvesting operations that increase the bulk density of the soil (Ampoorter et al., 2012; Nawaz et al., 2013; Jourgholami et al., 2014; Kormanek et al., 2015).

Soil deprivation has become associated with soil compaction in Africa (18 million ha), Asia (10 million ha), Australia (4 million ha), Europe (33 million ha), and a few parts of North America (Silveira et al., 2010). Two main and common conflicts affected by forest management practices are organic matter changes and soil compaction. Due to increase in

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soil compaction there will be 24% rise in bulk density, 50% decrease in aeration penetrability, which ultimately leads to lower temperature and moistness of soil. (Tan et al., 2005). At moderate soil compaction levels, 53% of plant species have greater biomass production due to better root-soil interaction, a comparative growth rate increase of 41%, and a total area increase by 35% (Alameda and Villar, 2012). Soil compaction has no interaction with soil microbial properties (SMP), while it has an adverse effect on Nitrogen (N) content (Nawaz et al., 2010). At the same level of compaction, air permeability changes are typically conferred to soil physical properties by the measurement of oxygen diffusion rates (Nawaz et al., 2013).

Dalbergia sissoo is a medium-sized deciduous tree belonging to the family of Papilionaceae. It is a nitrogen-fixing tree and has a great economic value. The successful regeneration of *D. sissoo* depends on minimum competition and plentiful moisture (Singh et al., 2011). It grows in sunlit zones with abundant moisture, as well as in the rich alluvial soil of sandy banks. It is native to Afghanistan, Pakistan, India, Bhutan, and Malaysia and has naturalized in Indonesia, Cyprus, Nigeria and the United States of America (Ahmad et al., 2013). It is generally used in farm forestry and agroforestry projects in Afghanistan, Pakistan, and India. Most of the useful timber produced from *D. sissoo* comes from those countries where it is native, where it is frequently used to make furniture products. It is also used for medicinal purposes and as a fuelwood. The pods of *D. sissoo* contain 2% tannin. Soil fertility for shade-loving crops improves under *D. sissoo*, as dense litter fall decomposes to supplement the soil with phosphorus, organic carbon, and nitrogen (Hossain et al., 2011). It has been recorded that the growth rate of *D. sissoo* in 1 year is 3.7 m and in 10 years about 15 m (Orwa et al., 2009). *Dalbergia sissoo* is an appropriate species for phytoremediation of seleniferous soils (Bitterli et al., 2010).

The purpose of the present study is to examine the response of *D. sissoo* to different soil compaction levels. Heavy machinery in different farm forestry programs produces shear stress on the soil surface (Edlund et al., 2013; Naghdi et al., 2017), and trampling from domestic animals (Ferrara et al., 2015) and vibration from steady heavy traffic can cause deep compaction in the soil (Cambi et al., 2015).

Considering these situations around the world, the present study has been designed to analyze the effect of soil compaction on to the growth of *D. sissoo* cuttings, a species which has already seen some decline and dieback. For this experiment, the *D. sissoo* tree was selected because of its multiple uses, deciduous nature, high timber value, importance for fodder production, good nitrogen-fixing ability, and importance to soil conservation so that it can be successfully grown in different regions with diverse soil textures and soil moisture contents.

Materials and methods

Site description

The experiment was carried out in the research area of the Department of Forestry and Range Management, University of Agriculture Faisalabad, Pakistan (*Fig. 1*). The site lies between Latitude 30.35 °N and 31.47 °N, and Longitude 72.08 °E and 73 °E, at an elevation of 130 to 150 m above sea level. Detailed weather conditions during the course of the experiment are provided in (*Table 1*). Soil physio-chemical properties of the site are provided in **(***Table 2*).

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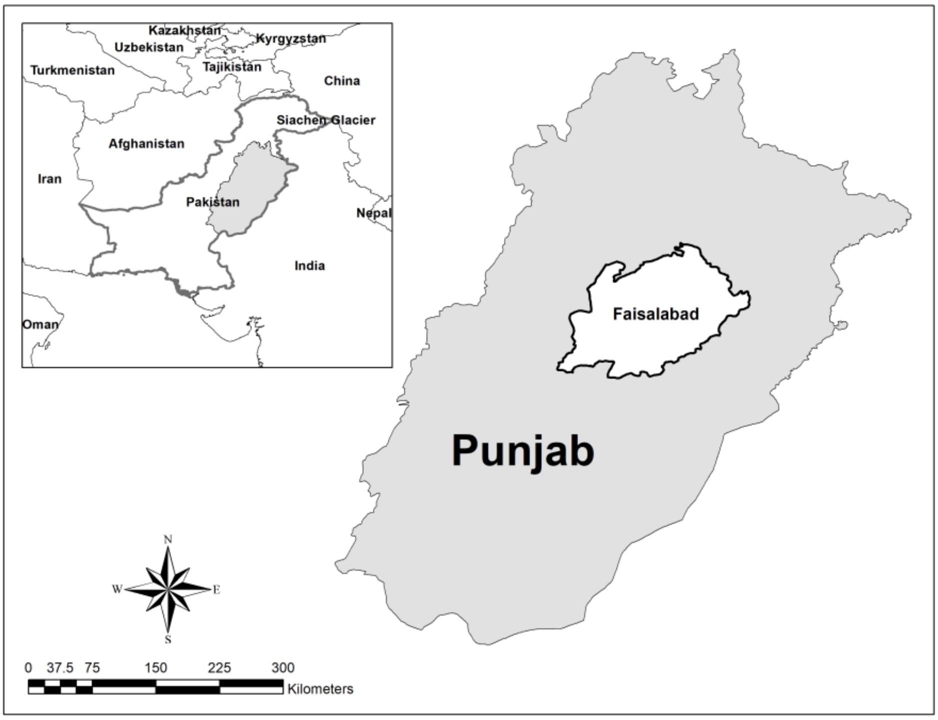

Figure 1. *Map of the research site*

Table 1. *Weather conditions of the study area. (Data taken from the agricultural meteorological cell, University of Agriculture Faisalabad)*

Month	Temperature			RH	Rainfall	Sunshine
	Max (°C)	Min (°C)	Avg (°C)	%	mm	hours
April	37.7	20.9	29.3	30.6	28.3	9.2
Avg-10 yrs	32.0	18.8	26.0	46.3	19.7	8.8
May	41.1	26.0	33.5	29.8	10.1	10.4
Avg-10 yrs	38.7	24.4	32.2	29.7	10.2	10.4
June	39.8	27.3	32.8	38.9	41.6	9.38
Avg-10 yrs	40.1	27.5	33.6	39.8	29.9	9.38
July	38.5	38.9	33.7	70.0	117.2	7.0
Avg-10 yrs	37.0	27.6	32.3	58.5	85.8	7.6
August	38.1	28.6	33.4	68.9	66.1	7.9
Avg-10 yrs	36.	26.8	31.4	61.2	50.9	7.6
September	36.7	24.4	30.5	67.7	35.6	8.8
Avg-10 yrs	33.8	22.4	28.1	57.0	47.8	8.3
October	35.0	19.2	27.1	68.2	22.2	7.6
Avg-10 yrs	32.1	19.1	25.5	55.4	10.4	8.05

Table 2. *Physical and chemical properties of experimental site*

Parameters	Sand (%)	Silt (%)	Clay (%)
0-15 cm	40	45	15
15-30 cm	69	18.5	12.5

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Parameters	pH	EC (dS m^{-1})	TSS (ppm)	Nitrogen (%)	Phosphorous (ppm)	Potassium (ppm)	Organic matter (%)
0-15 cm	8.0	1.68	1176	0.077	3.9	280	1.54
15-30 cm	8.2	1.35	1236	0.05	9.8	250	0.91

Experimental design

All plots were levelled and aligned by joining their edges. The length of each plot was 4.26 m, width was 1.21 m, the length of boundary pathway was 11.27 m, the length of the middle pathway was 11.58 m, and the width of pathways was 0.76 m (*Fig. 2*). A manual soil compactor was used to compact the soil and weeding was carried out on regular basis. The beds were prepared, and the experiment was laid out in randomized complete block design (RCBD). For the experiment six treatments were used; T0 (control), T1 (10 beatings with the manual soil compactor), T2 (20 beatings), T3 (30 beatings), T4 (40 beatings), and T5 (50 beatings). The number of replications for each treatment was 12. Beatings were applied with the manual soil compactor (weight, 10 kg) to compact the soil. This was performed by pulling the soil compactor up with the help of rope and then dropping it from a height of 0.6 m on all of the beds (*Fig. 3*).

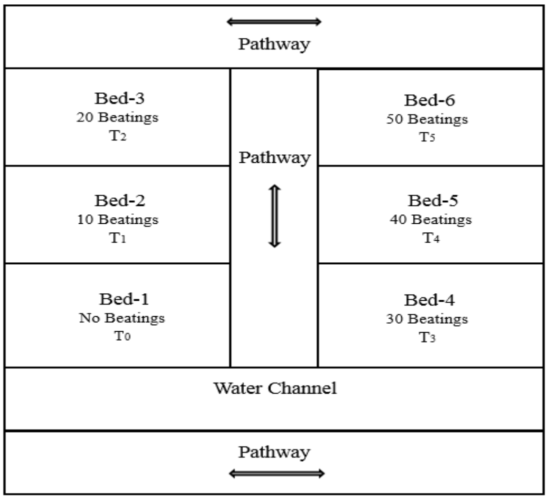

Figure 2. *Experimental design*

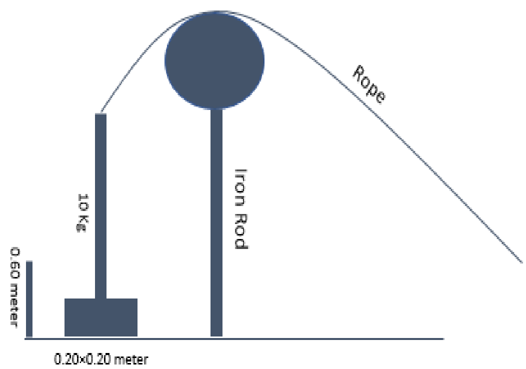

Figure 3. *Manual soil compactor used to develop compaction in the soil*

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Plant sowing and harvesting

Dalbergia sissoo cuttings were collected from the departmental nursery of the University of Agriculture Faisalabad. After compacting the soil, a planting rod was used to transplant the 0.15–0.22 m cuttings into the soil without disturbing the effect of the compaction of the soil. Transplanting was done on the 15th April. A water channel was used to apply irrigation after 3 to 4 days for all of the plots regularly (*Table 3*). The depth of the water channel was 0.45 m and it was 0.76 m wide. During irrigation, water was applied at the surface of the plots. The water absorption rate was very low in highly compacted soil and vice versa. Plants were harvested on the 7th October. Measured plant age was almost 6 months at the time of harvesting. The sampled plants were felled, and the roots were excavated by digging up to the maximum root depth. In the field, the soil was removed from the roots by hand to take the fresh weight. Then the samples were brought to the laboratory for further processing. In the lab, root samples were oven dried for the calculation of biomass production.

Table 3. *Different intervals of irrigation during the whole experiment*

Date	**15-04-16**	**19-04-16**	**23-04-16**	**27-04-16**	**05-05-16**	**11-05-16**
Irrigation	1st	2nd	3rd	4th	5th	6th
Date	18-05-16	25-05-16	01-06-16	08-06-16	15-06-16	22-06-16
Irrigation	7th	8th	9th	10th	11th	12th
Date	29-06-16	06-07-16	13-07-16	20-07-16	27-07-16	03-08-16
Irrigation	13th	14th	15th	16th	17th	18th
Date	10-08-16	17-08-16	24-08-16	31-08-16	08-09-16	15-09-16
Irrigation	19th	20th	21th	22th	23th	24th
Date	21-09-16	26-09-16	02-10-16			
Irrigation	25th	26th	27th			

Phenological parameters used in the study

Shoot length, root length, shoot fresh weight, root fresh weight, shoot dry weight, root dry weight, root-shoot ratio, biomass production, and moisture content availability were measured. After measuring shoot and root fresh weight of all individual plants, plants were transferred to paper bags and placed in a drying oven (DGH-9202 series thermal electric thermostat drying oven) in order to measure the dry stem and root weight of samples. Stem and root samples were packed in paper bags and dried at 75 °C for 24 h, and then weighed with an electrical balance (electronic scale JJ3000B).

Bulk density was also measured as it is the most frequently used parameter to characterize soil compaction (*Table 4*). Bulk density is difficult to measure in gravelly soils. To measure moisture content availability, the exact fresh weight of samples were taken and then samples were oven dried at 80 °C for 24 h. After oven drying, the dried weight was subtracted from the moist weight and the following equation was used (Jusoh et al., 2011):

$$MC\% = 100 \times \frac{Freshweight - Dryweight}{Freshweight}$$

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Table 4. *Soil bulk density (BD) of 6 different treatment plots*

Beds	**Bed-1**	**Bed-2**	**Bed-3**	**Bed-4**	**Bed-5**	**Bed-6**
Beatings	0	10	20	30	40	50
BD (Mg m^{-3})	1.3 ± 0.03	1.40 ± 0.05	1.45 ± 0.06	1.55 ± 0.04	1.65 ± 0.08	1.8 ± 0.1

Statistical analysis

One-way ANOVA was used and means that exhibited significant differences were compared with the least significant differences test (LSD). All statistical analyses were conducted using SPSS Statistical Package (SPSS 17.0, SPSS Ins., IL, U.S.A.). Results were statistically analyzed using a $P < 0.05$ level of significance. Correlation analysis was conducted using the Pearson correlation test (two-tail) to identify relationships between the measured properties

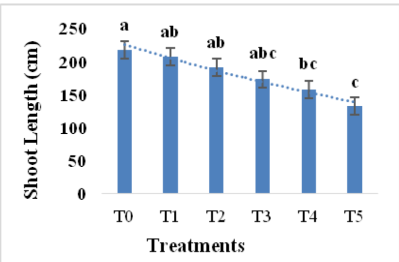
Results

Plant growth

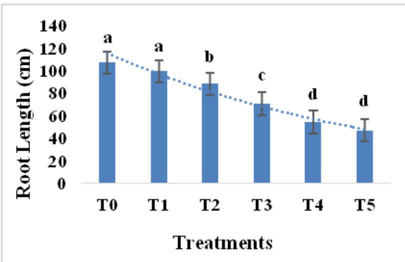
The total length of the shoot was measured with a measuring tape and an average was calculated to express the mean length of the plant. The root length was measured with the help of a meter rod from the base of the plant to the end of the plant and an average was calculated to express the mean root length per replication. According to the ANOVA test, the shoot and root length significantly decreased as compaction level increased, with the results showing significant variation among different compaction levels (*Fig. 4a, b*).

Biomass distribution pattern

The ANOVA showed variation in *D. sissoo* response at different compaction levels. The shoot and root (both fresh and dry) weight significantly varied with different compaction levels. As depicted in *Figure 4c, d, e,* and *f*, the shoot and root weights decreased with increasing compaction, and the root-shoot ratio also showed a decreasing trend with increasing compaction, though this result was not statistically significant (*Fig. 5a*). In terms of biomass production, ANOVA revealed highly significant variation among compaction levels, with decreasing biomass production with increasing compaction (*Fig. 5b*).



(a) LSD = 0.0365*



(b) LSD = 0.0001**

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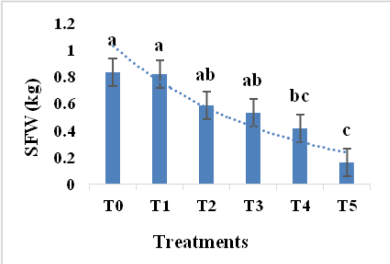
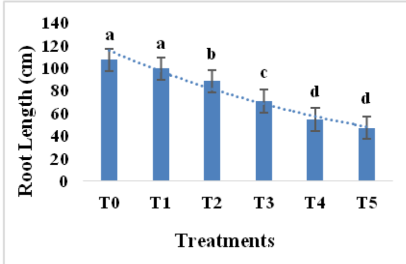
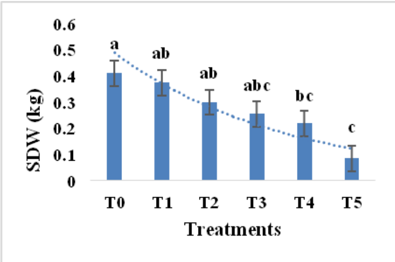


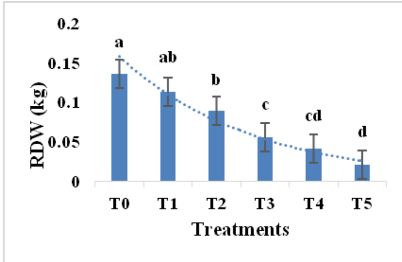
(c) LSD = 0.0085**



(d) LSD = 0.0005**



(e) LSD = 0.0258**



(f) LSD = 0.0085**

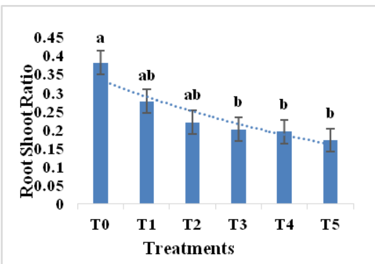
Figure 4. *(a) Shoot length, (b) root length, (c) shoot fresh weight, (d) root fresh weight, (e) shoot dry weight, and (f) root dry weight under different soil compaction levels (*significant, **highly significant)*

Moisture content availability

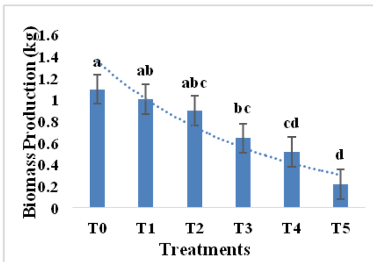
Moisture content availability showed a significant difference among compaction levels. The standard error mean at the level of zero compaction (control) was 0.5917, and went on decreasing down to the standard error mean of 0.0820 for the most compacted treatment (*Fig. 5c*).

Correlation between bulk density, biomass production, and moisture content availability

Bulk density (dry soil mass per unit volume) is the most frequently used parameter to characterize soil compaction, but in swelling and shrinking soils it is recommended to determine the bulk density at the standard moisture content. Bulk density is inversely proportional to shoot and root length, shoot and root dry weight, biomass production, and moisture content availability because bulk density increases with soil compaction, while all the aforementioned traits decrease. Increases in bulk density and soil compaction cause the growth of all these traits to become slow or stunted (*Table 5*).



(a) LSD = 0.1409^{NS}



(b) LSD = 0.0053**

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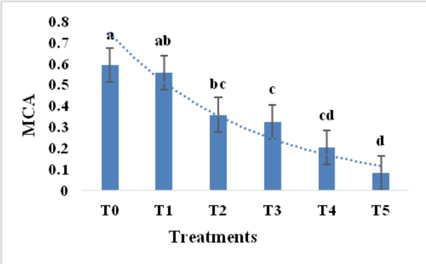

(c) LSD = 0.0016**

Figure 5. *Variation among root-shoot ratio (a), biomass production (kg) (b), and moisture content availability (kg) (c) under different soil compaction levels (*significant, **highly significant, ^{NS}non-significant)*

Table 5. *Correlation between bulk density (BD), biomass production (BM), and moisture content availability (MCA). There was significant negative correlation between bulk density and biomass production and moisture content availability. The correlation between biomass production and moisture content availability was significant and positive*

Parameters	BD	BM	MCA
Bulk density (BD)	1.0	-0.993**	-0.970**
Biomass production (BM)	-0.993**	1.0	0.965**
Moisture content availability (MCA)	-0.970**	0.965**	1.0

**P < 0.01

Discussion

Cuttings of *D. sissoo* were grown in the natural environment by applying six different compaction treatments. Compaction was done by an iron rod and the effect of compaction on the growth and development of stem and roots was observed. The compaction has a long-lasting effect on soil structure, and occasionally it causes an irreversible damage to plants. Compaction has a negative effect on plant growth and the forest ecosystem (Hartmann et al., 2014). The growth of shoot and roots showed a negative response to compaction in the form of stunted growth. As the compaction level increased from zero to a maximum fifty beatings with the soil compactor, the plant showed a reduced growth response.

Soil compaction severely affected the root system of plants by reducing their ability to access nutrients in the soil, but had a more moderate effect on shoot growth. When soils are highly compacted, the mobility of ions, oxygen, microorganisms, and water in the soil is reduced because macropores turn into micropores which strictly confine the root growth and may also limit shoot growth (Nawaz et al., 2016). The effect of soil compaction on plant growth depends on the soil type and plant species present. Our results showed the shoot weight (dry and fresh) and length decreasing with increased compaction level, in agreement with the results of Alameda and Villar, 2012. Roots have a significant role in nutrient uptake and plant growth. Increased soil compaction can be seen to increase the number of micropores and increase particle distribution (Magagnotti et al., 2012), which has a negative effect on root penetration, root length, and depth of the root. As our results show, the root weight (dry and fresh) and length decreased with increasing compaction, as in the work of Ramalingam et al., 2017.

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According to our analysis of variance, compaction level had a significant effect on root weight (fresh and dry). Tracy et al., 2012 found a negative effect of soil compaction on plant growth. Due to compaction, root growth can become stunted and nutrient availability decreases, which has a negative effect on plant biomass production (Kormanek et al., 2015).

If a soil has previously been degraded by salinity, the effect of compaction on the plant growth is compounded. Our statistical analysis showed biomass production (in leaves, stems, and roots) significantly declining as compaction levels increased as Bejarano et al., 2010; and Pérez-Ramos et al., 2010 concluded. For the measurement of soil compaction, water infiltration rate in the soil can be used because the total porosity of the soil decreases due to soil compaction (Bejarano et al., 2010; Arthur et al., 2013). In the same type of soil, the water penetration rate is slower in highly compacted soil as compared with uncompacted soil (Cudzik et al., 2010). Our results showed diminished moisture content availability to plants as compaction levels increased. This, in turn, reduces plant growth (Agherkakli, et al., 2010). Compaction levels in the present study had a significant effect on moisture content availability. Related work indicates that this results in reduced root-shoot ratio (Bengough et al., 2005; Kormanek et al., 2015). In our study, compaction levels had a significant effect on root-shoot ratio.

Conclusions

Different levels of soil compaction significantly affect the morphology and growth of *D. sissoo*, with increased soil compaction reducing growth. We found an overall negative effect of soil compaction on the growth of *D. sissoo*. Consequences of compaction on the soil include increased bulk density. By increasing the accumulation of organic matter, plant growth, and monitoring mechanical operations, we can reduce the problem of soil compaction.

Plantation of *D. sissoo* without compaction is a viable option for good quality timber production. Some other species in this region (e.g. *Eucalyptus camaldulensis*, *Morus alba*, *Acacia nilotica*, and *Bombax ceiba*) are also affected by soil compaction. In future work, we will focus on these species to observe their growth under different soil compaction levels.

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Authors contribution. MUHR and MA planned the research. MHUR, MA, IA contributed in field and lab work. Data analysis and interpretation of the results were done by MUHR, THF, MFN and PW. MUHR, and THF wrote the first version of the manuscript. MFN, PW, MMG, NPG and IA provided critical feedback, and all the authors reviewed the final manuscript.

Conflict of interests. Authors declare that there is no conflict of interests.

REFERENCES

[1] Agherkakli, B., Najafi, A., Sadeghi, S. H. (2010): Ground based operation effects on soil disturbance by steel tracked skidder in a steep slope of forest. – Journal of Forest Science 56(6): 278-284.

[2] Ahmad, B. I., Khan, R. A., Siddiqui, M. T. (2013): Incidence of dieback disease following fungal inoculations of sexually and asexually propagated shisham (*Dalbergia sissoo*). – Forest Pathology 43(1): 77-82.
[3] Alameda, D., Villar, R. (2012): Linking root traits to plant physiology and growth in *Fraxinus angustifolia* Vahl. seedlings under soil compaction conditions. – Environmental and Experimental Botany 79: 49-57.
[4] Ampoorter, E., De Schrijver, A., Van Nevel, L., Hermy, M., Verheyen, K. (2012): Impact of mechanized harvesting on compaction of sandy and clayey forest soils: results of a meta-analysis. – Annals of Forest Science 69(5): 533-542.
[5] Arbuckle, J. G., Lasley, P. (2013): Iowa Farm and Rural Life Poll. – Summary Report. Iowa State University Extension and Outreach, Ames, IA.
[6] Arthur, E., Schjønning, P., Moldrup, P., Tuller, M., de Jonge, L. W. (2013): Density and permeability of a loess soil: Long-term organic matter effect and the response to compressive stress. – Geoderma 193: 236-245.
[7] Bejarano, M. D., Villar, R., Murillo, A. M., Quero, J. L. (2010): Effects of soil compaction and light on growth of *Quercus pyrenaica* Willd. (Fagaceae) seedlings. – Soil and Tillage Research 110(1): 108-114.
[8] Bengough, A. G., Bransby, M. F., Hans, J., McKenna, S. J., Roberts, T. J., Valentine, T. A. (2005): Root responses to soil physical conditions; growth dynamics from field to cell. – Journal of Experimental Botany 57(2): 437-447.
[9] Bitterli, C., Bañuelos, G. S., Schulin, R. (2010): Use of transfer factors to characterize uptake of selenium by plants. – Journal of Geochemical Exploration 107(2): 206-216.
[10] 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.
[11] Cudzik, A., Białczyk, W., Czarnecki, J., Jamroży, K. (2010): Traction properties of the wheel-turfy soil system. – International Agrophysics 24(4): 343-350.
[12] Edlund, J., Keramati, E., Servin, M. (2013): A long-tracked bogie design for forestry machines on soft and rough terrain. – Journal of Terramechanics 50(2): 73-83.
[13] Ferrara, C., Barone, P. M., Salvati, L. (2015): Towards a socioeconomic profile for areas vulnerable to soil compaction? A case study in a Mediterranean country. – Geoderma 247: 97-107.
[14] Hartmann, M., Niklaus, P. A., Zimmermann, S., Schmutz, S., Kremer, J., Abarenkov, K., Frey, B. (2014): Resistance and resilience of the forest soil microbiome to logging-associated compaction. – The ISME Journal 8(1): 226.
[15] Hossain, M., Siddique, M. R. H., Rahman, M. S., Hossain, M. Z., Hasan, M. M. (2011): Nutrient dynamics associated with leaf litter decomposition of three agroforestry tree species (*Azadirachta indica, Dalbergia sissoo*, and *Melia azedarach*) of Bangladesh. – Journal of Forestry Research 22(4): 577.
[16] Jourgholami, M., Majnounian, B., Abari, M. E. (2014): Effects of tree-length timber skidding on soil compaction in the skid trail in Hyrcanian forest. – Forest Systems 2: 288-293.
[17] Jusoh, M. A., Abbas, Z., Lee, K. Y., You, K. Y., Norimi, A. M. (2011): Determination of Moisture Content in Mortar at Near Relaxation Frequency 17 GHz. – Measurement Science Review 11: 203-206.
[18] Kormanek, M., Głąb, T., Banach, J., Szewczyk, G. (2015): Effects of soil bulk density on sessile oak *Quercus petraea* Liebl seedlings. – European Journal of Forest Research 134(6): 969-979.
[19] Magagnotti, N., Spinelli, R., Güldner, O., Erler, J. (2012): Site impact after motor-manual and mechanised thinning in Mediterranean pine plantations. – Biosystems Engineering 113(2): 140-147.
[20] Naghdi, R., Solgi, A., Zenner, E. K., Najafi, A., Salehi, A., Nikooy, M. (2017): Compaction of forest soils with heavy logging machinery. – Silva 18: 1.

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DOI: http://dx.doi.org/10.15666/aeer/1701_10491059

[21] Nawaz, M. F. (2010): Geochemistry of hydromorphic soils and waters under rice culture and forest-continuous measurements, thermodynamic modelling and kinetics. – Doctoral Dissertation, Université Paul Cézanne-Aix-Marseille III.
[22] Nawaz, M. F., Bourrie, G., Trolard, F. (2013): Soil compaction impact and modelling. A review. – Agronomy for Sustainable Development 33(2): 291-309.
[23] Nawaz, M. F., Bourrié, G., Trolard, F., Ranger, J., Gul, S., Niazi, N. K. (2016): Early detection of the effects of compaction in forested soils: evidence from selective extraction techniques. – Journal of Soils and sedIments 16(9): 2223-2233.
[24] Orwa, C., Mutua, A., Kindt, R., Jamnadass, R., Simons, A. (2009): Agroforestree Database: A Tree Species Reference and Selection Guide Version 4.0. – World Agroforestry Centre ICRAF, Nairobi, KE.
[25] Pérez-Ramos, I. M., Gómez-Aparicio, L., Villar, R., García, L. V., Maranon, T. (2010): Seedling growth and morphology of three oak species along field resource gradients and seed mass variation: a seedling age-dependent response. – Journal of Vegetation Science 21(3): 419-437.
[26] Ramalingam, P., Kamoshita, A., Deshmukh, V., Yaginuma, S., Uga, Y. (2017): Association between root growth angle and root length density of a near-isogenic line of IR64 rice with DEEPER ROOTING 1 under different levels of soil compaction. – Plant Production Science 20(2): 162-175.
[27] Silveira, M. L., Comerford, N. B., Reddy, K. R., Prenger, J., DeBusk, W. F. (2010): Influence of military land uses on soil carbon dynamics in forest ecosystems of Georgia, USA. – Ecological Indicators 10(4): 905-909.
[28] Singh, B., Yadav, R., Bhatt, B. P. (2011): Effects of mother tree ages, different rooting mediums, light conditions and auxin treatments on rooting behaviour of *Dalbergia sissoo* branch cuttings. – Journal of Forestry Research 22(1): 53-57.
[29] Tan, X., Chang, S. X., Kabzems, R. (2005): Effects of soil compaction and forest floor removal on soil microbial properties and N transformations in a boreal forest long-term soil productivity study. – Forest Ecology and Management 217(2-3): 158-170.
[30] Tracy, S. R., Black, C. R., Roberts, J. A., Sturrock, C., Mairhofer, S., Craigon, J., Mooney, S. J. (2012): Quantifying the impact of soil compaction on root system architecture in tomato (*Solanum lycopersicum*) by X-ray micro-computed tomography. – Annals of Botany 110(2): 511-519.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/1701_10491059