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Research Article

Impact of Soil Compaction on Bulk Density and Root Biomass of *Quercus petraea* L. at Reclaimed Post-Lignite Mining Site in Lusatia, Germany

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The impact of soil compaction on bulk density and root biomass of *Quercus petraea* L. was assessed after 85 years of reclamation of post-lignite mining soil at Welzow-South, in Lusatia, Germany. Bulk density of core soils sampled from 20 to 25 cm, 100 to 105 cm, and 200 to 205 cm depths and oven-dried biomass of *Q. petraea* roots sampled from 0 to 30 cm and at successive depths of 20 cm, up to 210 cm depth at compacted and uncompacted sites were determined. Bulk density was significantly higher at 20 to 25 cm ($1.74 \pm 0.09\ g\ cm^{-3}$) and 100 to 105 cm ($1.65 \pm 0.06\ g\ cm^{-3}$) depths of the compacted site. Likewise, compaction induced significant greater root biomass within the 0 to 70 cm depth with higher bulk density; root biomass at this depth was 2-fold greater compared to the uncompacted site. Root biomass decreased with soil depth and showed significant relationship with depth at both sites. The result indicates that, after 85 years of reclamation, the impact of soil compaction persisted as evident in higher bulk density and greater root biomass.

1. Introduction

In the Lusatia region of Germany, large tracts of land have been degraded through the extraction of fossilized lignite resources to fuel industrial growth and socioeconomic development. The German Federal Mining Act, which forms the key basis for lignite mining in the region, mandates reclamation of the postmining landscape [1] to meet the socioeconomic requirement of the public [2]. Even though the techniques employed during the reclamation process largely minimize the spatial variability of the excavated mine substrates [3], the restructuring associated with dumping and levelling of the overburden substrate with heavy machinery often induce soil compaction [4].

Soil compaction caused by heavy machinery is known to result in increased soil bulk density [5, 6], reduced porosity and markedly limits root growth [7]. For instance, bulk density and soil strength of plant row impacted by heavy machinery traffic have been observed to be much greater compared to nontraffic area [8–10]. Consequently, increase in soil bulk density due to mechanical compaction may alter root configuration and root-soil interactions [11]. Furthermore, higher bulk density may increase resistance to root penetration, alter root development and proliferation [12, 13], and thereby affect root distribution and biomass within soil profile. In addition to restricting root growth into deeper soil layer, high bulk density may also interfere with the movement and distribution of water in the profile [14], nutrient availability, and uptake by plants, which may eventually affect plant growth. Other studies [15–17] have also shown that soil compaction reduced crop yields due to increased resistance to root growth and decrease in water and nutrient use efficiency. However, it seems that the impact of soil compaction on root growth and biomass of different tree species in compacted soils varies considerably [18, 19].

In the Lusatia mining region, reforestation constitutes an integral part of the reclamation process with most of the postmining landscape successfully afforested [20, 21]. However, there seems to be little information on the impact soil compaction caused by the use of heavy machinery during the reclamation process on bulk density and root biomass of *Quercus petraea* L. (sessile oak), one of the main tree species used in the reforestation. The objective of the study was to assess the impact of soil compaction induced by heavy machinery on bulk density and root biomass of *Quercus petraea* L. after 85 years of reclamation of post-lignite mining soils.

2. Materials and Methods

2.1. Site Characteristics. The study was conducted at Welzow-South, located at the Lusatia mining region in the federal state of Brandenburg, Germany. It is a reclaimed post-lignite mining site reforested with *Quercus petraea* L. (sessile oak) between 1925 and 1926. The soils comprised restructured heterogeneous mixtures of tertiary and quaternary materials composed mainly of loamy sands and loams [22], with low pH around 4, owing to the presence of pyrite originating from the tertiary fraction of the substrate [23]. The region is influenced by temperate subcontinental climatic conditions, characterized by high summer temperatures and pronounced drought periods [21]. Mean annual temperature and precipitation of the region varied around 9.4°C and 569 mm, respectively [22].

2.2. Field Sampling. Two sites were selected: a mechanically compacted site and an uncompacted site (only normal dumping of substrate without excessive compression). At each site, two *Q. petraea* trees with comparable morphology and height were selected for reference. For each site, two profile pits each 1 m away from the reference *Q. petraea* tree were marked (2 m × 1 m) and dug up to 2.5 m depth. Samples from the two soil profiles at each site were taken as field replicates.

Root biomass was sampled using root corer at successive depths of 0 to 30 cm, 30 to 50 cm, 50 to 70 cm, 70 to 90 cm, 110 to 130 cm, 130 to 150 cm, 150 to 170 cm, 170 to 190 cm, and 190 to 210 cm. Roots were carefully collected after passing the bulk soil samples through 2 mm followed by 1 mm sieves and thoroughly washed with water to ensure samples were devoid of soil particles. Roots samples were then oven-dried to a constant weight at 65°C for 72 hours [24] and weighed to determine the root biomass (g).

Bulk density was determined using the core method. Multiple core samples were taken from each profile at the compacted and uncompacted sites at 20 to 25 cm, 100 to 105 cm, and 200 to 205 cm soil depths using cylindrical cores (100 cm^3) and oven-dried to constant weight at 105°C for 48 hours.

2.3. Statistical Analysis. Presented values are means. Analysis of variance was carried out to determine the effects of soil compaction on root biomass and bulk density with increasing soil depth. In cases of significant effect ($P < 0.05$), all pairwise comparison (Fisher LSD Method) was employed to identify the source that differs. Pearson correlation and regression analysis were done to test for any relationship among root biomass, bulk density, and soil depth. Sigma Plot (Version 12) was used for all data analyses.

Table 1: Bulk density of compacted and uncompacted postmining soils at different depths under *Quercus petraea* L. plantation.

Depth [cm]	Bulk density [g cm^{-3}]		
	20–25	100–105	200–205
Compacted soils	1.74 ± 0.09 A^m	1.65 ± 0.06 A^n	1.62 ± 0.12 A^n
Uncompacted soils	1.56 ± 0.11 B^m	1.59 ± 0.06 B^m	1.56 ± 0.10 A^m

Different uppercase letters for the same column indicate significant difference in bulk density between compacted and uncompacted soils for a given depth; different lowercase letters as superscript on the same row indicate significant difference in bulk density within soil profile of compacted and uncompacted soils (Fisher LSD Method at $P < 0.05$). Values are means ± standard deviation.

3. Results

Bulk density was significantly affected by soil compaction (Table 1). Values at 20 to 25 cm and 100 to 105 cm depths of the compacted soils averaged 1.74 ± 0.09 g cm^{-3} and 1.65 ± 0.06 g cm^{-3}, respectively, with both values being significantly higher compared to that of the uncompacted soils at the respective depths (Table 1). However, at the underlying 200 to 205 cm depth, there was no significant difference in bulk density between compacted and uncompacted soils (Table 1).

Furthermore, the bulk density of compacted soils tended to decrease with increasing depth and was significantly the highest at the 20 to 25 cm depth compared to the deeper 100 to 105 cm and 200 to 205 cm depths (Table 1). In contrast, change in bulk density with increasing depth within uncompacted soil profile was insignificant; values ranged from 1.56 ± 0.11 g cm^{-3} to 1.59 ± 0.06 g cm^{-3} (Table 1).

Similarly, root biomass of *Q. petraea* at the 0 to 30 cm, 30 to 50 cm, and 50 to 70 cm depths of compacted soils (with significantly higher bulk density) were significantly greater compared to the uncompacted soils (Figure 1). Values at 0 to 30 cm, 30 to 50 cm, and 50 to 70 cm depths were approximately 1.7-fold, 2.7-fold, and 4.6-fold, respectively, more than those of uncompacted soils at the respective depths. However, beyond 70 cm depth, changes in root biomass with increasing depth were not significantly different between compacted and uncompacted soils (Figure 1). Besides, root biomass of *Q. petraea* in both compacted and uncompacted soils showed a general trend of decreasing with increasing depth up to the 70 cm depth, after which changes with depth were insignificant between compacted and uncompacted soils (Figure 1).

Pearson correlation showed significant positive relationship between root biomass and soil bulk density ($R = 0.46$, $P = 0.049$, and $n = 19$) at the compacted site. In contrast, similar significant correlation was not found for the uncompacted site. Furthermore, changes in root biomass within soil

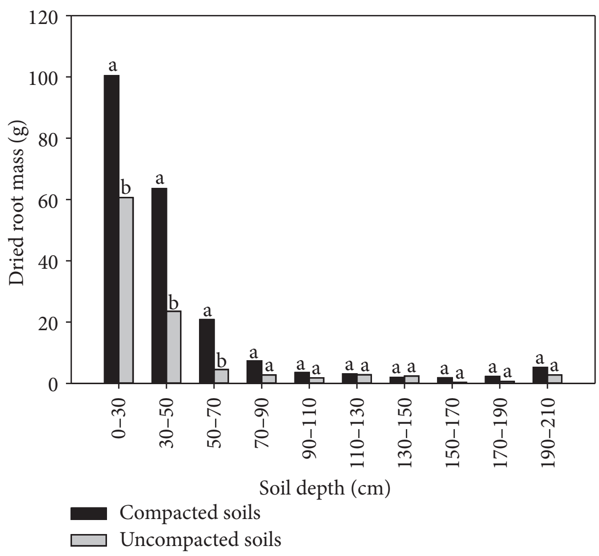

Figure 1: Root biomass of *Quercus petraea* L. at different depths in compacted and uncompacted reclaimed post-lignite mining soils. Different letters for the same depth indicate significant difference between root biomass in compacted and uncompacted soils ($P < 0.05$; Fisher LSD Method).

profile at both the compacted and uncompacted sites showed significant relationship with increasing soil depth (Figure 2). The relationship can be described by the regression models: $y = 290.29e^{-0.0343x}$ ($R^2 = 0.98$; $P < 0.0001$) for the compacted site and $y = 286.55e^{-0.0516x}$ ($R^2 = 0.99$; $P < 0.0001$) for the uncompacted site (Figure 2), where y and x represent root biomass and soil depth, respectively.

4. Discussion

Soil compaction has been shown to increase bulk density [25]. Thus, the significantly higher bulk density up to 70 cm soil depth can be attributed to direct effect of soil compaction due to compression of overburden substrates with heavy machinery during the reclamation process. Gomez et al. [26] noted pronounced changes in bulk density and total porosity in the upper 45 cm layer of sandy loam soils as a result of compaction. Furthermore, the bulk density at the compacted site exceeds the general range of 1.00 g cm^{-3} to 1.50 g cm^{-3} reported for uncompacted soils [27], whereas at the uncompacted site values varied around the upper limit. However, bulk density values within soil profile at the compacted site were within the range of 1.63 g cm^{-3} to 1.74 g cm^{-3} reported for top 20 cm depth of recently reclaimed postmining soils in the region cultivated to *Dactylis glomerata* L. [28]. Interestingly, bulk density within soil profile at the uncompacted site was around the range of 1.57 g cm^{-3} to 1.60 g cm^{-3} reported by Boldt et al. [29] for younger reclaimed site at the study area. As noted by Boldt et al. [29], the comparable bulk density with increasing soil depth at the uncompacted site may reflect the relatively homogenous soil physical conditions with depth and presumably indicate that the degree of soil compaction is not up to the extent of hindering root development and proliferation. Zisa et al. [30] observed that root penetration of *Pinus nigra* grown on sandy loam soil was not significantly restricted with depth up to bulk density of 1.60 g cm^{-3}; however, on silt loamy soil, root penetration reduced significantly at soil bulk density of 1.40 g cm^{-3}.

Soil compaction led to significant greater root biomass up to the 70 cm depth. This suggests that increase in bulk density as a result of soil compaction may have favourable effect on root biomass of *Q. petraea*. Probably, compaction may have induced vigorous root proliferation and growth as evident in more and relatively thicker roots in bulk soil samples collected from the compacted site. The significant positive correlation between root biomass and bulk density seems to corroborate this observation. Similar correlation between root biomass of lupine and oilseed rape with soil bulk density has been reported by Trükmann et al. [31]. Gilman et al. [32] observed more root growth in the top layer of compacted soil with about 70% of the total root length concentrated in the top 12 cm depth compared to around 40% in uncompacted soils. In this study, about 80% of total dry root biomass of *Q. petraea* at both sites was concentrated in the top 0 to 50 cm depth. However, root biomass in compacted soils within this depth was 2-fold greater compared to uncompacted soils. Lipiec et al. [33] attributed the greater amount of roots in the upper layer of compacted soil to more horizontal growth. The comparable root biomass at the deeper soil depth at both sites suggests that the extent of soil compaction is limited to the top 0 to 70 cm depth with higher bulk density. In contrast, soil compaction has been observed to restrict rooting area, hinder root penetration, and decrease root biomass [34]. Hakl et al. [35], found significant negative impact of increased soil compaction on root biomass and on the bulk of root nutrient reserves.

The regression models indicate strong relationship between root biomass of *Q. petraea* and soil depth; about 98% and 99% of the changes in root biomass with increasing depth in compacted and uncompacted soils, respectively, can be explained by the relationship between root biomass and depth.

Effects of soil compaction have been noted to persist over a longer period and may even tend to be permanent, especially in soils with low clay content [36] such as the postmining soils of the study area. The findings of this study concur with this observation. Thus, after 85 years of reclamation, the impact of soil compaction still persists as reflected in greater root biomass of *Q. petraea* and higher soil bulk density.

5. Conclusion

Compaction of reclaimed postmining soils by heavy machinery induced higher bulk density with corresponding greater root biomass of *Q. petraea* at soil depths with higher bulk density. The decrease in root biomass of *Q. petraea* showed significant relationship with soil depth. After 85 years of reclamation, the impact of soil compaction persists, as evident in higher bulk density and greater root biomass of *Q. petraea* at depths most affected by compaction.

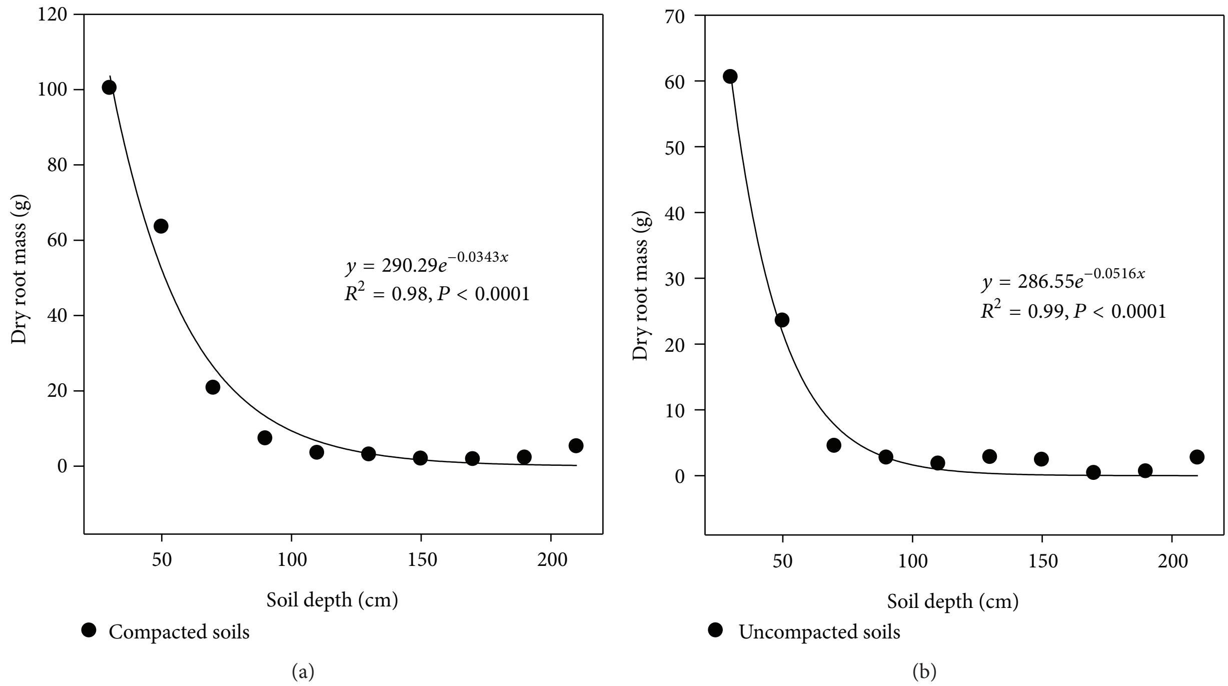

Figure 2: Relationship between dry root biomass (y) of *Quercus petraea* L. and soil depth (x) in compacted soils (a) and uncompacted soils (b) of reclaimed post-lignite mining soils.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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