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Impact of soil compaction on water content in sandy loam soil under sunflower

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Abstract: Soil compaction causes important physical modifications at the subsurface soil, especially from 10 to 30 cm depths. Compaction leads to a decrease in infiltration rates, in saturated hydraulic conductivity, and in porosity, as well as causes an increase in soil bulk density. However, compaction is considered to be a frequent negative consequence of applied agricultural management practices in Slovakia.

Detailed determination of soil compaction and the investigation of a compaction impact on water content, water penetration depth and potential change in water storage in sandy loam soil under sunflower (*Helianthus annuus* L.) was carried out at 3 plots (K1, K2 and K3) within an experimental site (field) K near Kalinkovo village (southwest Slovakia). Plot K1 was situated on the edge of the field, where heavy agricultural equipment was turning. Plot K2 represented the ridge (the crop row), and plot K3 the furrow (the inter–row area of the field). Soil penetration resistance and bulk density of undisturbed soil samples was determined together with the infiltration experiments taken at all defined plots.

The vertical bulk density distribution was similar to the vertical soil penetration resistance distribution, i.e., the highest values of bulk density and soil penetration resistance were estimated at the plot K1 in 15–20 cm depths, and the lowest values at the plot K2. Application of 50 mm of water resulted in the penetration depth of 30 cm only at all 3 plots. Soil water storage measured at the plot K2 (in the ridge) was higher than the soil water storage measured at the plot K3 (in the furrow), and 4.2 times higher than the soil water storage measured at the most compacted plot K1 on the edge of the field. Results of the experiments indicate the sequence in the thickness of compacted soil layers at studied plots in order (from the least to highest compacted ones): K2–K3–K1.

Keywords: Soil compaction; Soil penetration resistance; Bulk density; Water flow.

INTRODUCTION

The negative consequences of intensively exploited agricultural systems include also soil compaction from wheel traffic by heavy agricultural equipment. Compaction rearranges soil particles changing pore-size distribution and pore connectivity. The effect of soil compaction on saturated water flow is largely controlled by larger pores (i.e., preferential flow) (Ehlers, 1975; Lin et al., 1996; Lipiec et al., 1998) that are negatively related to soil compaction (Carter, 1990). It has been shown that increased soil compactness induced by vehicular traffic reduced the volume of stained macropores contributing to water flow (Håkansson and Lipiec, 2000) and their continuity (Lipiec and Stepniewski, 1995). It leads to a decrease in infiltration rates, saturated hydraulic conductivity and porosity, to an increase in soil bulk density, and to negative consequences for crop production (reduced growth, lower yield, increased fungi diseases, more weeds) (Horn, 2015; Martínez et al., 2008). There are many studies describing the effects of soil compaction on the soil water flow regime. Warkentin (1971) reviewed empirical evidence suggesting that macropores are the most significantly reduced in size following compaction, which can have a profound effect on both saturated and unsaturated water transmission. Recently an image analysis has been used to examine the differences in soil water flow associated with vehicle compaction (Kulli et al., 2003). Depending on soil texture and on the degree of soil compaction, preferential flow can also be favoured (Mooney and Nipattasuk, 2003). Kooistra (1994) studied the porosity of tilled sandy loam soils by optical microscopy of thin sections and distinguished macropores (mean diameter>100 μm) and smaller pores which were considered as micropores. It was shown that total porosity was often less decreased by compaction than the macroporosity, because the microporosity increased. Richard et al. (2001) demonstrated that compaction did not affect the textural porosity (i.e. matrix porosity), but it created relict structural pores that are accessible only through the micropores of the matrix. It showed the effect of soil compaction on the hydraulic properties, which can be used as an indicator of the consequences of compaction. In summary, according to Alaoui and Helbling (2006) the studies related to soil compaction show the necessity: a) to take into account matrix pores and macropores; b) to consider the field scale of soil profiles rather than the laboratory scale of cores to also assess the heterogeneity induced by compaction, and c) to consider directly the hydrodynamic functionality of the pores in conducting water and air rather than dwelling on the morphology of soil structure.

The degree of soil compaction depends not only on the applied load but also on soil characteristics and landscape position (Bertolino et al., 2010). However, some soils are inherently resilient to compaction, whereby they may recover following removal of the stress (Gregory et al., 2007). Bathke et al. (1992) found that the root elongation stopped where soil penetration resistance values ranged from 2 to 5 MPa.

The objectives of this study were (i) to estimate the soil compaction using the soil penetration resistance and bulk density distribution along the sandy loam soil profile and (ii) to assess the impact of soil compaction on water content, water penetration depth and potential increase in water storage in individual layers of sandy loam soil.

MATERIAL AND METHODS
Study area

Experimental site Kalinkovo (48°3’53’’ N, 17°12’12’’ E) at the Danubian Lowland, southwestern Slovakia, represents

Table 1. Particle-size distribution of the sandy-loam soil from Kalinkovo.

Depth (m)	Sand (%) ≥0.05 mm	Silt (%) 0.05–0.001 mm	Clay (%) ≤0.002 mm	Clay particles (%) ≤0.01 mm
0.10–0.20	61.81	32.70	5.49	15.71
0.25–0.35	62.47	32.23	5.30	17.09
0.45–0.55	66.60	29.56	3.84	14.31
0.75–0.85	67.93	28.91	3.16	11.45
1.10–1.20	10.88	79.52	11.60	45.19

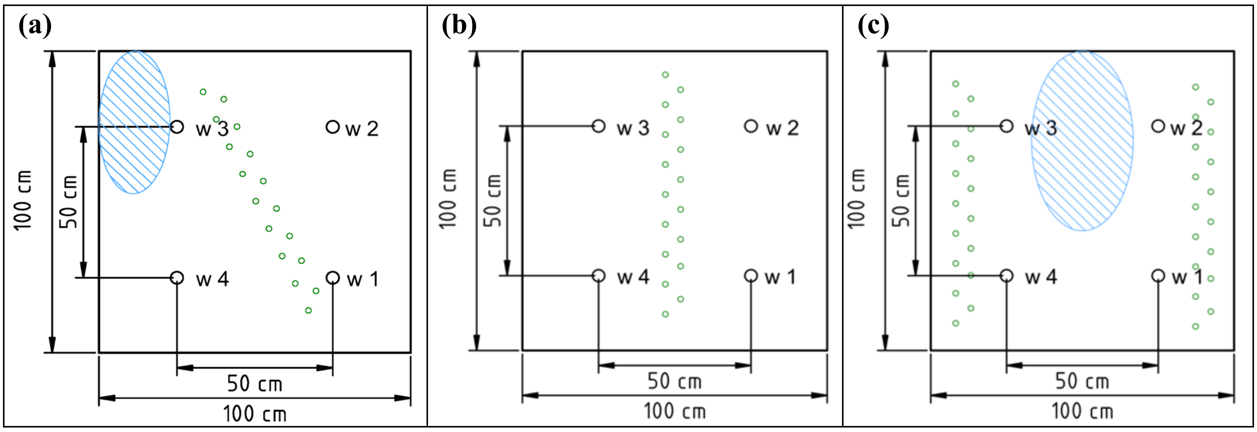

Fig. 1. Scheme of the field experiment with indication of ponding water (hatched ellipsoid), rows of sunflower (small circles) and location of the access tubes (w1–w4) for (a) K1 (the edge of the field), (b) K2 (ridge, crop row), and (c) K3 (furrow, inter-row area).

agricultural land, where sunflower (*Helianthus annuus* L.) was grown during the field campaign.

Soil at the experimental site, evolved on fluvial deposits of Danube River, is classified as Calcaric Fluvisol (IUSS Working Group WRB, 2015) and has a sandy loam texture (Soil Survey Division Staff, 1993). The top soil (0–5 cm) layer contained 52.67, 39.70 and 7.63% of sand, silt and clay respectively, 7.00% of $CaCO_3$, 1.27% of C_{org} with pH values 8.15 (H_2O) and 8.11 (KCl).

Particle-size distribution for whole soil profile is stated in Table 1.

According to MKSPS (Morphogenetic soil classification system of Slovakia–2000) the soil-type at Kalinkovo site is light sandy–loam fluvial anthrosol carbonate - FMac. The substrate is a carbonate sandy–loam alluvium; groundwater is located at the depth of 300 cm.

Pedon description:

Akpc 0–28 cm: colour 10YR 4/4, dry, loose, sandy-loam, weakly polyhedral, strong rooting, presence of carbonates,

A/Cc 28–38 cm: colour 10YR 5/4, slightly humid, crumbly, sandy-loam, weakly structural, medium rooting, presence of carbonates,

C1c 38–72 cm: colour 10YR 6/4, slightly humid, crumbly, sandy-loam, granular, rarely rooting, presence of carbonates (CaCO3 powders), carbonate alluvium,

C2c 72–138 cm: colour 10YR 6/3, slightly humid, crumbly, sandy-loam, granular, presence of carbonates (CaCO3 powders), carbonate alluvium,

C3c > 138 cm: colour 10YR 6/4, slightly humid, crumbly, sandy-loam, granular, presence of carbonates (CaCO3 powders), carbonate alluvium.

Three plots were studied at this site. Plot K1 (Fig. 1a) was situated on the edge of the field, where heavy agricultural equipment was turning. Plot K2 (Fig. 1b) was situated in the ridge (in the row), and plot K3 (Fig. 1c) in the furrow (in the bare soil inter-row area).

The BBCH-scale (Lancashire et al., 1991) identifies the phenological development stages of the sunflower (*Helianthus annuus* L.). At the time of field measurements from July 28 to July 31, the sunflower was in principal growth stage 6: Flowering (65 – Full flowering: disc florets in middle third of inflorescence in bloom – stamens and stigmata visible).

Agrotechnical operations at the field site

After the pre-crop was harvested, stubble tillage at a depth of 0.10–0.12 m was performed. The furrows were treated with rollers and then PK-fertilizers were applied through the medium-deep plowing (0.25 m). Dragging was the first agrotechnical operation in the spring followed by preparing the seed bed by the compactor. Sunflowers were sown with a seed drill to a depth of 40 mm on the April 21, 2015.

Field measurements

Soil penetration resistance was measured in 1 cm interval up to the depth of 50 cm with the Penetrologger (Eijkelkamp – Soil and Water), using the Cone with 1.0-cm^2 surface. Five sets of measurements were taken in the ridges (in the rows), five sets in the furrows (in the inter-row area), and five sets on the edge of the field. In this study, readings of ≥5 MPa serve as an indicator of soil compaction, which is in accordance with Carrara et al. (2007). Measured values of penetration resistance over 5 MPa in our study indicate compacted soil layer with serious consequences for the growth of plants and the transport of water and chemicals.

Bulk density ρ_d of undisturbed soil samples was determined according to the Soil Survey Manual (Soil Survey Division Staff, 1993). Kopecký steel cylinders (100-cm^3) were used to collect soil samples every 5 cm along the soil profile (0–100 cm). The field moist samples were weighed in the laboratory, oven dried at 105°C and weighed once more. Soil bulk density (g cm^{-3}) was calculated as the ratio of the mass of the oven-dried soil from the Kopecký cylinder and 100-cm^3 volume of the cylinder.

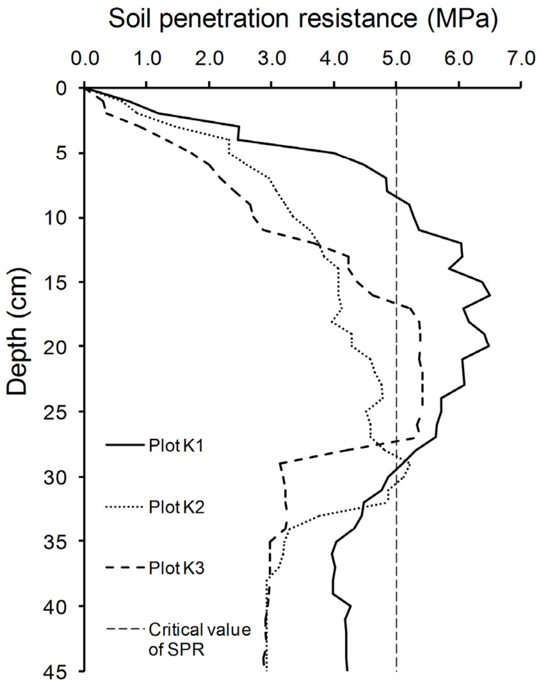

Fig. 2. Soil penetration resistance – SPR (average from 5 measurements) for the three experimental plots in Kalinkovo. Plot K1 – on the edge of the field, plot K2 – on the ridge (in the crop row), and plot K3 – in the furrow (in the inter-row position).

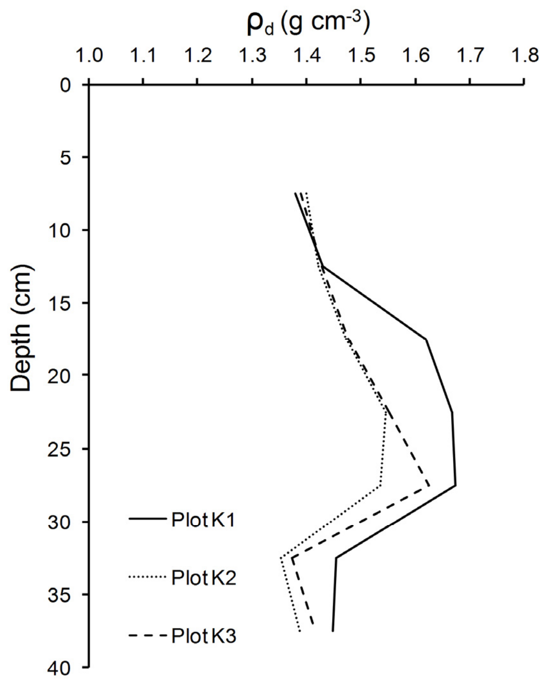

Fig. 3. Soil bulk density ρ_d (1 measurement per plot) for the three experimental plots in Kalinkovo. Plot K1 – on the edge of the field, plot K2 – on the ridge (in the crop row) and plot K3 – in the furrow (in the inter-row position).

Infiltration experiments were undertaken at three 100 cm × 100 cm plots (Fig. 1a, b, and c) from July 28 to July 31, 2015. At each of these plots four steel access tubes w1–w4 (with inner diameter of 4.3 cm and length of 200 cm) were inserted vertically into holes made with an auger. The volumetric soil water content ($m^3\ m^{-3}$) before and after irrigation was measured every 10 cm between 0 and 100 cm using the neutron moisture meter with Am-Be probe (Holdsworth, 1970).

Fifty mm of water was applied manually with a watering pot at a rate of about 2 mm min^{-1}, and the application and redistribution lasted 50 minutes. Two hours after water application, soil moisture was measured and the neutron counting rates, *CR*, were transformed to the volumetric water content, θ ($m^3\ m^{-3}$), using Equation (1) obtained from our former calibration using gravimetric method:

$$\theta = 0.001145\ CR + 0.001722\ c \qquad (1)$$

where c is clay content (%).

The above-mentioned calibration equation was developed for the upper 1.5 m of four soil profiles (one sandy soil and three sandy loam soils) using the multiple linear regression analysis of the dataset of simultaneously collecting *CR*, θ and soil texture.

The water penetration depth z_{max} was estimated as maximal depth of soil (soil layer) where the difference in volumetric water content measured prior and after irrigation was registered, i.e., where ($\theta_{170\ \min}$ – SD) > ($\theta_{0\ \min}$ + SD). The radius of influence r (cm) (equal to the radius of the spherical cloud containing 95% of neutrons retarded by the soil) as a function of volumetric water content θ ($m^3\ m^{-3}$) was calculated from equation (Sumner, 1999):

$$r = 15\ (1/\theta)^{1/3} \qquad (2)$$

RESULTS AND DISCUSSION

The depths, in which the soil penetration resistance was ≥5 MPa (indicated the soil compaction in this study) ranged from 9 to 31 cm below soil surface (Fig. 2). The thickest compacted soil layer (with a thickness of 21 cm) was measured at the plot K1. It occurred at depth from 9 to 30 cm. The thinnest compacted soil layer (with a thickness of 2 cm) was measured at plot K2. It occurred at the depth from 29 to 31 cm. The compacted soil layer at plot K3 was 10-cm thick and occurred at the depth from 17 to 27 cm. These findings are similar to the findings of Jabro et al. (2015), who found that less compaction was observed in crop rows compared to inter-rows. Maximum value (average from 5 measurements) of the soil penetration resistance was 6.38 MPa at the depth of 15 cm at the site K1, 5.22 MPa at the depth of 29 cm at the site K2, and 5.42 MPa at the depth from 22 to 25 cm at the site K3. These results are in line with the findings of Sağlam and Dengiz (2017), who claimed that the soils with high sand content have penetration resistance greater than 3.0 MPa (except for 0–5 cm).

The bulk density distribution along the soil profile (1 measurement per plot) for the three experimental plots in Kalinkovo is shown on Fig. 3. The results were similar with the results of vertical penetration resistance measurements, i.e., the highest values of bulk density and soil penetration resistance were measured at the plot K1, and the lowest values (with the exception of 28–33 cm depths, where the soil penetration resistance values culminated) at the plot K2. These findings are in line with the findings of Cassel (1983), who found that soil bulk density was significantly greater for trafficked inter-row position compared with row and non-trafficked inter-row positions.

The highest values of the soil bulk density at the plot K1 were measured at the depths of 15–20 cm, 20–25 cm, and 25–30 cm, which is in agreement with the results of soil penetration resistance measurements.

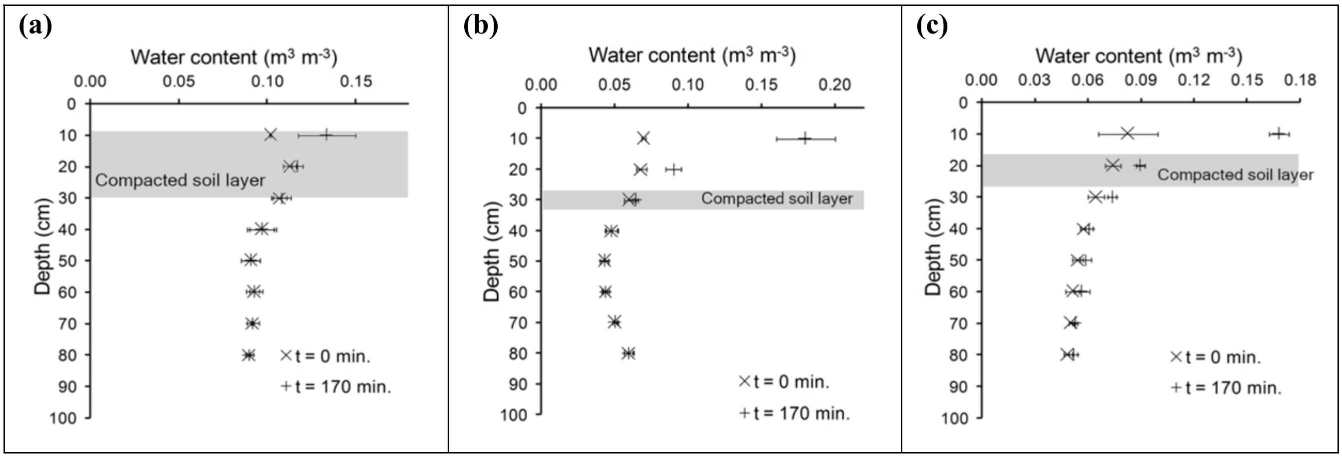

Fig. 4. Soil water content (mean values with standard deviations) at the plot K1 (edge of the field) before (×, t = 0 min) and after (+, t = 170 min) irrigation. Grey area represents compacted soil layer.

Comparison of the values taken at the plot K2 revealed that the highest values of the soil bulk density were measured at the depths of 20–25 cm and 25–30 cm, while the compacted soil layer occurred at the depth from 29 to 31 cm according to the soil penetration resistance measurements.

Comparison of the values taken at the plot K3 revealed that the highest values of bulk density were measured at the depths of 25–30 cm, while the compacted soil layer occurred at depth from 17 to 27 cm according to the soil penetration resistance measurements.

Mean values with standard deviations of the soil water content (m^3 m^{-3}) measured along the soil profiles of experimental plots are presented in Fig. 4. The impact of the compacted soil layer on the water flow was evident at all three plots. While the water penetration depth z_{max} was 30 cm at all three plots, increase in the soil water content was measured at the plot K1 to the depth of 20 cm only, and at the plots K2 and K3 to the depth of 30 cm.

The maximum increase in the soil water storage was estimated at the plot K2 and it was 12.82 mm, which means that the upper (0–30 cm) part of soil profile with sunflower roots retained 25.63% of applied water. Remaining water flowed out (drained) through the horizontal subsurface flow. At the plot K3, the increase in the soil water storage was 10.97 mm, which means that the upper (0–30 cm) part of soil profile retained 21.9% of applied water. Remaining water flowed out as in the previous case. At the extremely compacted plot K1, the increase in soil water storage was 3.73 mm only, which means that the upper (0–20 cm) part of soil profile retained 7.46% of applied water. Remaining water flowed out (drained) through the horizontal subsurface flow and/or along the access tube w3, where the ponded surface water infiltrated and flowed preferentially. For this reason, the vertical soil water content distribution and increase in soil water storage taken at the plot K1 in the access tube w3 had to be discarded and the average values of soil water content and increase in soil water storage were calculated from three values only.

The soil water content measured during this study is different from the soil water content measured after application of 50 mm of water at the three sites with uncultivated sandy soil covered with vegetation representing different stages of primary succession in Sekule, in the Borská nížina lowland of southwestern Slovakia (Šurda et al., 2015), at the two sites with non-tilled sandy loam soil covered with grassland in Zábrod (in mountainous area of the Šumava, Czech Republic) after an application of 62 and 112 mm of water (Lichner et al., 2014), and at the site with cultivated clay loam soil sown with spring barley in Most pri Bratislave (in the Danubian lowland in southwestern Slovakia) after an application of 100 mm of water (Lichner et al., 2013), where the increase in soil water content was registered up to the depth of 60–90 cm.

CONCLUSIONS

The soil bulk density distribution along the soil profiles was similar to vertical penetration resistance distribution, i.e., the highest values of bulk density and soil penetration resistance were measured at the plot K1, and the smallest values at the plot K2. The impact of compacted soil layers on water flow was evident at all three plots. Application of 50 mm of water resulted in the penetration depth of 30 cm only at all experimental plots. Increase in the soil water storage estimated after irrigation at the plot K2 on the ridge (in the crop row) was 1.17 times higher than the soil water storage estimated at the plot K3 in the furrow (in the inter-row position), and 3.43 times higher than the soil water storage estimated at the plot K1 on the edge of the field. Results of the experiment indicate the sequence in the thickness of compacted soil layers at studied plots in order (from the least to the most compacted ones): K2–K3–K1.

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