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The influence of agricultural traffic on soil infiltration rates

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Abstract. The objective of the study was to investigate the effect of agricultural machinery passes on soil infiltration rate. The experiment was conducted in a large covered area (Soil Hall) with the sandy loam soil type. Four compactions levels were applied: control, one, two and three tractor passes.

The infiltration measurements were conducted using two methods: Simplified Falling–Head (SFH) and Mini Disk (MD). The other supporting measurements were disturbed soil samples and cone index measurements.

Based on the SFH method it was observed that as the number of passes increased from 0 to 3 the infiltration rate decreased. The MD results also decreased with the increase in the number of passes. The bulk densities (at 0–0.07 m depth) increased with the number of tractor passes, under the conditions of soil gravimetric moisture content ranging between 14 and 18% vol. The cone index values at the depth of 0–0.05 m increased with the number of passes.

When comparing the results obtained using the MD and SFH, a strong relationship was not found. It could be concluded that the SFH method might be more robust and appropriate for determining the effect of the number of tractor passes on the soil water infiltration in these conditions.

Key words: cone index, infiltration rate, soil compaction.

INTRODUCTION

Infiltration rate is an important parameter of soil which is influenced by agricultural traffic and its intensity. Therefore, the infiltration characteristic of the soil is a good guide how to find out the soil compaction. Traffic intensity results in an increase in soil bulk density values which negatively affect the soil infiltration parameters in comparison to the non–trafficked soil (Liebig et al., 1993; Yuxia et al., 2001; Hamza & Anderson, 2005; Raper & Kirby, 2006). For example Chamen (2011) stated that the non–compacted soil has 4 or 5 times higher infiltration rate than once run over soil. During Yuxia's et al. (2001) controlled traffic farming (CTF) experiment, wheeled and non–wheeled areas were compared (compacted and non–compacted) in a field–scale experiment. This experiment was established on a field which was not trafficked for 5 years and a single wheeling compaction was created by a John Deere 4040 tractor (4,000 kg of rear axle weight). The infiltration was simulated by a portable rainfall simulator with a constant rainfall rate of 122 mm h^{-1} (the experiment included 10 and 20 minutes of simulated rainfall). The results of this experiment showed that the non–compacted soil had infiltration rate between 50 and 100 mm h^{-1} (with 80% cover and without any surface residue cover, respectively) while the compacted areas had infiltration rate between 10 and 25 mm h^{-1}. Therefore, the decrease in infiltration rate on the compacted soil ranged from 50 to 90% in comparison to the non–compacted soil. Zhang et al. (2006) used three levels of soil compaction by increasing bulk density by 0, 10 and 20% in laboratory conditions. The soil samples were taken from the depths of 0–0.5 cm and 0.10–0.15 cm on two plots (*Chromic Cambisols* and *Calcic Cambisols*). Two methods of infiltration rate measurements were used, which were: constant head method (saturated hydraulic conductivity) and the hot–air method (unsaturated hydraulic conductivity). The saturated hydraulic conductivity showed differences between each type of soil compaction in *Calcic Cambisols* at both depths, while in *Chromic Cambisols* the difference was observed just for the highest level of soil compaction (20%). For the unsaturated hydraulic conductivity there were no major differences among the compaction levels and depths.

Agricultural machinery is not the only factor which can influence soil physical and infiltration properties, the other factor is livestock traffic. The study of evaluating influence of grazing on soil physical and infiltration parameters was conducted in the USA (Castellano & Valone, 2007). This study focused on three grazing areas in Arizona, USA, with different grassland establishment (1954, 1977 and 1993) all with similar gravelly sandy loam soils. For the water infiltration rate measurements, a double ring infiltrometer was used and the measurements were done in and outside of the grazing site. The results showed a decrease in infiltration rate on the non–grazed areas by up to 30–50% for the 1954 and 1977 sites while for the 1993 site was no difference in water infiltration rate. The measurements of cone index during this experiment showed higher values for the non–grazed sites then the grazed sites, while again for 1993 site was no difference found. One of the causes of changes in soil physical properties can be the cycles of soil moisture content and also changes in temperature during the whole season. The other possibility is the long–time gap of livestock removal and vegetation change. Another research compared the effect of traffic intensity resulting from a tractor with a trailer and grazing livestock with the same target ground pressure of 200–250 kPa (Chyba et al., 2014). The study showed a decrease in cone index values at depths ranging from 0.10 to 0.25 m for livestock compared to the tractor with the trailer. However, there was no statistically significant difference in surface infiltration rate using the simplified falling–head (SFH) method.

The infiltration properties of the soil are very influenced by soil bulk density. Soil bulk density is described as the mass of soil particles over the overall soil volume which is occupied by the particles. The soil bulk density is also one of the key indicators of the soil compaction (Johnson & Bailey, 2002). The soil bulk density and its relation to the soil compaction were studied in many research studies. One research monitored soil bulk densities of wheeled and non–wheeled soil up to the depth of 0.6 m (Defossez & Richard, 2002). The research showed that the bulk density of the wheeled area near to the soil surface were up to 200 kg m^{-3} higher than the non–wheeled area to the depth of 0.25 m. These differences in soil bulk density decreased with depth down to 0.45 m where the differences were not observed. Similar results were obtained by

Dickson & Ritchie (1996), Gómez et al. (1999) and Ekwue & Harrilal (2010) who monitored three different compaction levels and their effects on soil bulk density.

Soil compaction can also be measured using a penetrometer/penetrologger where soil cone indexes are evaluated. Cone index is a value of soil resistance against a cone of known dimensions, its angle and area (ASAE, 2004). The cone index measurement has advantages over soil sampling (bulk density samples) as data from a whole soil profile (limited by penetrometer reach) can be simply obtained with a possibility of automation (Raper, 2005). A correlation between an increasing soil compaction and an increasing cone index values was observed in many studies (Alakukku, 1996; Arvidsson & Håkansson, 1996; Radford et al., 2007). On the other hand, the cone index measurement has also some disadvantages, the main one is its soil moisture dependence (Ayers & Perumpral, 1982; Varga et al., 2014; Chyba et al., 2016).

MATERIALS AND METHODS

This experiment was conducted in a large covered area measuring 60 x 30 m (Soil Hall) which is located at Harper Adams University, UK (latitude 52.781908, longitude – 2.427952) and the measurements were conducted on 22nd to 27th of June 2012. The Soil Hall provides good facilities for conducting practical studies without the influence of the weather. The soil type used in the experiment was sandy loam with the following soil fractions: 65% sand, 19% clay and 16% silt particles (Krištof et al., 2010). The soil used in the experiment was prepared by deep loosening (0.5 m), ploughing (0.2 m) and power harrowing (0.075 m). Three days after that four compaction levels were applied: 0 pass (control), one pass, two passes and three passes using a Massey Ferguson 8480 tractor (total weight 13,159 kg, 140 kPa and 7,655 kg tyre inflation pressure an weight for front axle, 120 kPa and 5,504 kg for the rear axle respectively). The traffic intensity treatments were selected based on Kroulik et al. (2010), who evaluated traffic parameters of agricultural vehicles. Once the area was prepared and trafficked the measurements of both types of soil infiltration rate, soil sampling and cone index were performed on all types of compaction. A randomised block design with five replications was used.

To estimate infiltration rate by the SFH method it is necessary to push or hammer a cylinder of known diameter A (m) into the soil so that water could flow down only vertically way into the soil. Then the known volume of water is poured into the cylinder onto the soil surface. While the water is poured the time measurement began. When all the water is drained into the soil, the time t_a (s) measurement ends. For the estimation of infiltration rate K_{fs} (mm h^{-1}), it is necessary to measure the soil moisture content inside of the cylinder (field saturated water content θfs) and outside of the cylinder (soil water content θi) and its difference $\Delta\theta$ (L^3 L^{-3}). The measurement of soil moisture content was conducted outside of the cylinder so the soil in the measuring area did not get disturbed. The measured values were than calculated using the following equation:

$$K_{fs} = \frac{\Delta\theta}{(1-\Delta\theta)t_a}\left[\frac{D}{\Delta\theta} - \frac{\left(D+\frac{1}{\alpha^*}\right)}{1-\Delta\theta} ln\left(1+\frac{(1-\Delta\theta)D}{\Delta\theta\left(D+\frac{1}{\alpha^*}\right)}\right)\right] \qquad (1)$$

where: D – is the proportion of V (volume of water) and A (diameter of cylinder) and represents the water level equal to the water volume (Bagarello et al., 2004 & 2006);

α^* (m^{-1}) – represents the proportion of saturated hydraulic conductivity and soil potential of saturation flow and was estimated by Elrick et al. (1989) (Table 1).

Table 1. Elrick´s estimation of α^* (Elrick et al., 1989)

$\alpha^* = 1\ m^{-1}$	Compacted clays (e.g., landfill caps and liners, lacustrine or marine sediments, etc.).
$\alpha^* = 4\ m^{-1}$	Unstructured fine textured soils primarily
$\alpha^* = 12\ m^{-1}$	Most structured soils from clays through clay loams; also includes unstructured medium and fine sands and sandy loams. The first choice for most soils.
$\alpha^* = 36\ m^{-1}$	Coarse and gravelly sands; may also include some highly structured soils with large cracks and macropores.

During the measurements based on the SFH method, cylinders with a diameter of 152 mm, height 150 mm and thickness of 2 mm were used (Fig. 1). The moisture content was measured using a Theta Probe (HH2 moisture meter, Delta T Devices) and the volume of water applied was 0.3 cm^3. Parameter α^* of 30 m^{-1} was used because of the poor structure of the soil.

Figure 1. SFH measurements where 5 cylinders were used.

The measurements using a Mini Disk (tension infiltrometer) were conducted according to the instructions of DECAGON Devices manual. The calculation and results were obtained from a spreadsheet macro (MS EXCEL) from the manufacturer website (DECAGON Devices, 2016). Each measurement took 900 s and the readings were performed every 30 s. The suction effect was set to 20 mm for 0 passes, 10 mm for 1 and 2 passes and 5 mm for 3 passes.

Soil samples were taken using stainless steel cylinders with a volume (V_s) of 285 cm^3 and height of 0.07 m. The sampling depth was up to 0.28 m. For the estimation of the soil moisture content the disturbed soil samples were dried to the constant weight at 105°C (Valla et al., 2011). The initial moisture content θ_{mom} (% vol.) was calculated from the equation:

$$\theta_{mom} = G_A - G_F \tag{2}$$

where: G_A – sample with natural moisture content (g); G_F – sample dried to the constant weight (g).

For the soil bulk density ρ_d (g cm^{-3}) the following equation was used:

$$\rho_d = \frac{G_F}{V_S} \tag{3}$$

If the sampling cylinder has a different volume than 100 cm^3, it is necessary to make a conversion for further calculations so that the resulting values are divided by the volume of the cylinder used (V_S) and multiplied by one hundred.

The measurements of the cone index values were taken using Eijkelkamp penetrologger ART.NR.06.15.01 with a cone angle of 30° and an area of 100 mm^2 up to the depth of 0.3 m (ASAE, 2004).

MS Office Excel and Statistica 12 software (*Tukey test*, *ANOVA*) were used for data evaluation.

RESULTS AND DISCUSSION

The soil volumetric moisture content ranged from 12 to18% vol. up to the depth of 0.28 m with mean value of 16% vol.

The results of the SFH and MD infiltration rates are shown in Fig. 2. The SFH values are highly dependent on number of passes. The soil infiltration rate was high for the untrafficked soil 22.43 mm h^{-1}, then the values after the first pass decreased by 82% (5.5 times lower) and after the second pass it decreased further by 16%, which was found to be in agreement with Yuxia et al. (2001) and Chamen (2011). After the second and third pass infiltration rate was found to be at lowest levels (in a region of 0.4 mm h^{-1}) and there was no significant difference between these two values. It is expected that there would be no changes in soil infiltration rate with additional passes of the tractor. The untrafficked soil showed very high variability (confidence intervals) which decreased with the number of passes.

The results of MD (tension infiltrometer) in contrast with head (SFH) method showed no statistically significant difference (Fig. 2). It is due to the large confidence interval spread. However, it can be seen that the mean values decreased with the increasing number of passes which was, in a small range of soil bulk density values, also monitored by Zhao et al. (2014). It is expected that the SFH method can monitor the first serious compaction while MD method could show the statistical difference after multiple passes of a tractor where the SFH is probably less sensitive.

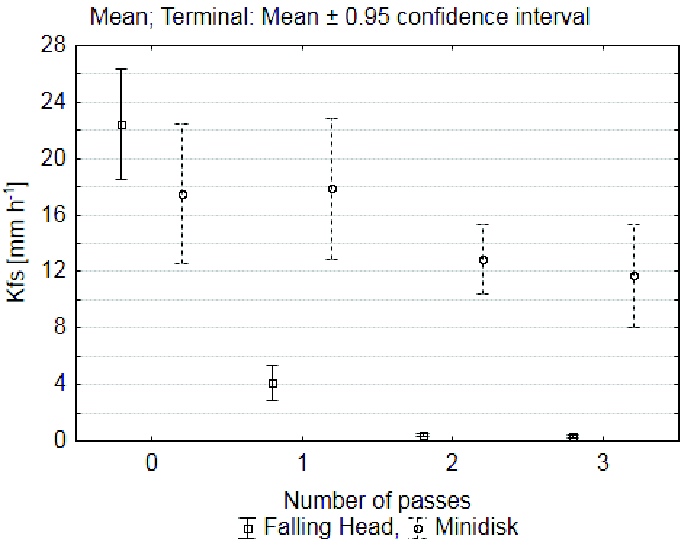

Figure 2. SFH and MD results.

The values of dry bulk density (Table 2) showed that the compaction level is uniform throughout the measured depth for each variant. It is also clear that as the number of passes increased in the most cases, the soil bulk density also increased as previously discussed (Defossez & Richard, 2002; Johnson & Bailey, 2002).

Table 2. The mean values of dry bulk density

Depth [m]	Bulk density [g cm^{-3}]							
	0 passes		1 pass		2 passes		3 passes	
0–0.07	1.42	a 1	1.60	a,b 1	1.71	b,c 1	1.68	b,c 1
0.07–0.14	1.41	a 1	1.58	a 1	1.61	a 1	1.60	a 1
0.14–0.21	1.44	a 1	1.58	a 1	1.59	a 1	1.57	a 1
0.21–0.28	1.43	a 1	1.56	a,b 1	1.63	b 1	1.59	a,b 1

Homogenous groups in: columns – 1, 2 …; rows – a,b ….

Also the values of cone indexes showed a significant effect of tractor passes on soil (Fig. 3). As the number of passes increased, the cone index values increased thought the soil profile. Concluding SFH, bulk densities and cone index values describe well the influence of soil compaction on the soil physical and infiltration properties.

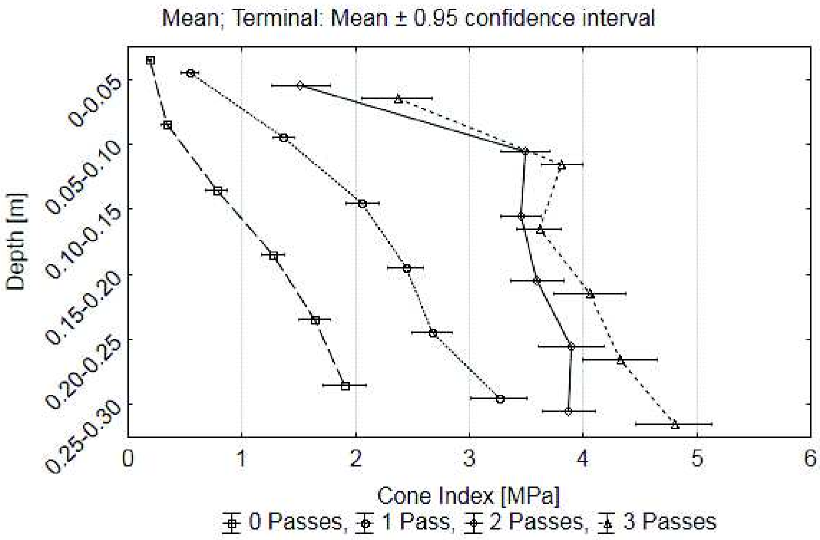

Figure 3. Cone index results at FC.

The comparison and identification of dependencies of the SFH and the MD infiltration methods (Fig. 4) showed a logarithmic trend with mid dependency ($R^2 = 0.2355$) according to Chráska (2000). As both methods measure the same parameter an increasing correlation was expected.

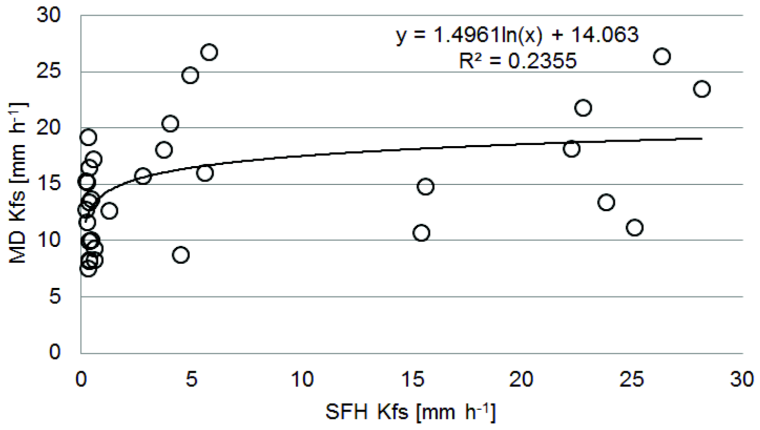

Figure 4. Correlation between MD and SFH method.

The correlation of both infiltration methods and soil bulk density (sampling depth of 0.07–0.14 m) showed linear trends with high dependency for the SFH method ($R^2 = 0.5944$) while for the MD method poor correlation ($R^2 = 0.0883$) was found (Fig. 5). According to the literature, a decreasing trend of correlation between soil water infiltration and bulk density was expected and also confirmed in both measured cases (Liebig et al., 1993; Yuxia et al., 2001).

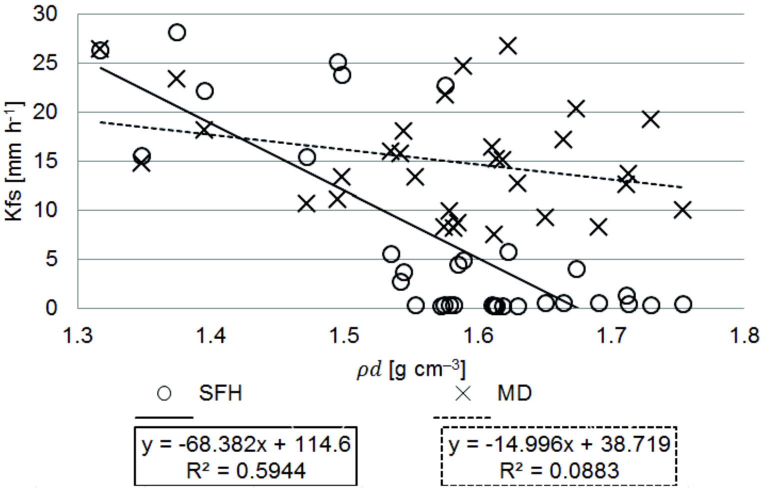

Figure 5. Correlation between infiltration methods (SFH and MD) and soil dry bulk density.

The expected trends of correlation of infiltration methods and cone index values should be similar to the trends showed in Fig. 5. As expected the linear decreasing correlation between the MD and cone index was confirmed with mid dependency ($R^2 = 0.1887$). In the case of SFH and cone index a decreasing power trend was found (Fig. 6) with a very high correlation ($R^2 = 0.865$).

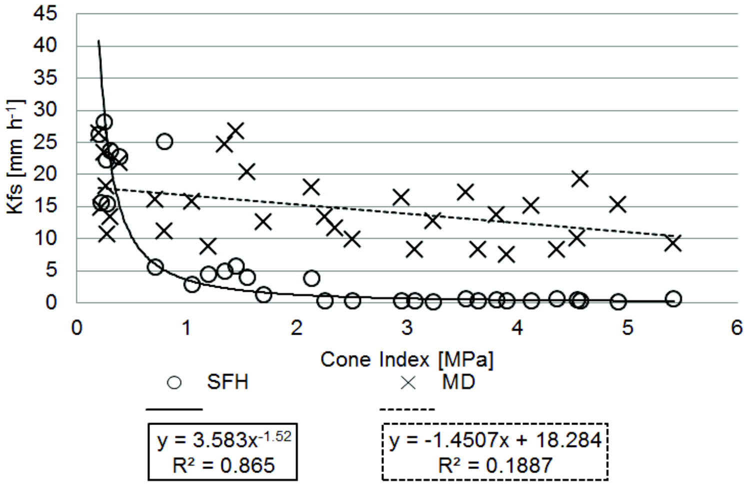

Figure 6. Correlation between infiltration methods (SFH and MD) and cone index.

The resulting measurements performed with MD and SFH method allowed a comparison of these methods to be made. However, the coefficients of correlation were at mid dependency (Fig. 5). The possible reason for this could be a different principle of the measurement methods. The minidisc method is based on the suction ability of the soil and is not affected by the ambient air pressure, while the SFH method is based on the Earth´s gravity and the ability of water to penetrate into the soil (Elrick et al., 1989).

CONCLUSIONS

1. The effect of vehicle traffic on soil infiltration has been significant:
    a) The non-compacted soil had its water infiltration rate up to 6 times higher than the trafficked;
    b) The results showed statistical differences between each compaction levels; moreover it was found that after two passes there were no changes in soil water infiltration rate measured by SFH method under these conditions;
    c) In case of the MD measurements, that the changes in soil water infiltration rate are expected to occur even after multiple passages.

2. A comparison of the infiltration methods used showed that both methods are applicable in practice, but not mutually interchangeable, as proven by a calculation of a coefficient of determination. The advantage of MD method is possibility to undertake many replications on a small area with almost no disturbance to the soil surface and small amount of water applied while the SFH method is more practical for field application. However, on severely compacted soils the MD method is less time consuming.

3. The effect of soil compaction on water infiltration highlights the importance of the techniques resulting in minimising soil compaction such as controlled traffic farming (CTF), linked operations, conservation tillage etc. These reduce trafficked areas which leads to a reduction of soil compaction and an increase in the water infiltration rate of a field.

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