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An investigation into the effect of traffic and tillage on soil properties using X-ray computed tomography

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ABSTRACT. Compaction of soils from agricultural machinery alters soil aggregate and pore structure whilst increasing bulk density. This leads to decreased soil aeration and water and nutrient uptake and increases root penetration resistance that can result in reduced crop yields. A randomised 3x3 factorial traffic (Random Traffic Farming, Controlled Traffic Farming and Low Ground Pressure systems) and tillage (Deep, 250mm; Shallow, 100mm and No-till) field experiment at Harper Adams University, UK, was set up in 2011. An investigation was conducted in 2016 using X-ray Computed Tomography (CT) to assess the effects of tillage and traffic on the soil pore size and distribution. The study highlighted that deep tillage reduces the ability of soil to support vehicular traffic which leads to soil recompaction. Deep tillage caused soil percentage porosity to decrease with depth with corresponding increases in the frequency of smaller size pores. Shallow tillage treatments increased the percentage porosity with depth whilst providing the lowest penetration resistance. Percentage porosity is higher in untrafficked treatments. Further investigation is required to investigate the effect that the complex interactions between soil pore structure and developing root architecture have on crop yield.

Keywords. compaction, computed tomography, no till, porosity, soils, tillage, tires, traffic, x ray.

Introduction

Compaction of agricultural soils by heavy machinery is a major agricultural problem and accounts for the degradation of an area of 33 million ha of soil in Europe (Kroulík et al., 2009). Compaction mainly affects larger soil pores reducing soil porosity for a given mass (Berisso et al., 2012) increasing bulk density and reducing the proportion of large to small pores (Kim et al., 2010) and can have an effect throughout the whole soil profile (Troldborg et al., 2013). The system of pores within the soil is essential for the transport of air and water (Eden et al., 2011) and nutrients necessary for the growing plant. The reduction in macroporosity from soil compaction can be sufficient to restrict root survival (Rab et al., 2014) leading to the reduction in crop yield (Czyz, 2004).

The heterogeneous nature of soil makes assessment of structure difficult (Munkholm et al., 2013). Porosity in the soil consists of a variety of pore shapes and sizes which have different effects on the movement and storage of water, aeration and resistance to root growth. Macropores (>30 µm dia.) allow water infiltration and drainage and have the most influence on soil aeration. Pores between 30 µm and 0.2 µm dia. (mesopores) are important for storage of water that is available to the plant. Micropores (below 0.2 µm dia.) store water that is not available for the plant and they do not support microbiological activity (Kay and VandenBygaart, 2002).

Determination of dry bulk density is a widely accepted means of identifying changes in soil compaction and total soil porosity in response to vehicular traffic and mechanical breaking from tillage operations (Campbell, 1994) but does not allow the quantification of pore sizes and distribution within the soil.

X-ray computed tomography (CT) is a non destructive 3D imaging technique that can be used to measure soil pore size and distribution (Rab et al., 2014). X-ray CT uses mathematical reconstructions from attenuation of radiation to produce stacked 2D images to produce 3D models of the soil sample (Vaz et al., 2011) allowing visualisation of changes in pore system structure through the soil profile.

A novel investigation was conducted in 2016 using X-ray CT to assess the effects of tillage and traffic in a long term agricultural field experiment on soil porosity, pore size and pore distribution.

Material and methods

Study area

An investigation was conducted in 2016 using X-ray CT on a long term randomised 3x3 factorial traffic (Random Traffic Farming (RTF), Controlled Traffic Farming (CTF) and Low Ground Pressure (LGP) systems) and tillage (Deep, 250mm; Shallow,100mm and No-till) plot experiment initiated in 2011 at Harper Adams University, UK. (52° 46' 56.316" N, 2° 25' 45.1704" W) as described by (Smith et al., 2013). The factorial design had nine plots 4 m wide x 80 m long replicated in four blocks (36 plots total).

Each plot had a pair of 'primary' wheelways about the centre line that were used for cultivation and drilling operations using a Massey Ferguson 8480 with Michelin Axiobib tyres (IF 650/85 R38 TL 179D, rear and IF 600/70 R30TL 159D, front). Tyre pressures were set to 1.2 bar front, 1.5 bar rear for RTF plots and 0.7 bar front and rear for LGP and CTF plots. Cultivation treatments were applied prior to drilling using a 4 metre Vaderstad Topdown (14 standard tines at 270 mm spacing with front discs set to 50 mm depth). Spring oats (Aspen) was drilled using a Vaderstad 4 metre Spirit drill in April 2016. The soil was mainly a slightly stony sandy loam (Clavererly Association) (Beard, 1988).

Data collection

Soil samples and penetration resistance readings were taken from primary wheelways in the RTF and LGP plots and from the untrafficked centres of the CTF plots during the period 8th - 12th August 2016.

Undisturbed soil cores were taken (36 total) using an Eijkelkamp liner sampler and were stored in the dark and upright at 4°C prior to X-ray scanning. The soil core liners measured 50 mm diameter x 300 mm length. The action of the corer during sampling and the storage of the cores on their bases loosened the soil at around 275-300 mm depth affecting porosity measurements. All analysis was, therefore, conducted on data between 0-250 mm.

Penetration resistance readings were taken from the sample areas using an Eijkelkamp pentrologger in accordance with Eijkelkamp (2000).

X-ray scanning

The soil cores were scanned using a Phoenix v|tome|x m X-ray microfocus CT system at the Hounsfield Facility, the University of Nottingham, UK. The CT system parameters were 160 kV, 180 µA, 200 ms detector time and 72 µm resolution. To cover the full length of the core required three scans, 0-100 mm, 100-200 mm and 200-300 mm depth. Scan files were exported as volume files. The three volume files were combined using VG Studio MAX 2.0 software and the resultant 3D X-ray attenuation maps exported as top view (cross sectional area) TIFF files.

As this was a comparative study, the compromise between resolution, sample size and CT scanner beam time was considered adequate. It was accepted, however, that the percentage porosity derived from the CT would be lower than porosity measured by physical methods as found by Vaz et al. (2011) who also reported that even at resolution of 3.7 µm CT derived porosities still underestimate physical soil porosity.

Image analysis

Stacked images were analysed using ImageJ version 1.50i. An area of interest 400 pixel (28.8 mm) x 400 pixel in the centre of the images was selected and the exterior of the images discarded to reduce any effect from beam hardening and deformation from the soil core tool. Soil pore space was selected by segmenting using the Li thresholding algorithm (based on Li and Tam, 1998) on binary images. Values below the threshold were identified as pore space.

Statistical analysis

Statistical analysis of data was conducted using two-way analysis of variance (ANOVA) and repeated measures ANOVA with Tukey's and Bonferroni tests in Genstat 18th Edition. Repeated measures ANOVA (50mm intervals) was used to determine the effect of traffic and tillage treatments together with depth.

Results and discussion

X-ray computed tomography

The vertical cross section sample images in Figure 1 were produced from the X-ray CT attenuation maps using ImageJ software. They show the differences in soil structure between cores subjected to the different treatments.

The deep tillage CTF core shows an open structure whilst the RTF and LGP show evidence of possible re-compaction after tillage as demonstrated by Soane et al. (1986). Shallow tillage images show the effect of the reduced tillage depth in the upper zone (0-60 mm). The soil structure around 150 mm depth in the RTF and LGP images shows horizontal cracking and lack of pore space indicating poorer soil structure. Zero tillage images show a more dense structure through the profile with the presence of horizontal cracks.

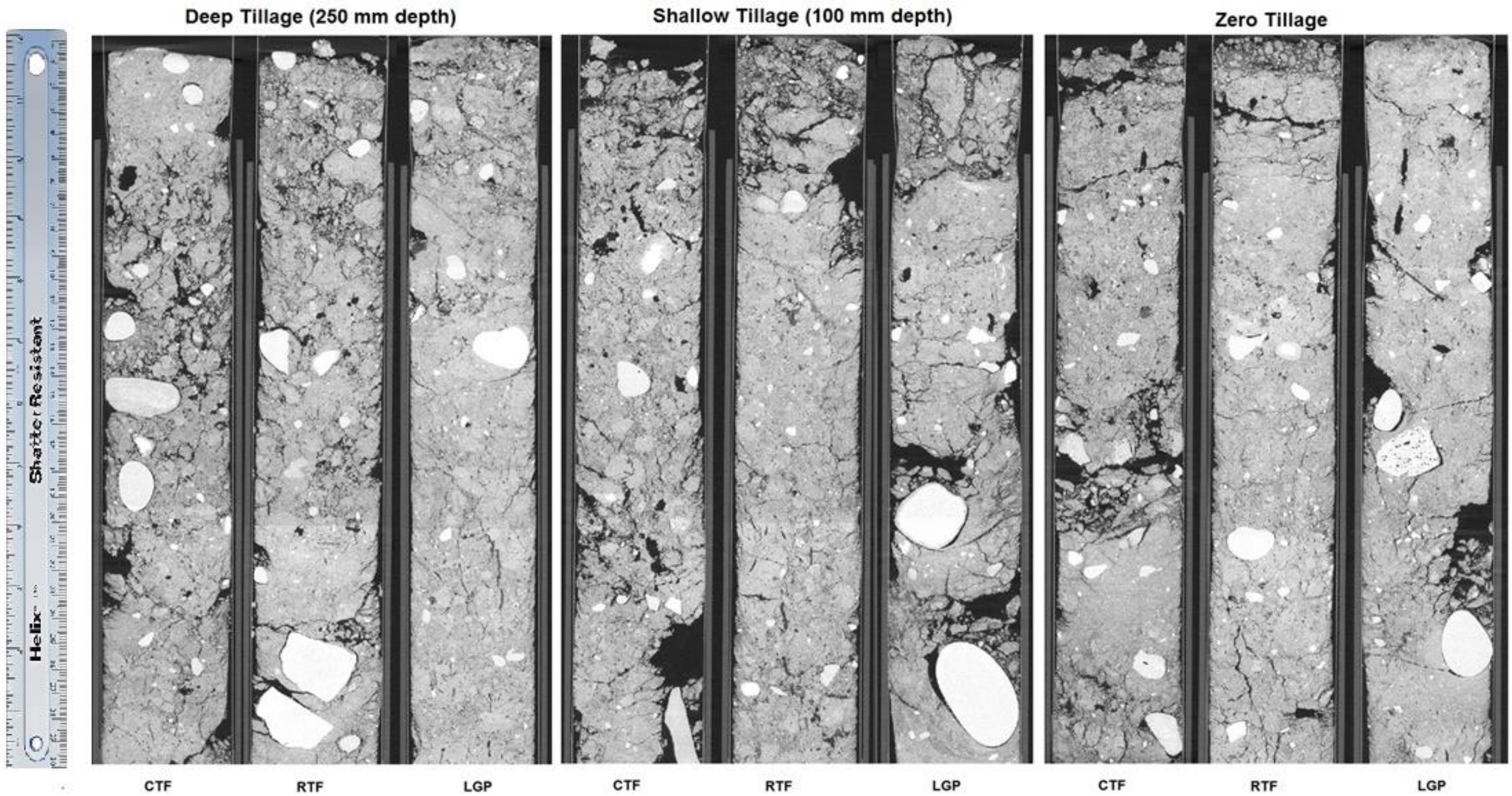


Figure 1 - Sample X-ray CT images through centre of soil cores produced using ImageJ software. Soil cores were 50 mm dia x 300 mm length

Percentage porosity

The results of the repeated means ANOVA analysis of the CT-measured porosity (0-250 mm depth in 50 mm increments) are shown in Table 1. Percentage porosity was significantly higher (p=0.006) in CTF (unwheeled) treatments than LGP and RTF treatments. Deep tillage increased porosity in the CTF treatments from 15.4% in CTF zero (control) to 19.5% and in LGP treatments from 7% (LGP zero) to 11.5%. In RTF treatments deep tillage reduced porosity from 10.8% (RTF zero) to 8.9%. Shallow tillage had little effect on porosity in the CTF plots but resulted in the maximum porosity for LGP and RTF plots (16.5% and 15.4%) similar to the CTF zero (control) porosity of 15.4%. This indicates that on unwheeled soil tillage is unnecessary but on trafficked soil is the most suitable tillage for returning porosity to levels comparable to untrafficked soil.

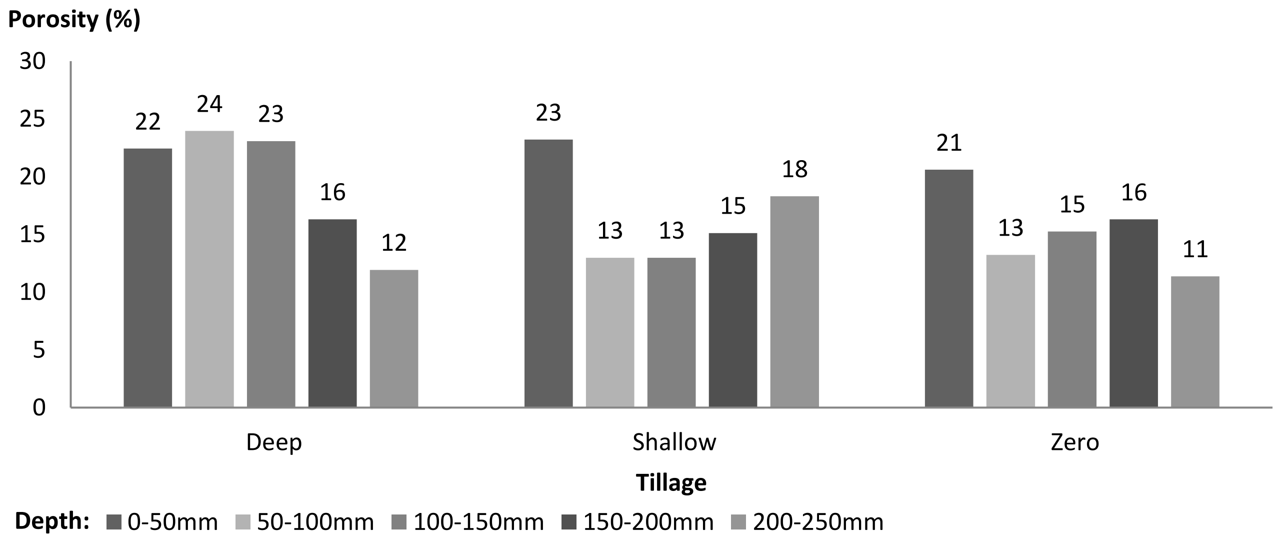
Table 1 - CT-measured porosity (0-250 mm depth in 50 mm increments)

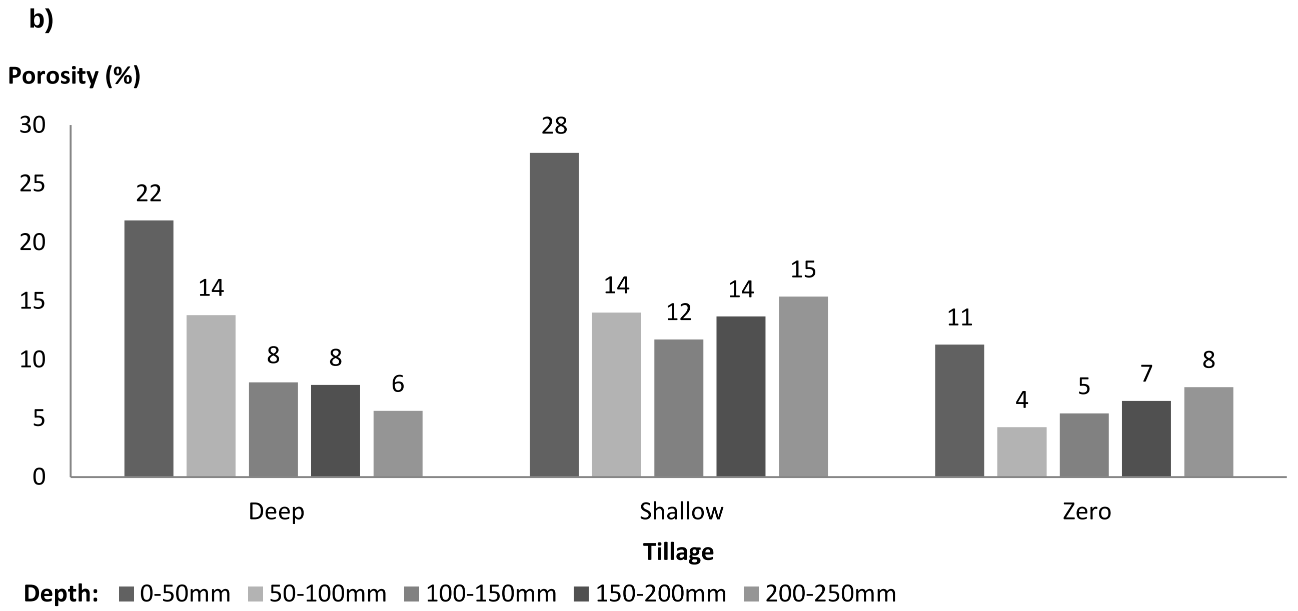
	CT-measured porosity (%)			
Traffic/Tillage	***Deep***	***Shallow***	***Zero***	***Mean***
CTF	***19.5***	***16.5***	***15.4***	***17.1*** [b]
LGP	***11.5***	***16.5***	***7.0***	***11.7*** [a]
RTF	***8.9***	***15.4***	***10.8***	***11.7*** [a]
Mean	***13.3*** [ab]	***16.2*** [b]	***11.1*** [a]	***13.5***
Treatment	***P-Value***	***S.E.M.***	***CV%***	
Traffic	***0.006***	***0.806***	***35.8***	
Tillage	***0.029***	***1.253***		
Traffic x Tillage	***0.123***	***1.253***		
Depth	***<.001***	***1.769***		
Depth x Traffic	***0.162***	***1.769***		
Depth x Tillage	***<.001***	***2.170***		
Depth x Traffic x Tillage	***0.300***	***3.065***		

Note: Means followed by different letters are significantly different from each other at the 0.05 probability level.

Changes in percentage porosity were significantly different with depth (p<0.001) and depth x tillage (p<0.001). The effect of tillage and depth on percentage soil porosity in the three traffic treatments is shown in Figure 2 a-c. The percentage porosity declines sharply with depth in deep tillage trafficked plots (Figure 2 b and c) when compared to the untrafficked deep tillage treatments (Figure 2 a). This is likely due to the reduced ability of deep cultivated soils to support traffic (Soane et al.,1986). Shallow tillage produces similar porosity values throughout the soil profile for all three traffic treatments. Porosity increases between 150 mm to 250 mm which is below the action of the tillage tool (set at 100 mm depth). This may be due to the action of crop roots and soil fauana (Kay and VandenBygaart, 2002). Wheeled traffic on the un-tilled (zero) plots (Figure 2 b and c) reduces soil porosity compared to untrafficked treatments (Figure 2 a).

a)





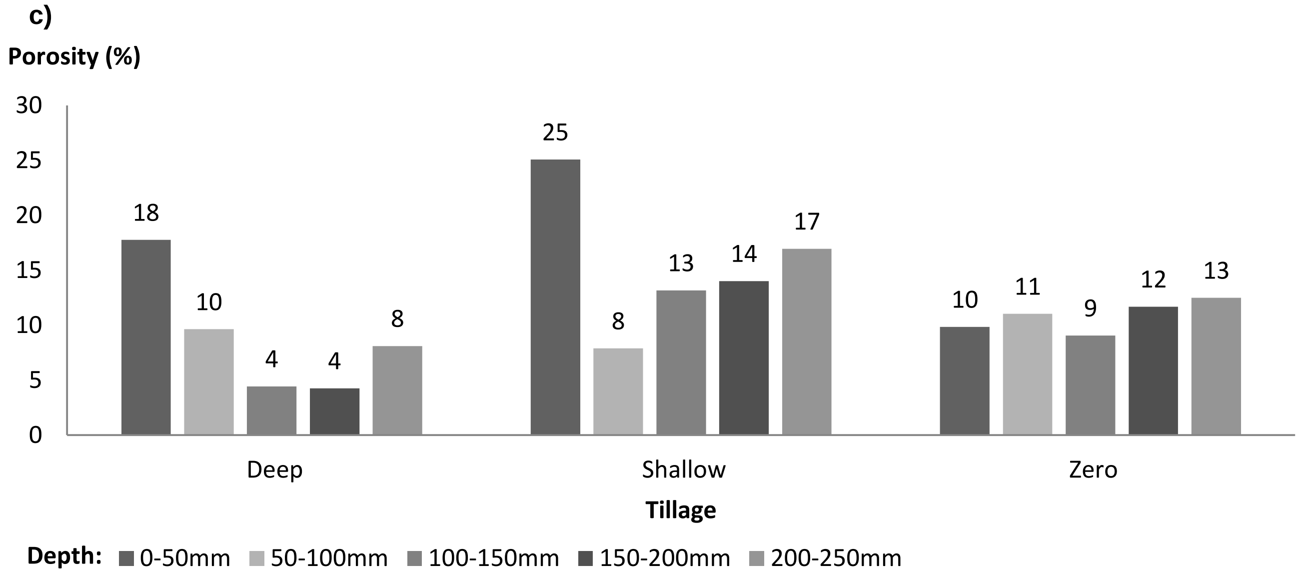


Figure 2 - The effect of tillage and soil depth on CT-measured percentage porosity for each traffic treatment a) CTF (unwheeled), b) LGP (low ground pressure tyres) and c) RTF (high pressure tyres)

Figure 3 shows the CT-measured percentage mean porosity for the nine treatments for the sample lengths 0-250 mm depth. The comparison of deep tillage treatments (Figure 3 a) illustrates the significant difference in porosity between unwheeled (CTF) and trafficked (RTF and LGP) treatments (see means in Table 1). Porosity in the three treatments was above 20% at the surface but RTF and LGP values steadily reduced to around 7% at 120 mm depth and then remained constantly low down to 250 mm. The porosity in the CTF treatments remained high (25%) until 120 mm depth and then reduced gradually to 15% at 200 mm depth and remained at this porosity until 205 mm depth. Soane et al. (1986) demonstrated that deep tilled soils lacked the strength to support vehicle traffic and consequently were susceptible to re-compaction often worst than previous to cultivation. This effect can be seen in the low percentage porosity in the curves from RTF and LGP with RTF being more compacted than LGP.

The percentage porosity curves in the shallow tillage treatments (Figure 3 b) were similar to each other in values and form as reflected in the mean values in Table 1. The action of the tillage can be seen to have increased porosity between 0-50 mm compared to the reasonably constant porosity of 10-20% between 50-250 mm. LGP and CTF curves were less variable in form than RTF.

Percentage porosity decreased in the no-till (zero) treatments for RTF and LGP (Figure 3 c). LGP had the lowest porosity (5-10%) with RTF having more variability with areas of increased porosity throughout the profile. CTF treatments had higher percentage porosity (15%) but had areas of increased porosity at 150 mm and 250 mm which may have been due to remnants of historical field management.

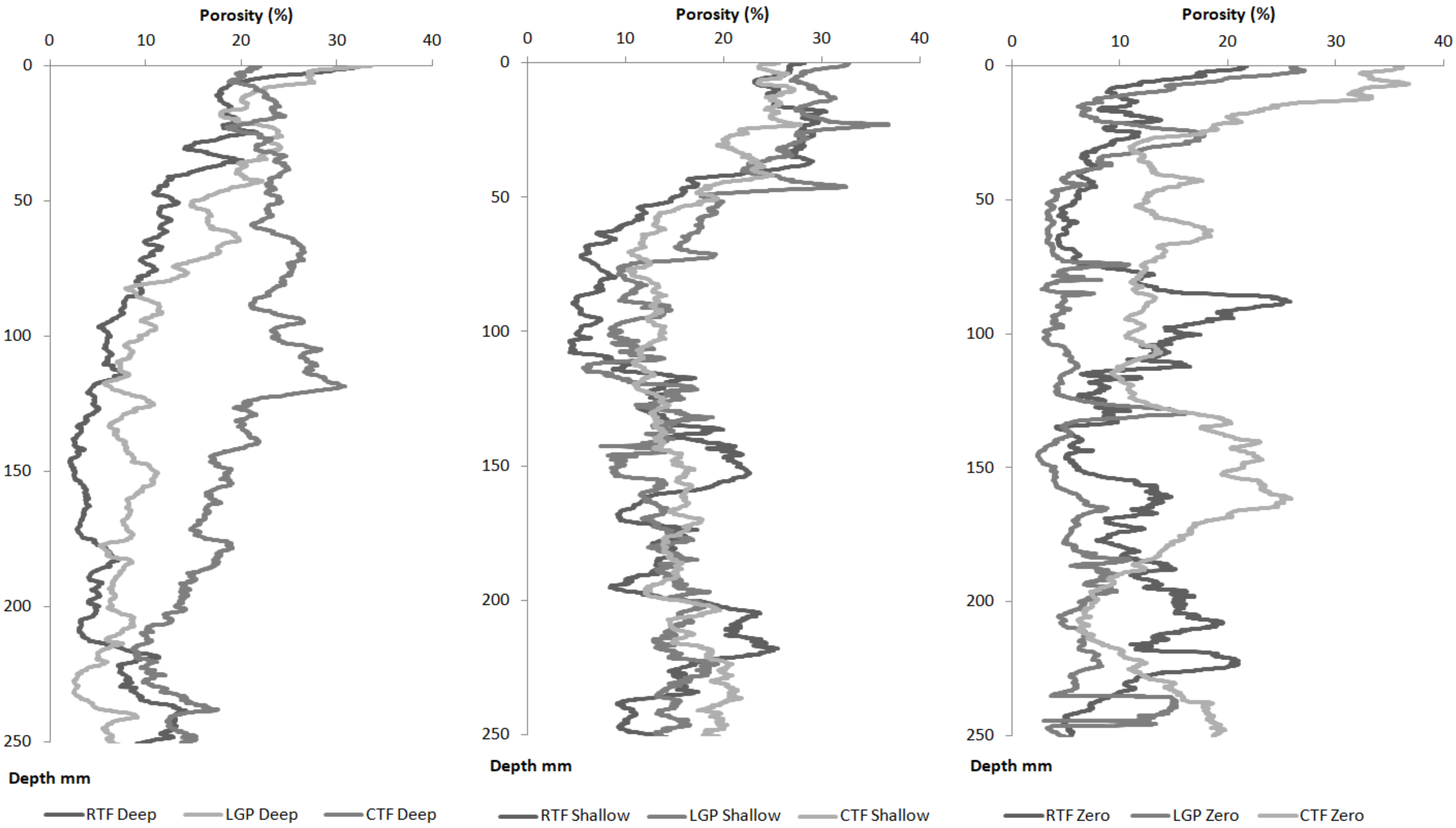


Figure 3 - CT-measured percentage porosity for traffic and tillage treatments 0-250 mm depth a) deep tillage treatments b) shallow tillage treatments c) zero tillage (no-till) treatments

Mean soil pore size and number of pores

There were no significant differences from mean pore size using ANOVA at any other depths. Repeated measures ANOVA found no significant differences for mean pore size, total number of pores or mean number of pores (per image) due to the traffic and tillage treatments but depth was found to have a significant effect. Table 2 shows the changes in CT-measured mean pore size and number of pores with depth. The mean pore size decreased exponentially with depth whilst the number of pores and mean number of pores increased.

Table 2 - Repeated measures ANOVA CT-measured total pore count, mean pore number (per image) and mean size (mm^2) for depth (50 mm intervals)

Depth (mm)	0-50	50-100	100-150	150-200	200-250	P-Value	Relationship	R^2
Mean pore size (mm^{-2})	0.403	0.285	0.206	0.191	0.195	<.001	$y = 1090.9e^{-9.397x}$	0.9607
Mean pores (qty)	456	423	513	544	602	0.011	y = 1.0281x - 396.87	0.8492
Total pores (qty)	316790	293476	350602	377472	401824	0.035	y = 0.0016x - 447.74	0.8362

Mean soil pore size frequency

The use of pore size distribution allows comparison between treatments that attempts to describe the complexity of the soil structure with depth that cannot be seen using percentage porosity (Nimmo, 2004). Figures 4 shows the mean pore size distribution in the CTF plots under the three tillage treatments (50-100mm depth). As the CTF samples were taken from unwheeled areas the results show the differences in pore size distribution due to tillage only. At this depth deep tillage produced larger mean pore sizes (0.4 mm^2 to 0.65 mm^2) than shallow and no-till treatments. Most mean pore sizes were between 0.15 mm^2 and 0.2 mm^2 in shallow tillage treatments. Pore frequency for no-till treatments was more distributed ranging between 0.15 mm^2 and 0.56 mm^2. At this depth deep tillage on untrafficked soil increases pore size but shallow tillage reduces pore size when compared to no tillage treatments.

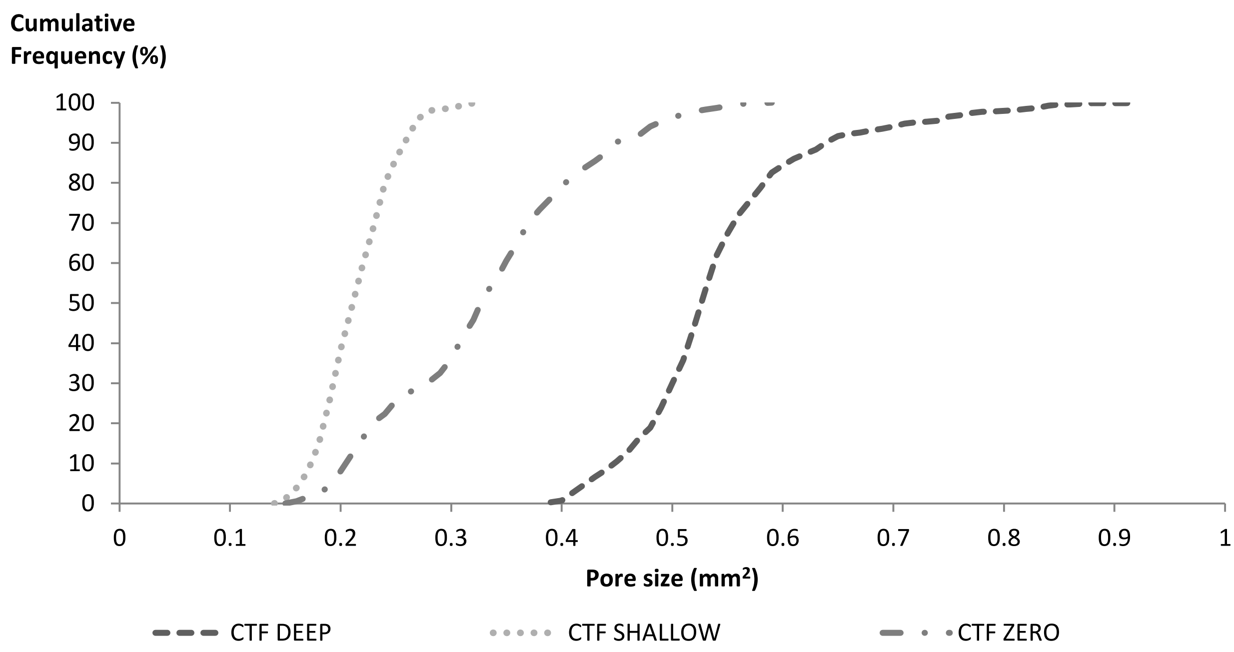


Figure 4 - CT-measured mean pore size cumulative frequency in untrafficked (CTF) plots between 50-100 mm depth

The compaction effect (reduction in pore size) from traffic (Kim et al., 2010) on pore size frequency in the deep tillage treatments can be seen in Figure 5. At 50-100 mm depth traffic increased the frequency of smaller pore size to between 0.2 mm^2 and 0.4 mm^2 compared to untrafficked (0.4 mm^2 to 0.55 mm^2). This would suggest that the use of agricultural machinery on deep tilled soil should be avoided (Soane et al., 1986).

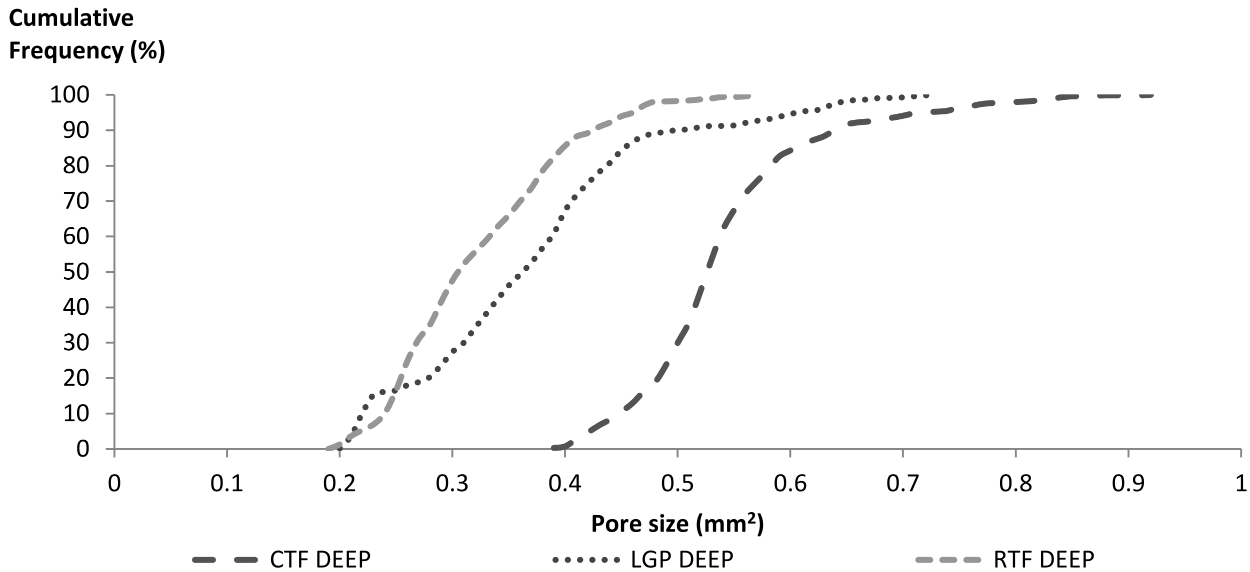
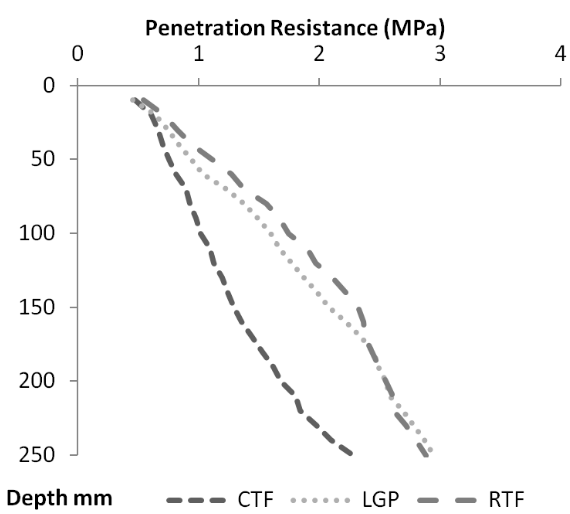


Figure 5 - CT-measured mean pore size cumulative frequency in deep tillage plots between 50-100 mm depth

Penetration resistance

Figure 6 a and b show the means for the traffic and tillage treatments. Readings were significantly higher in the traffic treatments than in untrafficked ($p<0.001$, S.E.M. = 0.0661) but there was no significant difference between RTF and LGP (Figure 6 a). The effect of tyre pressure on soil compaction in the upper soil profile can be seen between the higher penetration resistance in the RTF treatments compared to LGP treatments from 0-170 mm. The compaction effect below 170 mm is due to the load of the vehicle and is the same for both tyre pressures. This compaction lower in the soil profile due to load is consistent with the findings of earlier soil compaction researchers as reported by Raper (2005).

Zero tillage was significantly higher than for deep and shallow tillage treatments ($p=0.002$, S.E.M. = 0.0661). The statistical analysis did not show a significant difference between shallow and deep tillage but the effect of depth was significant ($p<0.001$, S.E.M. = 0.0460). Figure 6 b shows that at 150 mm depth, penetration resistance in the deep tillage treatments continued to increase at a higher rate than for shallow and zero tillage which increased but at a lower rate. This deep compaction in the deep tillage treatments agrees with the findings of Soane et al. (1986) that deep tillage reduced the carrying capacity of soil leading to recompaction.



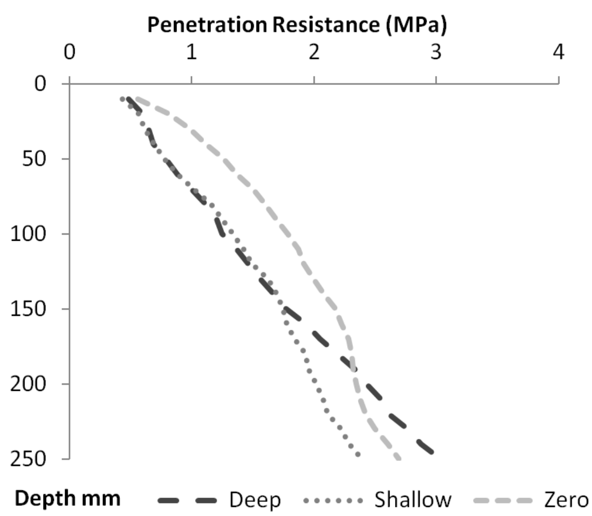


Figure 6 - Penetration resistance means for a) traffic and b) tillage treatments

Conclusions

This study highlights that deep tillage reduces the ability of soil to support vehicular traffic which leads to recompaction of the soil often to a worse extent than prior to the tillage operation as found by previous researchers. Deep tillage caused percentage porosity to decrease with depth with a corresponding increase in the frequency of smaller size pores.

Shallow tillage treatments significantly increased percentage porosity compared to zero tillage (p=0.029) and increased porosity with depth

Vehicular traffic has a negative effect on soil porosity. Percentage porosity was higher in untrafficked. Penetration resistance was significantly lower in untrafficked than trafficked treatments.

Further work

Further work is needed to calculate the total porosity derived from bulk density measurements of the soil cores used in this study to allow for calibration between the physical porosity of the soil samples and the CT-measured porosity. A future study is recommended to investigate the effect that the complex interactions between soil pore structure and developing root architecture have on crop yield.

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