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DOI: https://doi.org/10.15159/ar.19.136

Kaczorowska–Dolowy, M., Godwin, R.J., Dickin, E., White, D.R. and Misiewicz, P.A. 2019. Controlled traffic farming delivers better crop yield of winter bean as a result of improved root development. *Agronomy Research*, 17(3), pp.725-740.

Agronomy Research **17**(3), 725–740, 2019
https://doi.org/10.15159/AR.19.136

Controlled traffic farming delivers better crop yield of winter bean as a result of improved root development

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Abstract. This paper reports on the continuation of a long–term experiment on the effects of alternative field traffic systems (STP–random traffic with standard tyre inflation pressure, LTP–random traffic with low tyre inflation pressure and CTF–controlled traffic farming) on soil conditions and crop development as influenced by different tillage depths (DEEP–250 mm, SHALLOW–100 mm and ZERO–tillage), in a randomised 3 x 3 factorial design in 4 replicates launched by Harper Adams University in Edgmond, UK, in 2011. The results from season 2017–2018 revealed that CTF delivered 8% higher crop yield of winter field bean (*Vicia faba*) cv. *Tundra* comparing to STP ($p = 0.005$), i.e. 4.13 vs 3.82 tonnes ha^{-1} respectively (at 14% moisture content). The ZERO–tillage plots featured significantly lower plant establishment percentage comparing to shallow and deep tillage: 79% vs 83% and 83% respectively ($p = 0.012$). The research showed that roots traits differed significantly between contrasting traffic at depths greater than 50mm with $p < 0.05$ of: tap root biomass, number of lateral roots, biomass of lateral roots as well as total root biomass (tap+lateral roots), delivering significantly greater values of those before mentioned parameters on CTF comparing to STP. Tap root length significantly differed between traffic systems ($p < 0.001$) giving significantly greater results on CTF comparing to LTP and STP (17.7, 13.4 and 12.6 mm respectively). Significant differences in tap root diameter were found only at the depth of 100 mm ($p < 0.001$) where again CTF delivered significantly higher root diameter than the remaining 2 traffic systems.
In the shallow layer of soil (0–50 mm) a significant difference was found only for tap root biomass, for interactions, where STP ZERO gave significantly higher results than STP SHALLOW and CTF SHALLOW (1.430, 0.733 and 0.716 g respectively).

Key words: soil compaction, random and controlled traffic farming (CTF), standard and low tyre inflation pressure, *Vicia faba*, root morphology.

INTRODUCTION

The demand of high crop yields due to increasing world population has resulted in agricultural intensification, which has been accompanied by an increase in machinery size and weight, thus soil has been subject to increasing degrees of compaction (Chamen et al., 2011).

The physical structure and functional properties of trafficked soil can be significantly different when compared to untrafficked soil as a result of increased soil compaction inhibiting root development, water availability, nutrient uptake and yields (Raghavan et al., 1979; Czyz, 2004; Chamen et al., 2011).

There are many causes of soil compaction identified by researchers, but most significant compaction is a result from farming vehicles traffic imposed via wheels pressure, since compaction is a result of stress upon the soil, and is related to load, tyre pressure and contact area (Soane & van Ouwerkerk, 1994; Raper et al., 1995).

Increased tyre inflation pressure increases contact pressure as a result of the reduced contact area. This was confirmed by Raper et al. (1995), who reported that rut depth increased with an increase of tyre inflation pressure, confirming the relationship between high inflation pressure traffic and greater vertical impact on the soil profile. Further works by Antille et al. (2013) confirmed that the least change in soil bulk density and vertical soil displacement was found for larger tyres with lower inflation pressure. Under inflating tyres, however is not the solution for compaction problems as tyres operated with inflation pressures below those specified by the manufacturers can be dangerous, have higher rates of wear and suffer an increased risk of failure (Smith, 2017). Raper et al. (1995) reported that the load is moved towards the edge of the tyre in case of under–inflated tyres, and as a consequence increases rolling resistance and manoeuvring in the field and on the road is more difficult.

The results of many studies on the effects of tyres pressure on soil degradation triggered the development of low ground pressure tyres and tracks (Alakukku et al., 2003). Since additional tyres mounted on the tractor caused problems with external width of a vehicle moving on a highway, tyres of larger volume but the same external diameter as the standard equivalent became an option (Michelin, 2018). Moreover, Michelin has developed a range of improved flexion tyres (IF) and of very high flexion tyres (VF) that are suitable for many agricultural machines. According to the manufacturer, these tyres feature even load distribution thanks to a wider footprint of the tractor wheel, which in turn offers increased soil protection and improves longevity and fuel and time efficiency (Michelin, 2018) and operate at lower inflation pressures.

Depending on crop and agronomy measures, the trafficked area i.e. the area covered by wheel marks, might reach up to 90% (Soane et al., 1980). Further surveys where global positioning system–tracking devices were applied revealed that random traffic farming practices, with conventional tyre inflation pressures, for wheat production covered some 86%, 65% and 45% of the field with at least 1 wheel–pass for conventional (plough based) tillage, minimum tillage and direct drilling/zero–till respectively (Kroulik et al., 2009).

Soil compaction results in the reduction of macro–porosity and in turn may limit root development (Rab et al., 2014), resulting in the reduction of crop yield (Czyz, 2004) The system of pores within the soil is essential for the transport of air, water and nutrients necessary for the growing plant (Eden et al., 2011). The analysis of soil pores structure (size and distribution) using X–ray Computer Tomography technique showed that soil percentage porosity is higher in untrafficked treatments. The porosity decreased with depth where the soil had been tilled to 250mm, and smaller soil pores were more frequent (Millington et al., 2018). The author reveals that shallow tillage treatments (100 mm) increased the percentage porosity with depth whilst providing the lowest soil penetration resistance.

The roots depth and their distribution are important features upon which water and nutrients uptake depend, particularly in areas of low rain (Manschadi et al., 1998) which could apply to this experiment in 2018 when the total rainfall in 3 months preceding harvest (May–July) was 72 mm, compared to a long–term average of 216 mm (Harper Adams University weather data for 2007–2017). During period with water insufficiency, the capacity of water uptake is related to the depths and the uniformity of roots system (Dardanelli et al., 1997). To avoid water stress in dry soil it is the root length density (mm root/ml soil) that plays a vital role (Tron et al., 2015).

Soil compaction as a result of farming traffic has been suggested as the main reason for crop yield penalty by many researchers (Raghavan et al., 1979; Horn et al., 2003; Chamen, 2011). The yield reduction on trafficked soil is related to restricted root growth and lower access to nutrients as a result of increased bulk density and reduced pore size in trafficked areas (Rab et al. 2014, Aguilera Esteban et al., 2019). This suggests that much could be gained from controlled traffic farming practices (CTF) where field operations are focused on predetermined wheel ways and equipment widths and wheel track spacing are matched (Tullberg et al., 2007). Thanks to the global positioning satellite guidance and auto–steer systems with real time kinetic (RTK) controlled traffic farming (CTF) has become practical and adopted by many farmers. CTF due to the reduction in number of wheel ways reduces soil compaction, consequently its potential advantages are: improved crop yields, improved soil conditions and infiltration of rainfall/irrigation water, reduced tillage and crop establishment draught forces/energy (Godwin et al., 2015). The experiment at Harper Adams University focused on traffic contrasted with 3 tillage systems revealed that CTF delivered higher crop yield than STP (Smith, 2017). This is in agreement with other research: Chamen et al. (2011) reported yield improvements between 7% and 35% for CTF, while Godwin et al. (2015) reported yield increases of between 7.3 –10% when controlled traffic farming was applied.

CTF however requires much investment in equipment mounted on a tractor necessary for precise guiding on permanent wheel ways. Godwin et al. (2017) concluded that the required breakeven area was 312 ha for 30% trafficked area and 168 ha in case of 15% of trafficked area.

Previously reported studies have focused on the farming traffic with one depth of tillage. To fill the gap in knowledge, a long–term experiment was established in 2011 on a uniform sandy loam field by Smith (2017) to determine the effects of farming traffic subject to three tillage depths. Since the launch of the experiment, the same vehicular traffic and tillage depth have been applied each year to the given treatment plot to ensure the long–term effects of contrasting systems might be studied. This paper reports on a continuation of that research and focuses on the effects of 3 traffic systems, namely random traffic with standard tyre inflation pressure (STP), random traffic with low tyre inflation pressure (LTP) and controlled traffic farming (CTF) contrasted with 3 different tillage depths (250 mm, 100 mm and zero tillage) on plant establishment, root morphology and crop yield of winter bean (*Vicia faba*) cv. Tundra. The crop was established in November 2017, samples were taken and analysed in spring and summer 2018.

MATERIALS AND METHODS

Location and site description

The experimental site is located on a field called Large Marsh, within the Harper Adams University campus in Newport, TF 10 8NB, Shropshire, United Kingdom. Its geo references are: 52°46'58.0"N 2°25'43.9"W. The total area of the field is 3.12 ha, which consists of the area of the experimental plots and the surrounding headlands.

The field lies at about 63 metres above mean sea level. The predominant soil type was identified as Claverley (Cvy), a very slightly stony sandy loam, with small areas of Olerton and Salwick series soils (Beard, 1988).

Before launching the experiment, the field had previously been managed with conventional soil and agronomic practices, with a cropping history of barley in 2009 and 2008 and grass in 2010. A sub–surface gravel back-fill land drainage system at 13 m intervals was installed in September 2011 and subsoiled to a depth of 0.45–0.5 m.

To ensure uniformity across the study, soil properties were examined in scope of bulk density, penetration resistance, electro conductivity, surface and sub-surface soil moisture as well as crop yield from the uniformity year. Once the site uniformity was confirmed, the 4–m wide plots were established in a randomised block design with an 8–furrow mouldboard plough and drilled with combination rotary harrow/drill. Crop spaying and fertilising takes place at 90 degrees to plots at 24 m spacing, creating permanent tramlines.

The crop rotation in this study was chosen to represent the range of crops grown in arable farming in UK with cereal as the main crop. As a break crop with oil seed rape was not feasible in this experiment, the winter barley in 2015 was followed by cover crop.

The crop rotation since the first harvest in 2012 is presented below, the year indicates the year of harvest:

2012 Winter wheat (uniformity year); 2013 Winter wheat; 2014 Winter barley; 2015 Winter barley, followed by a cover crop TerraLife-N-Fixx (DSV United Kingdom Ltd, 2015); 2016 Spring oat; 2017 Spring wheat; 2018 Winter bean.

The experimental field has been subject to many analysis focused on soil properties and most important findings are presented below to describe the field soil conditions.

Soil bulk density was measured in 2012, 2013, and 2015 in the permanent wheelways and between the wheelways by Smith (2017) and Millington (2019). The results from both studies suggested that soil bulk density significantly differed between traffic systems – and it was significantly lower on CTF in comparison to STP and LTP in the overall analysed 0–250 mm depth ($p < 0.001$). LTP didn't differ significantly from STP. Both researchers also suggested that the soil bulk density increased with depth ($p < 0.001$). Millington (2019) found that the BD on CTF increased from 1.2 mg m^{-3} in the top layer of soil (0–50mm) to 1.4 mg m^{-3} at the depth of 200–250 mm. On STP and LTP the value of BD ranged from 1.3 mg m^{-3} at the 0–50 mm depth to the maximum around 1.5 mg m^{-3} (for STP) and 1.53 (for LTP) at the 100–150 mm depth. It slightly decreased at the depth of 150–200 mm and again increased at the depth of 200–250 mm. Smith (2017) suggested that deep tillage featured significantly lower BD than shallow and zero tillage (1.57 mg m^{-3}, 1.66 mg m^{-3} 1.65 mg m^{-3} respectively ($p = 0.042$). Zero tillage had a significantly ($p = 0.007$) higher BD in comparison to deep and shallow tillage, but only at 100 mm depth (Smith, 2017). It was confirmed by Millington (2019) who revealed that zero tillage featured the highest BD in the shallow stratum (0–100 mm), nevertheless the results of BD between tillage systems didn't differ significantly. He also suggested that shallow tillage produced a tillage pan at 100–150 mm depth just below the depth of cultivation of 100 mm.

Soil organic matter content (SOM) in the soil profile 0–200 mm (loss on ignition method used) was measured by Wookey (2016) and Crawford (2019). Both studies suggested that traffic did not have a significant effect on SOM, however significant differences were found between contrasting tillage systems ($p = 0.005$). Wookey (2016) found that deep tillage featured significantly lower SOM content than shallow and zero tillage: 4.44%, 4.82% and 4.95% respectively. In agreement, Crawford (2019) reported significantly lower SOM on deep tillage comparing to zero (3.5% and 3.9% respectively), and shallow tillage with its 3.7% of SOM did not differ significantly from the remaining two systems.

The field saturated hydraulic conductivity analysis was conducted in 2016 and showed deep tillage was significantly higher than zero tillage ($K_{fs} = 2.42\ 10^{-5}$ and $7.13\ 10^{-6}$ respectively); shallow tillage with the result of $K_{fs} = 1.6\ 10^{-5}$ did not differ significantly from either of tillage systems (Abell, 2016). The same study found that hydraulic conductivity also differed significantly between traffic systems. CTF featured significantly higher result than STP ($2.64\ 10^{-5}$ and $5.52\ 10^{-6}$ respectively). LTP result ($1.55\ 10^{-5}$) was not found significantly different from CTF or STP.

Infiltration rate analysis showed significant differences between traffic ($p < 0.001$) and tillage ($p < 0.001$) systems (Abell, 2016). Mean infiltration rate on deep tillage was 14.15 mm h^{-1}, on shallow – 8.25 mm h^{-1} and on zero tillage – 4.61 mm h^{-1}. All three means were found significantly different. CTF featured significantly greater infiltration rate than trafficked wheelways (13.9 mm h^{-1} and 4.1 mm h^{-1} respectively).

Design replications and statistics

The experimental design is a 3 x 3 factorial in 4 complete randomized blocks (3 traffic x 3 tillage systems). Nominally the plots in block 1–3 are 4 m wide by 84 m long and in block 4–82 m long, however for operational reasons, the last plot in block 4 (plot 36) is only 78.2 m long.

Data was analysed by factorial analysis of variance ANOVA. Post–hoc test for significant differences of means was carried out with Tukey's test with 95% confidence (unless otherwise stated). All the statistical analysis was conducted with Genstat 18th Edition Software.

Crop and variety

The crop in season 2017–2018 was winter bean variety Tundra, sown on 10 November 2017. Thousand Grain Weight (TGW) = 720, seed rate 160 kg ha^{-1} with a 25% increase for the zero tillage plots. The seed placement depth was approximately 80 mm (after Millington, 2019).

Farm equipment and tyres

For the main farming tasks: tillage and drilling treatments and applying the effects of compaction caused by other field traffic events, a 290 hp Massey Fergusson 8480 tractor was used. The track width was 2.1 metres. The tractor was fitted with increased flexion AxioBib tyres (IF 600/70 R30 159D TL at the front, and IF 650/85 R38 179D, TL on the rear axle).

Tyres pressure were checked using a calibrated Newbow Ltd © tyre pressure gauge (NB604).

For the compaction treatment the tractor was fitted with additional load – 540 kg front weight and 1,400 kg on the rear linkage. The STP plots were driven with the tractor on standard pressured tyres, i.e. front tyres – 1.1 bar, rear tyres – 0.9 bar. On both – the CTF and LTP plots the tractor was operated with tyre pressures of 0.8 bar for both front and rear axles (Michelin, 2013).

Tyres for tillage operation were inflated to 1bar both – front and rear for STP plots, while for CTF and LTP to 0.7 bar on the front axle and 0.8 bar on the rear axle. For the tillage operation, only the front ballast of 540 kg was applied, as part of the cultivator's weight was applied to the rear axle.

The tyre pressures were reflecting the common farming practice for this type of increased flexion tyres applied in farming. Low tyre pressure for CTF and LTP plots was adjusted to be the lowest tyre inflation pressure possible whilst maintaining traction and protecting tyre performance (Michelin, 2013).

The tillage operations were conducted with a multipurpose Vaderstad, Top-Down cultivator, which can be adjusted for both shallow and deep tillage.

The navigation of the tractor was provided by an in-vehicle auto-steer system Trimble FmX connected to a Trimble EZ-Steer steering system.

Vaderstad Spirit pneumatic seed drill has been used for drilling the crop. For ZERO tillage plots the tines and discs were lifted to avoid additional soil disturbance.

For harvest a Claas Dominator combine was used with a 4–m header, matching the plots size (after Smith, 2017 and Millington, 2019). To assess the grain weight/plot, an external hopper was hung on a load cell carried by a JCB tele handler.

Compaction treatment

This experiment was designed to apply additional traffic to obtain the trafficked area reported by Kroulik et al. (2009), who determined the percentage of total wheeled area depending on tillage practice. To mimic those values, additional traffic was precisely applied on each plot with Trimble RTK satellite navigation system. The compaction protocol included offsets of the vehicle from the centre of each plot (600 and 1,200 mm) to apply the additional traffic passes. Since the launch of the experiment the vehicular traffic on the plots have been applied in the same patern. As a result of comparatively narrow plots and constant wheeling width, as well as limitation with offset to avoid extra traffic applied on adjacent plots, the area repeatedly trafficked did not exactly achieve the figures from the work of Kroulík (2009).

Following the protocol established by Millington, (2019), the compaction treatment was split to 3 sequences which allowed to achieve the trafficked area of approximately:

75% on STP and LTP plots with DEEP tillage;

60% on STP and LTP plots with SHALLOW tillage;

45% on ZERO tillage plots;

30% on CTF plots- as a consequence of permanent wheelways for tillage and seeding operations. No additional compaction treatment was applied on CTF plots.

Tillage

Tillage was applied with the implement set for 250 mm for deep and 100 mm for shallow tillage plots. The tillage depth was checked with a ruler in the tine slot. Tyres pressures were set accordingly as described above.

Drilling

To facilitate combine navigation and to prevent harvesting the crop from the adjacent plot the 2 outermost coulters of the 24–coulter drill were blocked to ensure easily identified gaps between the plots. The row spacing is 167 mm. Wheel mark eradicator tines were lifted on zero tillage plots, while on the remaining plots they were in use. Tyres inflation pressures were set accordingly.

Plant establishment

For the plant count a transect 5 m wide was established across all plots, at a distance about 0.5 m from the third tramline to the north, apart from plot 36 which was scrutinised towards the south due to unexpected weed patch at the end of the plot. The plant count was conducted on 26 March 2018, in such a way that for each plot several high resolution (9.6 Megapixels) photographs were taken, from above the centreline to the right, and to the left, always keeping the centreline label as well as the corner labels visible. The plant count was then undertaken using the photographs.

Root collection and analysis

The roots sampling took place on 29th May 2018. The bean was in the stage of full flowering (stage 66 BBCH) to ensure fully developed roots. Beforhand, a preliminary trial was conducted on the headland to determine the depth of rooting. The samples were excavated from the ground using a spade and a fork according to the bean shovelomics methods (Bean shovelomics, 2018). The tools were dug into the soil perpendicular to the surface ensuring enough distance from the sample of at least 25 cm from the stem in each direction. If there was another plant growing within the distance to avoid damaging the root system of a chosen plant, the adjacent plant was collected together with the chosen sample and soaked in water. Once the soil was soft enough the additional plant was discarded. One plant (sample) was collected from each plot at a distance of approximately 1 m to the north of the first sprayer line, which ran perpendicular to the direction of the plots. Samples from the LTP and STP traffic plots, were taken from the primary wheelways; while samples from plots representing CTF traffic were taken from the middle of a plot (between the wheelways) representing un–compacted soil.

The roots were washed, measured and counted in two depths: 0–50 mm and > 50 mm, the tap root diameter was measured at the soil surface and the depth of 100 mm. Once all measurements were conducted, the roots were placed in perforated plastic bags in an oven set to 80 °C to determine the dry biomass (Jones, 2001). The analysis was split into lateral roots and tap root at the above–mentioned depths. The overall analysis of total root dry biomass was also carried out.

The diameter and length of roots was measured with electronic callipers and a ruler respectively. The number of lateral roots was taken as a result of cutting off all lateral roots (from a given depth of tap root) with scissors and counting them manually.

The roots were analysed in terms of tap root diameter, length, biomass, and for lateral roots: number and biomass.

Combine harvest

Combine harvesting took place on 10th August 2018. The combine harvester's header matched the width of the plots (4 m). It operated in the same direction for all plots and the grain yield was weighed; subsequently a sample for hectolitre weight was taken.

Further sample were taken from each plot for moisture content analysis and placed in airtight containers.

RESULTS

Plant establishment percentage

Table 1 shows the plant establishment percentage which was found significantly different for tillage (*p = 0.029*) and interactions (*p = 0.012*, *CV = 5.6%*) while for traffic significant differences were visible with reduced confidence level (*p = 0.061)*.

Accepting this lower confidence level, CTF resulted in significantly higher plant establishment percentage than STP. For tillage, ZERO tillage plots featured significantly lower plant establishment percentage than SHALLOW and DEEP. For interactions ZERO STP featured the lowest establishment percentage while SHALLOW STP and DEEP CTF– the highest; the remaining interactions did not differ significantly one from another.

Table 1. Plant establishment percentage (number of plants established as a percentage of seeds sown) of winter bean for 3 tillage and 3 traffic systems as well as for interaction between tillage and traffic system. Significant differences between means are represented by different letters

Plant establishment percentage		
Tillage (93% confidence intervals)	Mean	
ZERO	79%	a
DEEP	83%	b
SHALLOW	83%	b
Traffic (94% confidence intervals)	Mean	
STP	80%	a
LTP	81%	ab
CTF	84%	b
Interactions Tillage.Traffic (95% confidence intervals)	Mean	
ZERO STP	73%	a
DEEP LTP	79%	ab
ZERO LTP	81%	ab
DEEP STP	81%	ab
SHALLOW CTF	82%	ab
ZERO CTF	82%	ab
SHALLOW LTP	83%	ab
SHALLOW STP	86%	b
DEEP CTF	89%	b

Root analysis

Statistical analysis revealed that significant differences (with $p \leq 0.05$) of roots characteristics were found for contrasting traffic systems as well as for interaction between traffic and tillage. There was no significant difference found of any root characteristics for contrasting tillage systems *with* $p \leq 0.05$.

Most of the roots characteristics revealed significant differences in the deeper layer of soil (> 50 mm) only. In the shallow stratum (0–50 mm) as well as total across both depths, only tap root biomass featured significant differences for interactions between traffic and tillage (*p < 0.015; CV = 27%*): ZERO STP delivered almost 100% greater result than SHALLOW CTF and SHALLOW STP, Table 2.

Table 3 presents that across both depths (0–50 mm and > 50 mm), tap root biomass delivered significantly different results for interactions (*p = 0.016, CV* = 29%). Tukey's test with confidence at 93% revealed that DEEP CTF featured significantly greater (over twice) tap root biomass, than SHALOW STP.

Table 2. Average tap root biomass (g) of winter bean at 0–50 mm stratum for interactions between 3 traffic and 3 tillage systems. Significant differences between means are represented by different letters

Tap root biomass at 0–50mm stratum		
Interactions Tillage. Traffic (95% confidence intervals)	Mean	
SHALLOW CTF	0.72	a
SHALLOW STP	0.73	a
DEEP STP	0.98	ab
DEEP LTP	0.99	ab
ZERO CTF	1.01	ab
ZERO LTP	1.04	ab
DEEP CTF	1.20	ab
SHALLOW LTP	1.24	ab
ZERO STP	1.43	b

Table 3. Average total tap root biomass (g) of winter bean across both depths: 0–50 mm and > 50 mm for interactions between 3 traffic and 3 tillage systems. Significant differences between means are represented by different letters

Total tap root biomass (across both depth)		
Interactions Tillage.Traffic (93% confidence intervals)	Mean	
SHALLOW STP	0.89	a
SHALLOW CTF	1.10	ab
DEEP STP	1.13	ab
DEEP LTP	1.20	ab
ZERO LTP	1.49	ab
ZERO CTF	1.61	ab
ZERO STP	1.71	ab
SHALLOW LTP	1.76	ab
DEEP CTF	1.86	b

At the depth > 50 mm, significant differences between contrasting traffic systems were found for: biomass of tap root (*p = 0.002, CV55%),* biomass of lateral roots (*p = 0.005*, *CV = 57%*), total (tap + lateral) root biomass (*p = 0.002, CV = 52%*) as well as number of lateral roots (*p = 0.03, CV = 36%*), giving significantly higher results for CTF than STP, delivering the below described results.

Table 4 shows that at the depth > 50 mm, tap root biomass was over two times greater on CTF than STP and LTP did not differ significantly from the two other traffic systems.

The results given in Table 5 show that the CTF treatments resulted in over 100% greater lateral root biomass than STP and over 67% greater than LTP. The LTP did not differ significantly from STP.

Table 4. Mean tap root biomass (g) of winter bean at the depth > 50 mm for contrasting 3 traffic systems. Significant differences between means are represented by different letters

Tap root biomass at the depths > 50 mm		
Traffic (95% confidence intervals)	Mean	
STP	0.19	a
LTP	0.39	ab
CTF	0.55	b

Table 5. Means of lateral roots biomass (g) of winter bean at the depth > 50 mm for contrasting 3 traffic systems. Significant differences between means are represented by different letters

Lateral roots biomass at the depth > 50 mm		
Traffic (95% confidence intervals)	Mean	
STP	0.23	a
LTP	0.31	a
CTF	0.52	b

Table 6 shows that the total roots biomass (tap+lateral) from the CTF treatment was more than twice of that from the STP, and LTP's result was not significantly different from the two other traffic systems.

Table 7 shows that CTF treatments resulted in 53% greater number of lateral roots, in comparison to STP. LTP didn't differ significantly from two remaining traffic systems. Number of lateral roots also significantly differed for interactions: ZERO STP gave significantly smaller result than DEEP CTF, while the remaining interactions didn't differ significantly one from another.

Significant differences between tap root diameter for contrasting traffic treatments were revealed only at the depth of 100 mm with $p < 0.001$, $CV = 49.9\%$. Tillage or interactions did not have significant effect on this feature. The results in Table 8 show that CTF resulted in significantly greater tap root diameter over the remaining 2 other traffic systems; LTP and STP didn't differ significantly one from another.

Tap root length differed significantly between traffic systems with $p < 0.001$, CV 20.7%. Table 9 shows that CTF treatments featured the greatest tap root length which differed significantly from STP and LTP and was over 40% and 35% longer. LTP and STP didn't differ significantly one from another.

Table 6. Means of total roots biomass (g) of winter bean, at the depth > 50 mm for contrasting 3 traffic systems. Significant differences between means are represented by different letters

Total (tap+lateral) roots biomass at the depth > 50 mm		
Traffic (95% confidence intervals)	Mean	
STP	0.42	a
LTP	0.71	ab
CTF	1.07	b

Table 7. Average number of lateral roots of winter bean at the depth > 50 mm for contrasting 3 traffic systems and interactions between 3 traffic and 3 tillage systems. Significant differences between means are represented by different letters

Number of lateral roots at the depth > 50 mm		
Traffic (95% confidence intervals)	Mean	
STP	26.3	a
LTP	32.6	ab
CTF	40.3	b
Interactions Tillage. Traffic (95% confidence intervals)	Mean	
ZERO STP	19.5	a
DEEP LTP	23.3	ab
DEEP STP	24.5	ab
SHALLOW CTF	29.0	ab
ZERO LTP	33.3	ab
SHALLOW STP	34.8	ab
SHALLOW LTP	41.3	ab
ZERO CTF	42.8	ab
DEEP CTF	49.0	b

Table 8. Mean tap root diameter (mm) of winter bean at 100 mm depth for contrasting 3 traffic systems. Significant differences between means are represented by different letters

Tap root diameter (mm)		
Traffic (95% confidence intervals)	Mean	
STP	1.4	a
LTP	1.7	a
CTF	3.4	b

Table 9. Mean tap root length (mm) of winter bean for contrasting 3 traffic systems. Significant differences between means are represented by different letters

Tap root diameter (mm)		
Traffic (95% confidence intervals)	Mean	
STP	1.4	a
LTP	1.7	a
CTF	3.4	b

Combine harvest data

The yield of winter bean significantly differed between contrasting traffic systems ($p = 0.005$, $CV = 5.3\%$), with no significant differences between tillage or interactions. Fig. 1 shows that the CTF treatment produced 8% higher yield than STP. The LTP did not differ significantly from the remaining two systems.

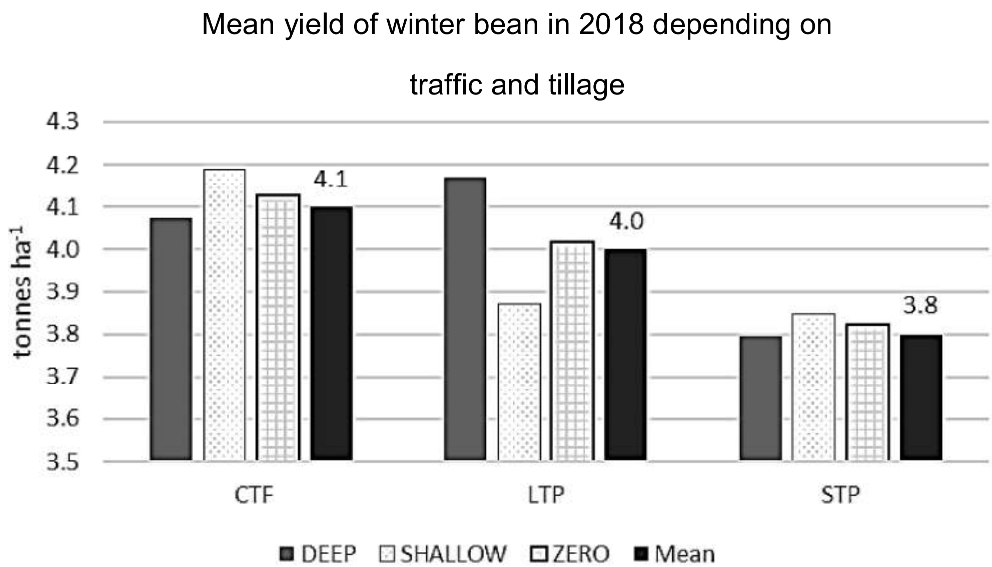

Figure 1. The mean yield of winter bean cv. Tundra in 2018 depending on 3 traffic and 3 tillage systems. The number above the black bar indicates the mean yield from each traffic system.

Discussion

There are many factors that can affect plant establishment and root growth, such as soil bulk density, oxygen and nutrients availability (Soane and van Ouwerkerk, 1994; Fan Jian Ling et al., 2016). The results from this work confirm that soil compaction as a result of field traffic affects root growth, plant establishment percentage and yield, and is in agreement with results from many studies. The winter bean crop is vulnerable to compaction thus the significant differences are visible between different traffic treatments, and is in agreement with Arvidsson and Håkansson (2014) who concluded that dicotyledons are more sensitive to compaction than monocotyledons. The lowest plant establishment percentage on ZERO tillage plots might be a result of water logging and oxygen deficit as concluded by Boone (Soane & van Ouwerkerk, 1994).

It is important to highlight that while the overall growing season was dry which possibly reduced the overall yield of the crop, the total precipitation from crop establishment (November 2017) until the root sampling (end of May 2018) was slightly higher than the average for preceding 10 years for the same period (397 mm vs 388 mm long-term average) which suggests that the root growth would not be subject to any greater water stress than normal.

The observed largest tap root diameter at the depth of 100 mm were found in the least compacted soil i.e. CTF. On average CTF tap root diameter at 100 mm below the soil surface is almost twice that of the LTP treatment and almost two and a half times larger in diameter than the STP traffic system. This characteristic is highly correlated with the tap root length, as a number of samples from STP and LTP failed to reach that depth, thus their diameter was zero. Shortening of roots in highly compacted soil is in agreement with Głąb (2008) who found out that tractor traffic resulted in shortening of roots of lucerne (*Madicago sativa*), as well as in agreement with Chen et al. (2014) who observed that the root system of narrow-leafed lupin on compacted soil in Australia was characterised by a short and thickened taproot.

Among 6 roots characteristics analysed, only tap root biomass at the shallow stratum (0–50 mm) delivered significantly different results. The remaining features showed differences in the deeper stratum only (> 50mm). This is in agreement with Głąb, (2013) who showed that significant differences between roots traits of grass and clover mixture as a result of soil compaction and fertilization were only found at depths greater than 50 mm.

ZERO STP delivered highest tap root biomass, what is in agreement with Materechera et al. (1991) who found out that in strong soil elongation of roots is reduced, however the diameter increases. Muñoz-Romero et al. (2011) concluded that no-till featured significantly greater results of length and diameter of *Faba bean* than conventional ploughing. Hettiaratchi (1990) suggested that thickening of roots in strong soil is a result of a mechanism of overcoming limiting axial stress by loosening the soil at the root tip.

CTF featured significantly greater roots biomass for both tap and lateral roots as well as for number of lateral roots at the depth greater than 50 mm, in agreement with Głąb (2013) who reported highest root biomass from uncompacted soil but contradicts another study of the same author (Głąb, 2008) who found out that Lucerne's roots biomass increased with an increase in soil density. The higher root biomass found within CTF resulted from better root penetration in uncompacted soil and possibly better oxygen availability as suggested by Czyz (2004).

The significantly higher yield of winter bean delivered on CTF plots was 8% higher than on STP which agrees with other studies that report yield increases of between 7.3–10% when controlled traffic farming was applied (Lamers et al., 1986; Li et al., 2007; Chamen et al., 2011; Godwin et al., 2015; Godwin et al., 2017). Soil compaction as a result of field traffic has been suggested as the main reason for crop yield penalties by many researchers (Raghavan et al., 1979; Horn et al., 2003; Kroulik et al., 2009; Chamen et al., 2011; Chyba, 2012). The yield reduction on trafficked soil is related to restricted root growth and lower access to nutrients as a result of increased bulk density and reduced pore size in trafficked areas. Results from the same experiment collected by Smith (2017) and Millington (2019) confirmed that across 5 years of observations, CTF has delivered higher yield than STP, however the differences between the means were statistically significant for 2 seasons/crops: winter wheat in 2013 with $p = 0.073$ and for spring oat in 2016 with $p = 0.057$ (Millington, 2019).

The highest yield from CTF plots may have resulted from a greater number and length of roots which allowed the plants to uptake more water in comparatively dry months (May–July) preceding harvest (August). The total precipitation in these 3 months was m, compared to a long-term average of 216 mm (Harper Adams University weather data for 2007–2017). Bond et al. (1994) found that *Faba bean* is very sensitive to water stress particularly when filling pods. This could explain why the CTF benefited the most from the well-developed roots and why ZERO tillage despite comparatively high number of plants at the beginning of the season, delivered lower yield. For logistical reasons, following the early harvest, due to the dry summer any soil moisture analysis was delayed until 3rd October 2018 after 132 mm of rain. This analysis revealed that the ZERO tillage plots had a significanly lower ($p = 0.005$) gravimetric soil moisture content compared to SHALLOW and DEEP tillage (15.2%, 16.7% and 17.1% respectively). These correspond to soil water potentials in the range of -20 kPa to -10 kPa, for typical sandy loam soils in the UK (Hall et al., 1977) where the field capacity soil water potential is considered to be -5 kPa.

LTP resulted in greater crop yield by 5% comparing to STP (4.020 t ha^{-1} and 3.821 t ha^{-1} respectively), albeit the result was not found to be significantly different. The result is in line with the results from previous years from Large Marsh and Illinois experiments (Shaheb et al., 2018), where LTP delivered higher yields than STP. The Large Marsh 2013–2017 results revealed that LTP gave greater yields than STP, however the means of yields were not significantly different (with $p < 0.05$) from STP or CTF. The experiment in Illinois focused on different tyres pressures (Shaheb et al., 2018) and revealed significantly greater yields of corn in 2017 by 4.31% ($p = 0.005$) and in 2018 by 2.8% ($p = 0.019$) and of soybean in 2018 by 3.7% ($p = 0.021$) when comparing LTP to STP.

The reason for lack of significant differences between LTP and STP might be high soil moisture on the date of soil compaction treatment (3rd October 2017) before the crop was drilled causing the soil susceptible to compaction. The precipitation in the preceding month (total for Sept. 69 mm) was much higher than the average in previous 4 years (2013–2016 average for Sept. was 28 mm) (Harper Adams weather data). Moist soil is more vulnerable for soil compaction (Sohne, 1958) so the soil was posed to the stress that exceeded its strength, regardless the low tyre inflation pressure. On the other hand, LTP did not differ significantly from CTF, therefore leading to a conclusion that LTP might be a simple practical mitigation measure for soil compaction, agreeing with Godwin et al. (2015), who suggested that 'low ground pressure systems for wheel loads up to a maximum of around 5 t can offer farmers an alternative to controlled traffic.'

CONCLUSIONS

1. Controlled traffic farming resulted in significantly better plant establishment percentage, improved root development and greater yield of winter bean, in comparison to random traffic farming with standard tyre presures.

2. The type of tillage system and its interactions with the traffic system had no significant effect on the crop yield.

3. The significant differences between roots traits were observed mainly at depths greater than 50 mm. The total root biomass, tap root biomass, number of lateral roots, and biomass of lateral roots deeper than 50 mm of the winter bean crop, were significantly higher for the controlled traffic farming, in comparison to random traffic with standard tyre pressures.

4. Tillage systems did not result in significant differences between roots characteristics, only traffic and interactions between traffic and tillage. The tap root biomass in the shallow stratum of soil (0–50 mm) was significantly greater for zero tillage together with random traffic and standard tyre pressures in comparison to shallow

tillage contrasted with random traffic with standard tyre pressures as well as with controlled traffic farming.

5. Controlled traffic farming subject to deep tillage gave significantly greater tap root biomass at both depths (0–50 mm and > 50 mm) than random traffic farming with standard tyre pressures.

6. Plant establishment percentage, root development and crop yield of the low tyre pressure treatments was greater but not significantly different from the standard tyre presures treatments.

7. Zero tillage delivered significantly lower plant establishment percentage in comparison to deep and shallow tillage.

ACKNOWLEDGEMENTS. This research has been funded by Douglas Bomford Trust and Morley Agricultural Foundation, with equipment support from Michelin Manufacture Française des Pneumatiques and Vaderstad UK Ltd.

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