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An ASABE Meeting Presentation
DOI: 10.13031/aim.20162461725
Paper Number: 162461725

An investigation into the effect of soil compaction and tillage on plant growth and yield of winter barley *(Hordeum vulgare L.)*

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Written for presentation at the
2016 ASABE Annual International Meeting
Sponsored by ASABE
Orlando, Florida
July 17-20, 2016

ABSTRACT. *The use of heavy machinery in agriculture is a major cause of compaction which, alters soil aggregate and pore structure affecting soil strength, porosity/availability of air and its response to heat. Compacted soils can lead to reductions in water and fertiliser uptakes leading to lower crop production and increased water runoff. Nutrient losses have been found to increase in compacted soil. A long-term 3x3 factorial Traffic (Random Traffic Farming, Controlled Traffic Farming and Low Ground Pressure systems) and Tillage (Deep, 250mm; Shallow, 100mm and no till) field trial at Harper Adams University, UK, was established in 2011. Initial results indicated benefits to crop yields from both Controlled Traffic Farming and Low Ground Pressure systems especially when applied under shallow tillage systems. An investigation was carried out in 2015 to determine whether the trial treatments had an effect on winter barley early growth and final yield by comparing components of yield at GS 30 and at harvest. Results for early growth found reductions in plant establishment and root dry mass for compacted areas possibly due to anaerobic conditions due to reduced soil pore size, however, the Barley yields were not significantly different (p>0.1). The compensation by the barley crop for the reduced plant numbers was by increased tiller survival and is thought to be due to the lower annual rainfall (22% reduction compared to the previous three year mean) especially during grain filling (33% reduction) which allowed sufficient soil moisture for optimum crop growth whilst sufficient soil pore air was maintained.*

Keywords. *agriculture, barley, cereals, compaction, depth, growth, ground pressure, no till, soil compaction, tillage, tire pressure, tires, traffic, wheels, yields.*

Introduction

To make modern crop production systems highly productive and to lower costs, agricultural machinery has become more powerful and correspondingly become heavier (Tullberg *et al*., 2007). Consequential soil compaction from heavy machinery is now a major problem in agriculture and responsible for soil degradation of an area of 33 million ha in Europe. Increased loads applied to soil increases subsoil compaction, which is difficult to remove (Kroulik *et al*., 2009). Tillage to remove traffic induced soil compaction is seen by many to be more of a problem than soil compaction as it results in soil structure degradation and erosion. Reduced tillage is considered to be a solution for this problem (Tullberg *et al*., 2007). Chamen *et al*. (2015) identify the use of low ground pressure tyres and the adoption of controlled traffic farming as methods to avoid soil compaction.

In 2011, a long-term study was set up on the Large Marsh field at Harper Adams University UK to investigate the effect of three traffic systems (Random Traffic Farming (RTF), Low Ground Pressure (LGP) and Controlled Traffic Farming (CTF)) and three tillage systems (deep (250mm), shallow (100mm) and no till) on soil properties, crop yield and energy requirements. The soil is sandy loam, mainly Claverley, with small areas of Olerton and Salwick (Beard, 1988). This study was designed to enable a full arable rotation to be studied (i.e. winter wheat, winter barley, winter barley, winter cover crop, spring oats, winter wheat). The randomised 3x3 factorial study (three tillage x three traffic) with four replicated blocks was established in September 2012 (Smith *et al*., 2014).

Earlier findings

Winter wheat (*Triticum aestivum* var. *Duxford*) was planted in November 2012. Crop establishment (plants m^{-2}) was determined at Growth Stage (GS) 11/12 (January 2013). There were no significant effects from the traffic and tillage treatments on establishment. Photographic crop assessment at GS 37/39 and immediately prior to harvest showed visual evidence of limited establishment in primary wheel ways and non-uniformity in the no-till plots. There were no significant differences in the combine harvest yields as a result of the interaction of tillage and traffic treatments at 5% probability level. The CTF treatment produced the highest mean yields (7.7 t ha^{-1}). CTF shallow tillage treatment had the highest yield of 8.3 t ha^{-1} which was 14% higher than the mean of the other treatments (7.4 t ha^{-1}) and significantly higher by 15% (1.1 t ha^{-1}) than the RTF deep tillage mean yield at 10% probability level. The RTF - no tillage had the lowest mean yield of 6.8 t ha^{-1} (Smith *et al*., 2014 and Godwin *et al*., 2015).

Methodology

The three tillage (deep, shallow, no till) x three traffic (RTF - high pressure tyres, LGP - low ground pressure tyres, CTF - controlled traffic) trial with four replicated blocks each containing nine plots nominally 4m wide by 80m long and with randomised treatments were as follows:

1. RTF Deep Tillage	4. LGP Deep Tillage	7. CTF Deep Tillage
2. RTF Shallow Tillage	5. LGP Shallow Tillage	8. CTF Shallow Tillage
3. RTF No Till	6. LGP Direct No Till	9. CTF No Till

A Massey Ferguson 8480 tractor (12.7 tonne) applied the traffic compaction treatments. The number of vehicle passes applied and plot area covered simulated real farm traffic systems (Smith *et al*., 2013) based on the findings of Kroulik *et al*. (2009). The area of random traffic and low ground pressure plots wheeled was 86%, 65% and 45% for deep, shallow and no tillage respectively and 30% for all controlled traffic plots. This is shown diagrammatically at Appendix 1. Tyres were Michelin Axiobib IF 650/85 R38 TL 179D (rear), IF 600/70 R30TL 159D (front) both with a width was 600mm. Tyre pressures were set to 1.2 bar front, 1.5 bar rear for RTF plots. For LGP plots tyre pressures were set to 0.7 bar front and rear (Smith *et al*., 2014). The deep and shallow tillage treatments were then applied using a 4m Vaderstad Topdown pulled by a Cat Challenger MT765C along the primary wheel ways (Figure 1). Prior to drilling the crop the deep and shallow tillage plots were tilled to 250mm and 100mm deep respectively.

The crop was a two row winter barley (cv. *Cassia*) planted 20th October 2014 at a density of 226 kg ha^{-1} at a depth of 40mm at row spacing 167mm using 4m Vaderstad Spirit. Figure 1 shows the position and number of treatment passes (one pass represents compaction applied by one pass of the front and rear wheel on one side of the tractor) in trial block 1. Wheel track widths were 0.6m. Sample locations were the centrelines of compaction treatments identified in the field using flexi-canes (Figure 2).

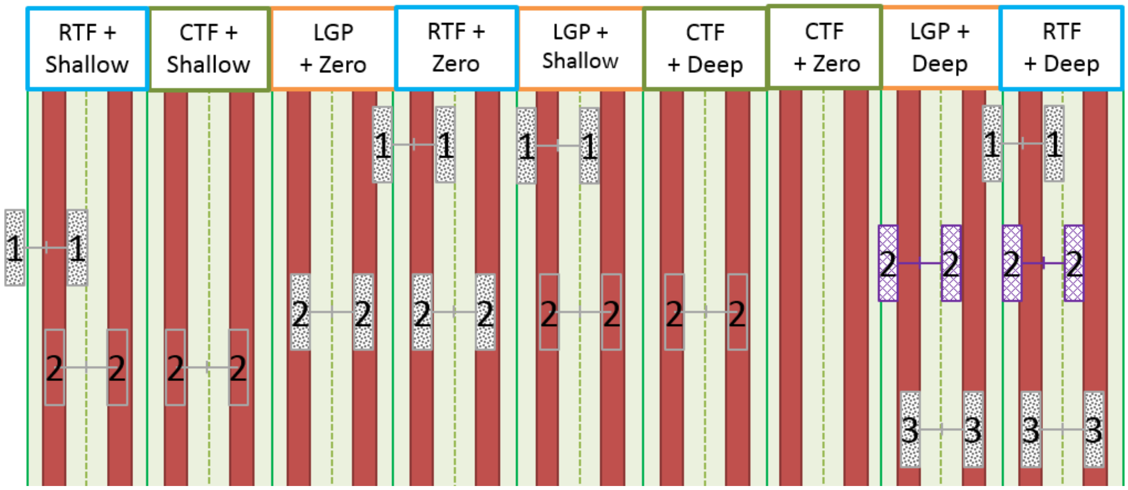

Figure 1- Trial plot compaction map

(Coloured columns identify the primary wheel ways created in all plots by the Cat Challenger MT765C during cultivation and drilling operations. Numbers in blocks represents number of passes)

(Adapted from: Smith, 2015. Personal Communication).

Figure 2 - Centrelines of compaction treatments identified using flexi-canes

(Plots run left to right. Flexi-canes run parallel to fertiliser/herbicide spray tramline across plots)

For the early growth samples, plants (whole) were taken from two adjacent 500mm rows as shown in Figure 3 (i.e. one linear metre) using a 500mm measure. This is the optimum method and size for cereal sampling recommended by Hudson (1939) cited by Sylvester-Bradley *et al*. (1985).

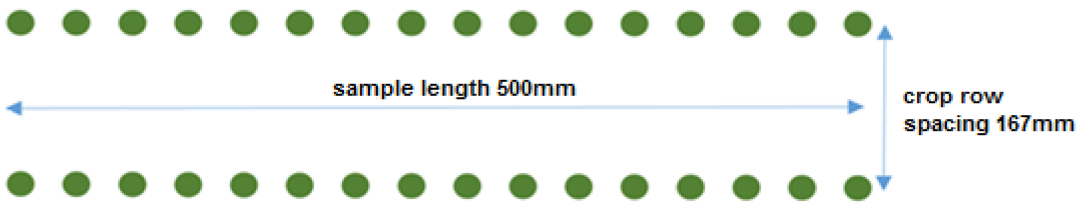

Figure 3 - Schematic showing sample selection from two rows of crop

(Green circles represent barley crop rows)

Hand harvest samples were determined by the same method as for early growth (Figure 3), located adjacent to the previous sample plots and cut with hand shears at ground level. The early growth sampling took place at the start of April 2015 at GS 29/30. Hand harvest samples were taken immediately prior to combine harvest in July 2015. Statistical analysis of data was conducted using a two-way analysis of variance (ANOVA) and Tukey's test in Genstat 17th Edition and Microsoft Excel 2007 was used for chi-squared test.

Results

This paper focuses on the full set of results from the controlled traffic farming plots**.** The samples taken in the controlled traffic plots were from zero passes (unwheeled) and the primary wheel ways (wheeled).

Plant establishment

Unwheeled areas had the greatest plant establishment with the number of plants m^{-2} (Figure 4) for deep tillage being higher than shallow but with no significant differences in the means at 5% probability level.

Figure 4 - Mean number of plants m^{-2} for CTF traffic and tillage treatments at GS 30

(Means not followed by the same letters are significantly different from each other at the 0.05 probability level).

Wheeled treatment total plant density was 29% less than in the unwheeled areas (44% less in deep and no tillage but only 5% in for shallow). In the wheel ways, the plant density of the shallow tillage treatment was the highest and significantly different from the no till, but not deep tillage. The deep tillage unwheeled mean was significantly different from deep tillage wheeled. The ANOVA analysis (Appendix 2) showed that traffic and tillage were both highly significant factors in the differences in plants m^{-2} (i.e. traffic p=0.002, tillage p=0.004).

Number of crop stems at GS 30

The mean stem numbers m^{-2} for wheeled – no tillage and wheeled – deep tillage were not significantly different from each other but were from the means of wheeled – shallow tillage and all three unwheeled tillage means (Figure 5). Traffic was a very highly significant factor ($p<0.001$) and tillage and traffic x tillage were highly significant factors in the differences in stems numbers m^{-2} (i.e. tillage $p=0.005$, traffic x tillage $p=0.007$).

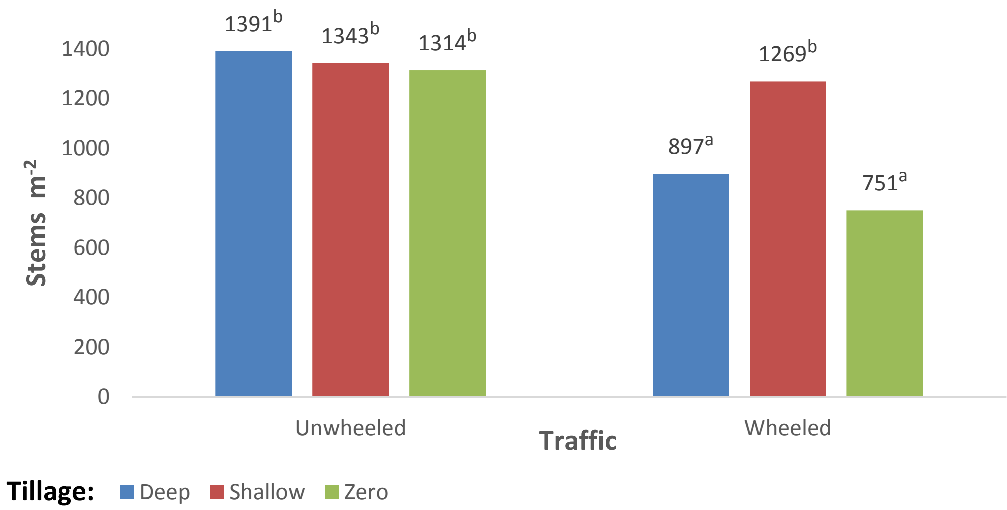

Figure 5 - Mean number of stems m^{-2} for CTF traffic and tillage treatments at GS 30

(Means not followed by the same letters are significantly different from each other at the 0.05 probability level).

Root:stem ratio at GS 30

The root to stem ratio means varied from 31.7% for unwheeled to 35.7% for wheeled. This difference from the traffic treatment was significant ($p=0.025$) but there were no significant differences between the tillage treatments (Appendix 2). This shows that the dry roots had proportionately less mass than the dry stems in wheeled treatments indicating that root growth may have been reduced. Dry root mass was 42% higher and dry stem mass was 66% higher in unwheeled than in wheeled areas making the mean total biomass 59% higher (Table 1). A chi-squared test showed that there was no significant difference between the root:stem ratio for wheeled and unwheeled samples ($p=0.703$).

Table 1 - Mean dry mass (g) of barley components for CTF plots at GS 30

Component	Mean Dry Mass Wheeled g m^{-2}	Mean Dry Mass Unwheeled g m^{-2}	Increase
Root	10	14	42%
Stem	28	47	66%
Total	38	61	59%

Number of ears at harvest

There was a significant difference in means (at 0.053 probability level) in CTF plots for ears m^{-2} as a result of tillage (Appendix 2). In general ear numbers declined with the reduction in tillage and from unwheeled to wheeled treatments except for the shallow tillage wheeled treatments.

Yield at harvest

The highest yield (12.37 t ha^{-1}) was from the wheeled - shallow tillage areas and the lowest from wheeled - no tillage was 9.14 t ha^{-1} (Figure 6), an increase in yield of 3.23 t ha^{-1}. ANOVA analysis found no significant differences in mean yield for the traffic or tillage treatment factors (p>0.1).

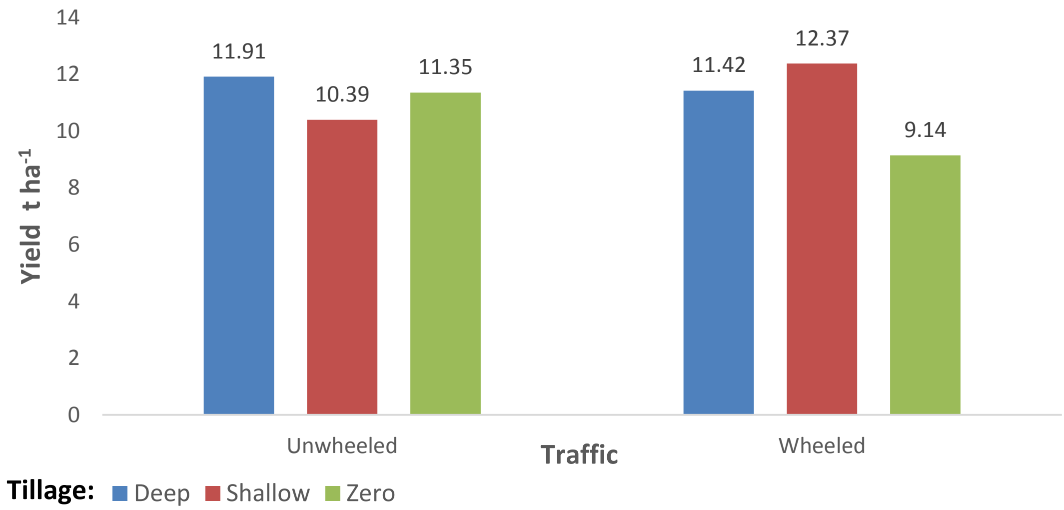

Figure 6 - Mean yield t ha^{-1} for CTF treatments at harvest

1000 grain weight at harvest

The differences in 1000-grain weight were small and not found to be significantly different. The 1000-grain weight increased as tillage decreased in the unwheeled areas (Table 4). Shallow tillage-wheeled produced the highest 1000 grain weight (57.44g).

Straw weight at harvest

There was a decline in straw weight m^{-2} between unwheeled and wheeled areas except from shallow tillage plots, which showed an increase (Appendix 2). There was no significant difference between means for the traffic and tillage treatment factors.

Rainfall

The yearly total rainfall for 2014-2015 (Table 2) was 651mm a reduction of 22% when compared to 2011-2014 mean of 840mm. Table 3 shows the rainfall during the critical growth periods of tillering and grain filling. Comparing 2014-2015 to the 2011-2014 mean, during the tillering period there was 11% less total rain equating to 23% less mean daily rainfall. There was also less total rainfall in the grain filling period (33%) with daily mean reduction of 24%.

Table 2 - Monthly mean and total rainfall (mm) for years 2011-2015

September to August	2011 - 2012	2012 - 2013	2013 - 2014	2014 - 2015
Monthly Mean (mm)	73	67	70	54
Total (mm)	873	809	836	651

(Adapted from: Page, 2015. Personal Communication. Richard Page is the technician responsible for the Harper Adams University weather station)

Table 3 - Rainfall during critical growth periods 2011-2015 (tillering and grain filling)

Critical Growth Period	Rainfall	2011 - 2014 Mean	2014 - 2015	Reduction
Tillering (13 Nov - 02 April)	No-rain days	65.0	53.0	18%
	Daily mean (mm)	3.9	3.0	23%
	Total (mm)	295.0	263.0	11%
Grain Filling (26 May - 05 Jul)	No-rain days	19.0	22.0	-14%
	Daily mean (mm)	4.6	3.5	24%
	Total (mm)	99.0	66.0	33%

(Adapted from: Page, 2015. Personal Communication)

Discussion

Early growth results

The results show that although not statistically significant at 5% probability level (Figure 4), tillage in the CTF plots has increased plant establishment in the unwheeled treatments by 23% for shallow and 29% for deep tillage compared to unwheeled no till treatments (control). Compaction has had an effect on establishment with wheeled treatments producing 36% less plants than unwheeled under deep and no tillage. Shallow tillage however has almost removed the effect of the compaction in the wheeled areas. This could indicate that the compaction in the primary wheel ways is greatest in the top 100mm and that deep tillage is not as effective at improving the soil structure of the compacted soil in this zone as shallow tillage or deep tillage is more vulnerable to re-compaction than shallow tillage. It also suggests that soil structure in the upper profile is important for winter barley establishment. The improvement in establishment may be due to increased aeration and warmth in the top layer of soil as suggested by Lipec *et al*., 2003).

The number of stems m^{-2} are related to the number of plants m^{-2} and the number of stems per plant does not seem to be affected by compaction x tillage ranging from 4.2 to 4.4 stems per plant. This ratio is increased in no tillage plots to 4.7 in wheeled and 5.3 in unwheeled.

Tillage did not significantly affect root to stem ratio but compaction reduced root growth and therefore affected green matter production. This effect could be due to poorer root penetration due to higher bulk density but is more likely attributed to water logging and possibly anaerobic conditions due to associated smaller pore spaces as suggested by Czyz

(2004). The presence of anaerobic conditions may have been determined if the field test described by Batey and Childs (1982) for locating anoxic soil had been used. It is also likely that these conditions have reduced seed viability and early plant survival to reduce the plant establishment in compacted zones. The decrease in mean rainfall during the tillering phase may have relieved anaerobic conditions sufficiently for the number of tillers per plant to be largely unaffected (Bullock *et al*., 1985).

Hand harvest results

Although at hand harvest there were differences in yield, these were not significant at 5% or 10% probability levels. These results are not in agreement with the expectations from the components of yield found at GS 30. A possible explanation for this is that the barley crop had compensated for reduced plant numbers by increased tiller survival to produce yields that are not significantly different between treatments. This effect could be due to the reduced rainfall over the season and especially during the grain filling period. During this period rainfall total was 33% lower than the previous three year mean (Table 3) with smaller daily rainfall amounts spread over more days. This may have allowed the soil to retain sufficient moisture, providing necessary water and nutrients for the plant but without removing air availability in the smaller pore spaces associated with the compacted soil. In 2015 the UK experienced exceptional cereal yields with winter barley yields 13% higher than the national 10 year mean due to sufficient moisture during spring and summer and sunshine during the grain filling period (AHDB, 2015).

Comparison to wheat crop 2012

Unlike the results of the wheat crop study 2012 (introduction) this investigation found differences at early growth stages for the barley crop and no significant differences in yield. This may be due to differences of wheat and barley response to compaction and tillage but is thought to be more likely to rainfall amount. It is probable that if the barley crop had been exposed to the rainfall experienced over the preceding three years (2011-2014) then yields would have been lower and the differences observed at GS 30 would have been translated into similar differences in the yield (Raper, 2005).

Conclusion

1. The hand harvest results found no significant differences at 10% probability level to yield due to compaction or tillage but shallow tillage did improve yields over no tillage by 3.23 t ha^{-1}. The reduced rainfall of 22% and especially during the grain filling period (33%) may have enabled the barley to compensate for reduced plant density in compacted areas by increased tiller survival due to optimum water nutrient and pore space air availability.

2. The effectiveness of shallow tillage in the compacted wheel ways suggests that it is the compaction in the top 100mm that most affects barley plant establishment and which suggests that the shallow tillage may have increased aeration and warming in the top layer of the soil.

3. Waterlogged and possibly anaerobic conditions due to smaller pore sizes in compacted soil is thought to have caused the reductions in the yield components (plant m^{-2} and stems m^{-2}) and dry root mass.

Acknowledgements

The author gratefully acknowledges the Douglas Bomford Trust, Michelin and Vaderstad Ltd

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Appendix 1

Compaction area of plots

Figures 7, 8 and 9 show the layout and area subjected to compaction treatments in the trial plots. The numbers across the centre of the boxes indicates the number of tractor passes (one pass represents compaction applied by front and rear wheel on one side of the tractor). The percentage at the bottom indicate the area of each plot subjected to compaction treatment. This is based on the findings of Kroulik *et al*. (2009).

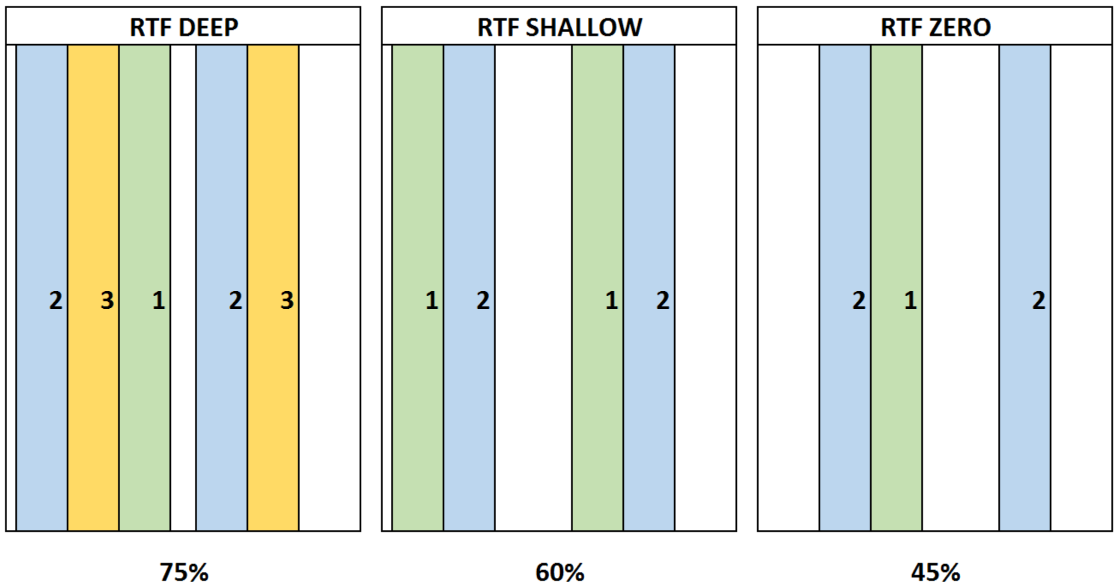

Figure 7 - Layout and area of compaction treatments in the RTF plots

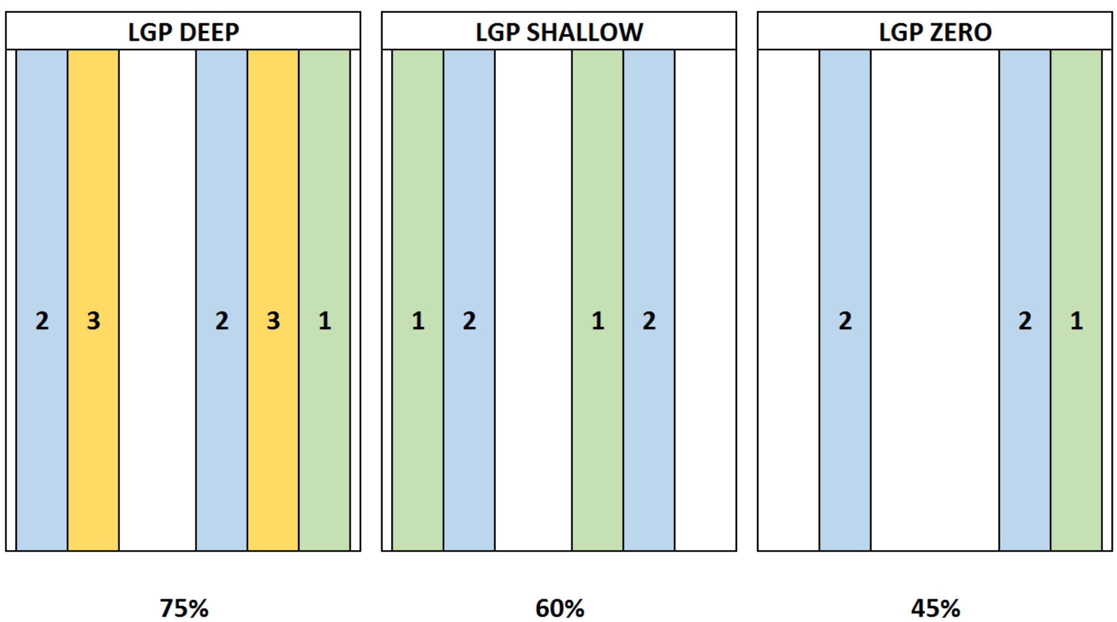

Figure 8 - Layout and area of compaction treatments in the LGP plots

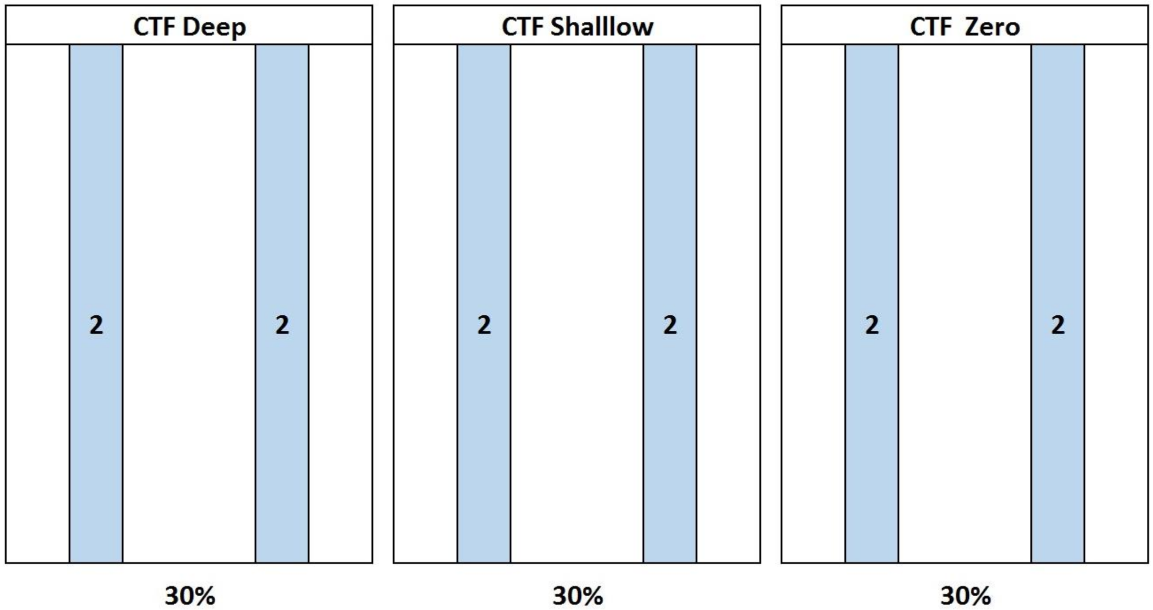

Figure 9 - Layout and area of compaction treatments in the CTF plots

Appendix 2

Table 4 - Summary of ANOVA output for traffic and tillage treatments in CTF plots

	Number of Plants m^{-2}	Number of Stems m^{-2}	Root/Stem Ratio	Number of Ears m^{-2}	Grain weight $g\ m^{-2}$	1000 Grain Weight g	Straw Weight $g\ m^{-2}$	Yield $t\ ha^{-1}$
Grand mean	253	1161	0.337	828	1110	55.30	696	11.10
Traffic mean								
Unwheeled	289	1349	0.317	842	1122	54.91	702	11.22
Wheeled	216	973	0.357	814	1098	55.68	690	10.98
Tillage mean								
Deep	260	1144	0.344	922	1167	54.42	739	11.67
Shallow	296	1306	0.328	850	1138	55.97	687	11.38
Zero	201	1033	0.339	713	1024	55.50	660	10.24
Traffic x Tillage mean								
Unwheeled Deep	317	1391	0.314	963	1191	53.99	760	11.91
Unwheeled Shallow	304	1343	0.333	820	1039	54.51	646	10.39
Unwheeled Zero	246	1314	0.304	744	1135	56.25	699	11.35
Wheeled Deep	202	897	0.373	882	1142	54.86	718	11.42
Wheeled Shallow	289	1269	0.323	879	1237	57.44	729	12.37
Wheeled Zero	157	751	0.375	683	914	54.74	621	9.14
Standard Errors of Mean								
Traffic	13.9	40.8	0.011	45.6	54.8	1.03	34.2	0.55
Tillage	17.02	50.0	0.014	55.9	67.1	1.26	41.9	0.67
Traffic x Tillage	24.07	70.7	0.020	79.0	94.9	1.78	59.3	0.95
P								
Traffic	0.002	<.001	0.025	0.671	0.762	0.606	0.807	0.762
Tillage	0.004	0.005	0.717	0.053	0.311	0.679	0.419	0.311
Traffic x Tillage	0.132	0.007	0.117	0.643	0.119	0.475	0.385	0.119
l.s.d.								
Traffic	41.9	123.1	0.034	137.5	165.1	3.09	103.1	1.65
Tillage	51.3	150.8	0.042	168.4	202.2	3.79	126.3	2.02
Traffic x Tillage	72.6	213.3	0.059	238.2	286.0	5.36	178.6	2.86
CV% Block.*Units*	19.1	12.2	11.6	19.1	17.1	6.4	17	17.1