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AN INVESTIGATION OF THE EFFECTS OF TRACTOR TYRE WIDTH ON SOIL COMPACTION AND CROP DAMAGE

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Abstract

Soil compaction is a prevailing problem in the UK agricultural industry. This investigation focuses on the effect of tractor tyre width on a temporary grass crop used for both grazing and silage conservation. The tyres used were 650/75 R38 on the rear and 600/70R28 on the front, with wider tyres 900/70 R42 on the rear and 710/55 R30 on the front axles for comparison. Measurements identified the areas affected by the tyres, included the degree of soil compaction and damage to the crop. The results proved the wider the tyre, although creating a wider track, compacted a lower volume of soil when compared to the narrower tyre. The narrower tyre width compacted the soil to a greater depth where compaction is more difficult to relieve without disturbing the soil structure.

Key words: *soil compaction, soil structure, tyre width, crop damage.*

INTRODUCTION

Soil compaction and problems associated with it have been experienced in agriculture since the early use of draft animals, and the effects have been amplified with the increase in size and weight of machinery used in crop production. Arable crop production has been the main area of focus for many pieces of research into the effects of compaction on crop growth and techniques to reduce compaction, such as controlled traffic farming, are becoming increasingly popular on large-scale arable farms (Antille et al, 2019).

As of 2021 the total area of agricultural land in the UK was 18.6 million hectares, with permanent grassland making up 9.9 million hectares and temporary grass under five years old making up 1.2 million hectares. Grass is the most common crop in UK agriculture with just 4.4 million hectares of arable crops grown in the UK in 2021 (UK Agricultural Departments, 2022). From 2019 to 2021, temporary grass under five years old has increased from 1.19 to 1.21 million hectares, where as permanent grass has dropped from 6.20 to 6.07 million hectares.

The increase in area of temporary grassland under five years old brings increased traffic from operations such as reseeding, cultivation and maintenance operations such as rolling and fertiliser spreading. The average UK farm size is eighty-one hectares and almost half of all farms are twenty hectares or less. The gap between the counties smallest and largest farms is increasing as large farms grow (DEFRA, 2022), combined with an increasingly vulnerable market for farm produce, smaller farms need to maximise their output so that they can remain profitable (Antonpoulos et al., 2022). Strategies may include improving efficiency in smaller areas like reducing compaction to reduce damage to soil and crops, which have not previously been an area of concern for smaller holdings.

Soil compaction is created as a result of forces acting on soil, therefore, to reduce compaction levels, farmers should look in to methods of reducing surface pressure such as wider tyres. The issue with using wider tyres in established crops is that the increased surface area of the tyre covers a greater area of crop and could lead to direct damage to the plants whilst tyring to reduce damage to the soil (Arvidsson & Keller, 2007). In early days of agricultural mechanisation, tyre width has been a favourable option to reduce ground pressure but the increase in tractor sizes has led to the use of taller tyres. Taller tyres have a larger rolling circumference and a longer footprint, this long

footprint could have the same footprint on the ground as a shorter, wider tyre but would cover a smaller area of the field (Bridgestone Agriculture, 2021).
The effects of tractor tyres and their influence on soil stresses has been broadly researched (Botta et al., 2009; Shangoli & Abuali, 2015; Arvidsson et al., 2011; Acquah & Chen, 2022; Arvidsson & Keller, 2007), research around the knock-on effects of soil compaction in grass crops is more limited.
The main aim of the investigation was to gather data on compaction levels created by two different sizes of tyres commonly used on tractors from 150-200 horsepower (hp), covering the UK average tractor size of 168.4 hp (Ford, 2023). Compaction data would be used to artificially compact soil trays which would be used to grow the same variety of grass as is grown in the field investigation. Varied growth rates and changes in compaction would be monitored throughout the growth of the plants. The artificial growing environment allows for a controlled growth of the plants outside of the growing season and eliminates variables in nature which may obscure results.
The investigation prioritised tractor tyres which were practical and would be used for work by farmers and contractors within the UK, this meant tyres that were large enough to carry out a larger range of tasks with heavy loads but not too wide that they would deem impractical in transport on UK roads. To ensure real-world accuracy, field tests will be carried out measuring compaction of both front and rear tyres on the same pass, unlike other studies which focus on a single size of tyre.
The project involved primary collection of data through a mixed methods approach. Quantitative data was gathered through experiments and measurements and qualitative data was gathered through analysis of experiment conditions to support conclusions and theories made from results (Stokes and Wall, 2014). A mixed method research approach allows for a larger scope of investigation than just a quantitative or qualitative method (Blair, 2016), it often works when quantitative data, from closed questions, are used to provide a straight answer to a question but qualitative data, from an open question, is then used to support an answer or result (Williams, 2007).
The variables which are likely to be influenced by tyre movement on soil are soil compaction and grass plant damage. There are also many variables which could directly influence the results, including root structure, soil aeration, soil type, soil moisture, and the slope or gradient of the ground (Lipiec et al., 2003). The type of soil measured affects the measurability of soil bulk density, gravelly soil is difficult to measure bulk density in as the gravel cannot compress and reduce the volume of soil in the sample (Webb, 2002).
There are many ways in which soil compaction levels can be measured. The cone index (CI) is used to measure the penetration resistance of soil using a cone-shaped probe with a set force pushing it into the soil (Herrick & Jones, 2002). A common tool used to measure the cone index is a cone penetrometer, a metal probe (<0.5 cm diameter) with a pressure sensor which measures the force applied to move a cone, with a thirty-degree tip, through the soil (Jabro et al., 2021). Penetrometer readings ca be used to create soil compaction maps which can be interpreted using statistical variograms, fractal analysis, or by comparison of spatial differences in soil compaction (Eguchi & Muro, 2007).
Another method of measuring soil bulk density was tested by Sirjacobs et al. (2002). The measurement technique involved a single chisel shank pulled through the soil at a constant depth of thirty centimetres (cm) and a constant speed of five kilometres per hour. The horizontal and vertical forces acting on the shank are recorded using a transducer fixed to the machines frame. This method was proved to be highly accurate and results directly correlated with cone penetration measurements taken along the same line (Hanquet et al., 2004). The shank can be used easily in ploughed soils or harvested fields but is not a favourable method when measuring compaction in an established crop as it rips up the soil and damages the crop, a simple penetrometer can measure with higher accuracy with less disturbance to the crop and soil (Hemmat & Adamchuk, 2008).
Measuring the water infiltration rate can identify effects of compaction on soil macropores. Water infiltrates uncompacted soil faster than compacted soil of the same type, the intake is directly linked to numbers of macropores and links between macropores

(Hamza and Anderson, 2003). When a machine has made a pass over a field with a standard lugged agricultural tyre, the lugs make troughs where they grip into the soil. These troughs are likely to hold water as they trap surface water above the compacted soil (Seginer, 1971).

A digital soil compaction metre (Figure 1) was used during the data collection. This device provides a higher level of accuracy than a simple penetrometer by storing data in a log which can be reviewed after collection. The pressure required to push a cone of half an inch diameter is recorded every two and a half centimetres and can be recorded up to fifty centimetres deep.

Figure 1. Soil resistance meter

Soil layer maps (Figure 2) can be created from soil penetrometer data. Grid tables can be created which use a colour spectrum to highlight varying levels of compaction (Zeraatpisheh et al., 2020). One map is created for each depth of measurement and can clearly highlight varied levels of compaction in each depth. The downside to this method is that using data from a large range of depths means that a lot of tables must be created for each depth (Hapca et al., 2011).

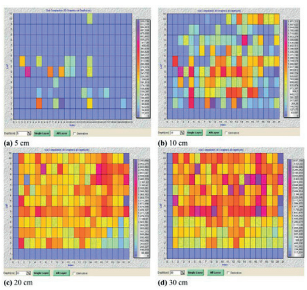

Figure 2. Showing 2D Soil Layer Mapping (Tekin et al., 2008)

Creating a three-dimensional (3D) soil compaction map (Figure 3) cuts down on the number of graphs used compared to 2D visuals and provide a more accurate method of visually demonstrating soil compaction. A 3D graphic can aid in analysis of soil compaction and can be easily understood and created using software which connects to a digital penetrometer or by manually inputting data into a 3D graph (Tekin et al., 2008).

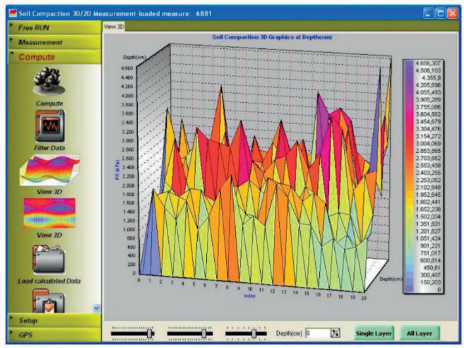

Figure 3. Soil Compaction Graphics (Tekin et al., 2008)

The growing season for grass for lowland farms in the UK usually begins in late March or early April and growth will continue until mid-October, during this time the growth rates can vary from 5.1 to 15.6 milligrams of dry matter per hectare (Mg DM ha) (Broad & Hough, 1993) (Huson et al, 2020). As the research was to be conducted between September and April, the timescale and climate during the allowed window were not suitable to measure grass growth in the field after a machine had passed over a crop. Simulating the soil conditions from the field in a controlled growing environment would be a possible solution to this problem. The data from soil maps can be used to simulate pressures in a lab using a hydraulic press compacting ten-centimetre squares to simulate compaction and coverage of a tyre in the field.

Variables within soil properties mean the applying a set pressure to the soil does not always result in the same compaction level of the soil (Nawaz et al., 2013). For this reason, when compacting the soil in the controlled environment, the pressure should be applied in small increments until the average compaction level of the measured area meets the level recorded from the field experiment. The main variable between the field soil and the greenhouse soil is that pressure is being applied in a large scale, covering the whole sample at the same time in the field. Whereas in the greenhouse or laboratory, the press would only apply pressure to one small sample at a time, to ensure the compaction pressures of each plot would match those of the field. The vertical pressure applied to one sample plot may be applied horizontally within the soil, affecting another plot. Pressure will be applied to the plots one at a time and the press will be moved along a line of plots. Pressure applied to one plot could lead to sub soil movement into the previously compacted plot and apply vertical forces which could lift the soil in another plot (Figure 4). The action of the tyre applying pressure to the soil is much more even (Figure 5), the increased width compared to the press means that each plot is compacted at the same time, and horizontal pressure only affects soil outside of the compaction area.

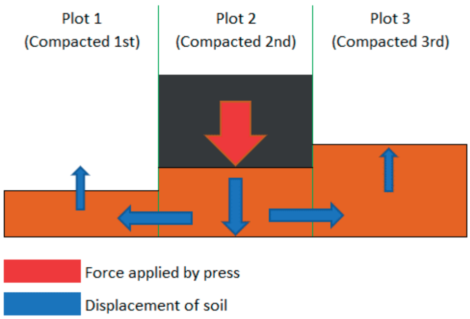

Figure 4. Individual compaction of measuring points

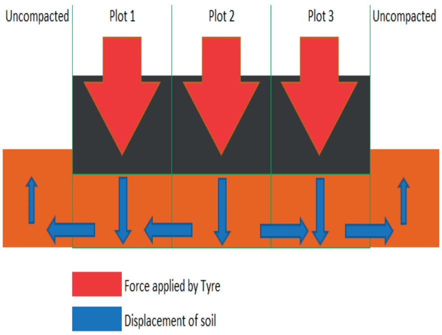

Figure 5. Simultaneous Compaction of Measuring Points

The prediction is based on the findings of Keller et al. (2004) who concluded that, at low pressures (<5 kPa), an increase of one kilopascals (kPa) will result in soil displacement of ± 102 millimetres (mm) horizontally. A radial tyre exerts seven to fourteen kPa more pressure to the ground than the internal tyre pressure, in kPa (Arvidsson & Keller, 2007). Therefore, average tyre pressures for a 650/75 R38 of twenty-three PSI can result in a ground pressure of 158 kPa. At ground pressures this high, displacement reaches a limit as compaction increases, increasing the resistance of soil movement (Alexandrou & Earl, 1995).

The field investigation took place on Upper Nisbet Farm in central Scottish Borders. The soil around the experiment site is predominantly clay loam and sandy clay loam soil. The crop of grass was in its second year of establishment and was sown with a combination disc-coulter drill into a tine-disc-press Sumo Trio combination cultivator. The field had been grazed by one hundred and fifty ewe lambs in the autumn of 2022 but had been untouched through the winter of 2022-2023 until the first week of April when fertiliser was applied to the field. The minimum disturbance to the field meant that there would be fewer factors which could obscure pre-test compaction levels.

The main area of data collection was the compaction created by two sets of tyres fitted to a John Deere 6155R. One set was made up of Michelin 600/65 R28 tyres on the front wheels and 650/75 R38's fitted to the rear wheels, while the other set was made up of Bridgestone VF710/55 R30's on the front and VF900/50 R42's on the rear. Each set of tyres were run at the manufacturers recommended pressures for ten kilometres per hour, these were calculated by weighing each axle on a weight bridge with the tractor unladen (Figure 6).

Figure 6. Calculating optimal tyre pressures using a weighbridge

RESULTS AND DISCUSSIONS

To improve the accuracy of the results and allow for easy comparisons of the two data sets, the measurements for each set of tyres were taken in the same area of the field with similar existing compaction levels. The soil moisture and temperature beneath the two tracks were similar, averaging 42.4 percent moisture and 4.6 degrees Celsius on the track for the standard tyres and 44.7% percent moisture and 4.3 degrees Celsius beneath the wide tyre track. The moisture and temperature of the soil were collected from a Soil Moisture Sense Ltd sensor which was lifted and positioned on both edges and the centre of each wheel track site prior to running the tractor up the field.

Several tests with the compaction metre, measuring the same sample of soil several times undisturbed, concluded that the tolerances in data could reach as high as ±20 kPa. lower rates of compaction from the tyres could lead to smaller increases that could be mistaken for varying tolerance, these figures can be differed by identifying patterns in data around each point. If there is a trend of low increases in resistance, it is more likely to be as a result of tyre compaction, whereas one figure with a larger change but low changes around it is more likely to be as a result of equipment tolerances.

The data collected in the field experiment, measured in kilopascals of force needed to push a half inch cone through the soil, were input into tables which created two-dimensional soil maps of the cross profile of the wheel tracks. The different layers of soil can be identified through the data collected; the first measurement labelled as zero centimetres has the lowest average resistance of 739 and 786 kPa, this is likely to as a result of the soil on the ground surface being softened due to weathering and the breakdown of organic matter into the atmosphere at this level.

A ten centimetre deep block of soil was dug out (Figure 7), a visual analysis of the soil showed that the top two and a half centimetres of soil were high in organic matter content. The cross section of the soil sample also proved that from two and a half to around seven and a half the soil was denser, and therefore had a higher cone resistance.

Figure 7. Pre-test soil profile

Below seven and a half centimetres the soil was much drier and there was an increase in the diameter and the number of pores in the soil, this was also a common area for the plant roots to end.

Fro 600/70 R28

Pre Compaction

	Distance Across Track (cm)										
Cone Depth (cm)	5	0	10	20	30	40	50	60	65	70	Average
0	739	784	724	814	737	773	719	859	737	746	763.2
2.5	847	958	850	797	775	804	754	730	848	824	763
5	976	917	839	849	836	830	817	872	834	837	819
7.5	736	794	836	774	869	832	881	853	863	819	861
10	773	804	793	814	735	726	693	762	884	784	826
12.5	803	740	729	684	752	720	772	759	793	772	777
15	849	793	734	771	740	862	837	763	759	763	752
17.5	862	837	883	814	813	873	883	793	855	782	787
20	874	907	933	863	814	864	921	848	851	795	840
22.5	960	947	976	940	853	842	950	864	839	803	897
25	1073	1193	1048	1283	1027	1072	994	938	904	847	1038
Average	862.909	879.455	849.545	854.818	813.727	836.182	838.273	821.909	833.364	797.455	

After Pass

	Distance Across Track (cm)											
Cone Depth (cm)	-5	0	10	20	30	40	50	60	65	70	Average	Avg Change
0	758	809	780	902	772	818	784	917	763	774	807.7	45
2.5	859	982	891	849	807	847	794	761	856	832	808	29
5	979	932	859	873	847	852	843	895	838	836	848	15
7.5	738	804	858	794	884	862	908	866	877	823	875	16
10	779	809	804	820	743	731	704	760	889	781	841	5
12.5	796	744	732	680	759	729	786	756	797	783	782	4
15	845	803	737	774	752	866	826	752	754	760	756	0
17.5	869	835	887	812	808	874	887	801	893	787	787	6
20	883	914	936	859	819	862	925	841	857	792	845	2
22.5	958	964	970	947	850	847	958	863	834	809	900	3
25	1070	1186	1052	1285	1033	1075	1024	940	901	851	1042	4
Average	867	889	864	872	825	851	858	832	842	803		
Avg Change	2	8	11	10	9	12	15	5	7	3		

Figure 8. Standard tyre results:
Front 600/70 R28 Rear 650/75 R38

Pre Compaction

	Distance Across Track (cm)												
Cone Depth (cm)	-10	0	10	20	30	40	50	60	70	80	90	100	Average
0	983	803	784	801	763	721	770	693	683	719	528	787	753
2.5	1138	1006	978	1120	1053	990	927	813	808	1005	769	832	953
5	702	996	857	963	947	957	1048	977	989	1024	1051	877	949
7.5	877	670	913	638	720	947	983	841	829	916	1048	930	859
10	772	923	837	854	752	759	749	709	593	1028	958	749	807
12.5	877	673	729	821	746	830	752	750	629	849	812	839	776
15	807	923	836	826	859	839	802	793	757	739	693	845	810
17.5	1158	771	928	837	813	917	836	862	841	799	715	922	867
20	1088	1004	1384	940	979	1248	851	903	863	847	783	1077	997
22.5	948	1675	1048	1038	1027	1491	928	958	1072	937	849	1494	1122
25	2387	1698	1184	1485	1649	1707	1649	1728	1582	925	1294	1850	1595
Average	1067	1013	953	938	937	1037	936	912	877	890	864	1018	

After Pass

	Distance Across Track (cm)													
Cone Depth (cm)	-10	0	10	20	30	40	50	60	70	80	90	100	Average	Avg Change
0	994	816	825	863	792	753	824	754	746	758	537	793	788	35
2.5	1146	1025	1023	1160	1087	1016	957	862	837	1014	779	842	979	26
5	715	1015	874	974	957	966	1062	995	1007	1043	1071	893	964	15
7.5	886	674	917	643	728	958	984	861	815	947	1057	936	867	8
10	786	917	848	864	747	763	745	716	584	724	943	749	782	-25
12.5	863	690	743	808	760	841	740	711	619	865	832	826	775	-1
15	822	940	823	749	920	826	817	808	756	753	682	834	811	1
17.5	1140	763	946	840	800	934	866	848	828	839	704	939	871	4
20	1071	1023	946	925	998	1049	897	889	849	834	771	1135	949	-48
22.5	999	1649	1068	982	1082	1467	1004	976	1076	987	865	1470	1135	13
25	1894	1789	1165	1565	1623	1493	1680	1821	1557	910	1364	1885	1562	-33
Average	1029	1027	925	943	954	1006	961	931	879	879	873	1028		
Avg Change	-38	14	-27	5	17	-31	26	20	3	-10	9	9		

Figure 9. Wide tyre results Front:
710/55 R30 Rear 900/50 R42

The change in cone resistance from before and after wheeling was calculated and displayed to show different areas within the soil profile. The changes in soil resistance for the standard tyres (Figure 10) shows two areas of high soil compaction, at ten, twenty, fifty and sixty centimetres across the track width. The pressure spikes occur below the troughs created by the tyre tread, this would be as a result of soil being compacted vertically beneath the tread. A similar pattern can be seen for the wide tyres (Figure 11) from ten to thirty and sixty to seventy.

Front: 600/70 R28

Change		Distance Across Track (cm)									
	Cone Depth (cm)	-5	0	10	20	30	40	50	60	65	70
	0	19	25	56	88	35	45	65	58	26	28
	2.5	12	24	41	52	32	43	40	31	8	8
	5	3	15	20	24	11	22	26	23	4	-1
	7.5	2	10	22	20	15	30	27	13	14	4
	10	6	5	11	6	8	5	11	-2	5	-3
	12.5	-7	4	3	-4	7	9	14	-3	4	11
	15	-4	10	3	3	12	4	-11	-11	-5	-3
	17.5	7	-2	4	-2	-5	1	4	8	38	5
	20	9	7	3	-4	5	-2	4	-7	6	-3
	22.5	-2	17	-6	7	-3	5	8	-1	-5	6
	25	-3	-7	4	2	6	3	30	2	-3	4

Figure 10. Changes in cone resistance; standard tyres

Change		Distance Across Track (cm)											
	Cone Depth (cm)	-5	0	10	20	30	40	50	60	70	80	90	95
	0	11	13	41	62	29	32	54	61	63	39	9	6
	2.5	8	19	45	40	34	26	30	49	29	9	10	10
	5	13	19	17	11	10	9	14	18	18	19	20	16
	7.5	9	4	4	5	8	11	1	20	-14	31	9	6
	10	14	-6	11	10	-5	4	-4	7	-9	-304	-15	0
	12.5	-14	17	14	-13	14	11	-12	-39	-10	16	20	-13
	15	15	17	-13	-77	61	-13	15	15	-1	14	-11	-11
	17.5	-18	-8	18	3	-13	17	30	-14	-13	40	-11	17
	20	-17	19	-438	-15	19	-199	46	-14	-14	-13	-12	58
	22.5	51	-26	20	-56	55	-24	76	18	4	50	16	-24
	25	-493	91	-19	80	-26	-214	31	93	-25	-15	70	35

Figure 11. Changes in cone resistance wide tyres.

The compaction beneath the tread of the narrower, standard tyres reaches a deeper depth of seven and a half centimetres, whereas the compaction of the wider tyres only leads to a significant increase in compaction down to two and a half to five centimetres. This is likely to be as a result of a higher force per area of the smaller contact patch of the standard tyres.

The depth of troughs created by the tread of each tyre set was measured using vernier callipers and averages were used to compare the two sets. The standard tyre set left an average trough depth of 3.8cm whereas the wider tyres created troughs with an average depth of 2.2cm

The difference in compaction below the tread can be seen in the profile of the soil (Figure 12). Digging a turf sample 15 x 15 cm and seven centimetres deep shows the depth of compaction is around two centimetres deeper than the rest of the tyre, where the soil at the same depth fell away from the turf as it was less compacted. This trend occurred on both the inside and outside of the tread and for the full length of the sample. An increase in soil compaction reduces the diameter of soil pores, restricting infiltration and leading to larger volumes of surface water held in the troughs. The reduced compaction depth created by the wider tyres means that pore diameters within the upper soil layers remain wider than those beneath the standard tyres. The troughs created by the tyre tread are almost two centimetres shallower from the wide tyres (Figure 13), this keeps the surface leveller and reduced the distance the soil needs to expand to return to its original level.

Figure 12. Soil profile with standard tyres

Figure 13. Soil profile with wide tyres

There was a clear difference between the pre-compaction soil profile and the two samples taken after the tractor wheeling. The soil in the first sample was clearly looser and had large pores which led to a larger volume of soil dropping off the turf when it was lifted. The compacted soil held together much more than the uncompacted sample, especially down to the base of the roots at around seven to nine centimetres deep.

A visual analysis of the grass plants after wheeling determined an average of how many plants were damaged by the tyres. The percentage of damaged plants per hundred centimetres squared was recorded along the width of the track. Each percentage was an estimate to the nearest ten, using a quadrat-style observation.

	Distance Across Track										
Site Number	0	10	20	30	40	50	60	70	80	90	Average
1	0%	0%	10%	30%	20%	30%	10%	10%	0%	0%	11%
2	0%	10%	30%	20%	30%	10%	30%	40%	20%	0%	19%
3	0%	10%	40%	40%	20%	40%	30%	30%	10%	0%	22%
Average	0%	7%	27%	30%	23%	27%	23%	27%	10%	0%	

Figure 14. Percentage of Leaf Damage from using wide tyres

	Distance Across Track								
Site Number	0	10	20	30	40	50	60	65	Average
1	0%	30%	40%	20%	50%	30%	10%	0%	23%
2	0%	20%	10%	30%	20%	20%	20%	0%	15%
3	10%	20%	50%	30%	40%	50%	30%	10%	30%
Average	3%	23%	33%	27%	37%	33%	20%	3%	

Figure 15. Percentage of Leaf Damage from using standard tyres

The results show a higher damage to plants using the narrower tyre set, the main areas of damage were around the edges of the tread areas where the edge of the tread acted like a shear against the longer blades of grass. Leaf damage was recorded on plants with part of the leaf completely or over fifty percent removed, the average length of leaf removed from damaged plants was 4.3 cm from the standard tyres, and 3.2 cm from the wider tyres.

DISCUSSIONS

Significant compaction occurs in the top layers of the soil under both sets of tyres, with the largest increases in compaction in the top 2.5 cm. The deepest trough created by the tyre tread, by the standard tyre set, was 4.1 cm deep in a trough which measured ten centimetres by forty-two centimetres, a total area of four and a half square metres. Therefore, a total area of around seventeen metres cubed of soil was displaced from the surface and the data shows that there was limited increase in compaction below ten centimetres, the bulk density of the topsoil would be significantly increased. The high level of compaction will alter the intake of water and air and change the root growth of the grass (Batey & McKenzie, 2006).

The levels of compaction experienced from both sets of tyres are severe enough in the top five centimetres to reduce the flow of water and air into the soil around the roots. This problem is amplified during drier growing seasons when there is less precipitation and lower rates of transpiration, in wetter and colder climates, compaction may have very little effect on the growth of the crop as soil water content naturally increases but the uptake of water from plants is less (Unger & Kasper, 1994).

The greatest increase in cone force for the standard tyres was 88 kPa and 63 kPa from the wide set. The highest levels of compaction increase all occurred in the top two and a half centimetres and directly below the tyre tread lugs. The standard tyres saw an increased rate of compaction at the edge and outside the width of the tyres, this indicates an increased horizontal shift of soil. The increased vertical pressure of the narrower, standard tyres is a likely cause of the horizontal movement as compacted soil in the lower layers of soil restrict downwards movement and therefore soil is pushed outwards (Mohsenimanesh & Ward, 2010).

Another reason that could increase the movement of soil across the track is the movement of air and water through the pores. As pores are compressed in the high pressure areas, it is pushed through pores due to the change in pressures, pores that the air or water travel through open up and apply outward pressure to the soil around the pores, causing small movements in the soil (Veenhof & McBride, 1996).

The recovery rate of soil and grass after wheeling from the narrower 650/75 R38 tyres is expected to be slower due to the increased depth of wheel tracks and the higher plant damage rate. Some of the damage to the grass plants stunted the leaf length by ten centimetres, this loss of plant matter significantly stunts the growth of plants affected which can add up to a loss of silage dry matter over the coverage of a whole field.

To compare the total compaction areas for each track, each reading with an increase of twenty kilopascals or more within the top ten centimetres was recorded. The area between each reading was twenty-five square centimetres, this was multiplied by the number of readings over twenty kilopascals to get the total area for each. The 650/75 R38's compacted an area of 6.25 m^2 and the 900/50 R42's compacted an area of 4.5 m^2. Although the wider tyres cover a larger area across the surface, the wider footprint spreads the vertical forces across the ground, reducing the depth of compaction by 2.5-5 cm.

To analyse the total compacted area of each tyre set in a real-world scenario, using an implement with a width of ten metres as an example, the standard tyres would compact 6250m^3 and the wide tyres would compact 4500m³ of soil per hectare of land. The wider tyres, therefore, are an effective method of reducing soil compaction, especially at depths below 5-7.5 cm. Soil at a deeper depth below the surface has a lower rate of natural compaction relief as a result of larger (Correa et al., 2019).

The shallow depth of compaction in both tests make it easier to accurately simulate the compaction levels in an artificial growing environment used to measure the grass growth. It is harder to compact deeper soils at the desired rate without over compacting the upper layers (Bolling, 1985). Elasticity is higher in the upper soil layers as flowing water and air open up pores and relieve compaction, meaning both sets of tyres are efficient in preventing long-term compaction in soil which would have to be relieved by ploughing or by grass rejuvenation equipment.

The effects of compaction created by the two tyre sets could vary between different climates. In hot, dry climates, less precipitation means there is less erosion on the topsoil. Erosion on top soil aids in lifting compaction as the flow of water breaks the soil up on the surface. In hot climates, the water content of the top soil is significantly lowered as water evaporates in the heat, drying out the top soil and hardening it, reducing the rate of erosion (Amelung et al., 1997).

Reduced macro-porosity in the soil beneath the 650/75 R38 tyres, shown in the soil profile cut, as the highest compaction was experienced in the trough created by the tread, the water will be unable to run off across the surface and will increase the saturation of the soil. The lack of open pores in the soil also reduce the drainage and means the soil will hold the water longer, leading to over saturation and reduced oxygen uptake in the roots and can stunt growth or kill plants (Drewry et al., 2008).

Shallow compaction levels means that operations which are carried out to relieve compaction such as slot discs or tines do not have run at a large depth, opening the soil up and releasing carbon deposits from the soil, reducing soil organic carbon (SOC) into the atmosphere (Rawls et al., 2003). The release of SOC reduces the volume held in carbon stores within the soil and leaves less carbon in the soil which plants absorb to grow.

The results show pressure spike below the tread of each tyre. The tread on the tyres used are R1 type of tread, this consists of deep, aggressive treads which are designed to dig into the ground in soft conditions, aiding traction over soil conservation. Many operations carried out in grass silage crops are done in dry conditions when the soil saturation is low to reduce damage to the soil. In dryer conditions when the surface soil is harder, traction is less of an issue as when soil is highly saturated. A possibility for farmers looking at reducing damage to soil is using alternative tyre treads such as an R3 industrial tractor tyre (Figure 17), often labelled as turf tyres, or R4 'wide lug' tractor tyres (Figure 16). The R3 tyre is designed with a small, shallow tread pattern with a high coverage of small lugs, around seventy percent the depth of the R1 tread depth, designed to spread the weight more evenly across the soil to limit damage. R3 tyres are available in smaller tractor sizes, up to 74 horsepower (John Deere, 2013).

Figure 16. R3 Turf tyre (Goodyear)

Figure 17. R4 Wide lug tyre (Goodyear)

The R4 wide lug tyre is an alternative tread which is shallower and wider than the R1 tread and are often designed with an overlap across the centre of the tyre but maintain similar lug spacing. R4 tyres can provide similar grip to the

R1 tyres in dry conditions but can be limited in wetter soils. The wide lugs can increase the lug footprint by up to forty percent more than an R1 lug and depths can be fifty to sixty percent lower than an R1 tyre (Bridgestone Ag, 2018).

CONCLUSIONS

Soil compaction is a prevailing problem which is often overlooked in grass forage production.

Compromises are often taken with tyre choices which priorities practicality over reducing soil compaction and plant damage. Reductions in agricultural land in the UK has led to increased focus on small efficiencies to improve crop yields. Soil compaction is a prevailing problem in crop and grass production.

Clear differences were identified between the standard and wider sets of tractor tyres. The increased with of the 900/50 R42's allowed for the vertical load to be spread across a larger area, reducing the depth of compaction but creating a wider profile. The overall area compacted by the wider tyres was twenty-eight percent less than the area compacted by the narrower 650/75 R38's. The movement of soil under the forces of the tyres are not only vertical, but horizontal forces also acted on the soil outside the width of the tyres, increasing compaction levels. The wider tyres created a wider but shallower area of compaction with a lower average compaction level, this would make the compaction from the wider tyres easier to relieve without disturbing subsoil.

Shallower compaction levels from the wider tyres also mean that processes such as soil rejuvenation with discs or tines can be carried out at shallower depths without disturbing the subsoiling and opening up deeper soil, which can lead to the release of SOC. Methods of relieving compaction in the upper soil layers are also faster and require less effort than methods like ploughing to relieve deeper compaction.

Reduced macroporosity in the soil beneath the tyre treads reduces transpiration rates of surface water and reducing drainage of ground water, increasing the saturation of the soil which in turn limits the oxygen uptake of plants and can stunt growth and cause plants to die. Damage to plant leaves caused by the shear effect of the tyre tread edges can also stunt the growth of the crop up to five centimetres, with the deeper tread of the narrower tyres causing more damage than the wide tyres with shallower tread.

The narrower set of tyres created a larger amount of horizontal movement in the soil, this was shown as the level of compaction outside the width of the tyres increased, this is due to the increased downwards force and resistance acting on vertical forces.

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