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The Effect of Tyres and a Rubber Track at High Axle Loads on Soil Compaction, Part 1: Single Axle Studies

D Ansorge; R J Godwin

Cranfield University, Cranfield, Bedford, MK43 0AL, UK; email of corresponding author:

d.ansorge.s04@cranfield.ac.uk

One option for ground drive systems with large harvesting equipment is to use rubber belted tracks; however, little is known about the performance of these relative to appropriately sized pneumatic tyres. We aimed to study the effect of self propelled wheels and a track with high axle loads (9-24t) on soil compaction. This was assessed by embedding talcum powder lines as tracer into the soil during preparation to measure soil displacement and soil density changes. Additionally, soil dry bulk density and penetrometer resistance were measured. The track with loads of both 10.5 and 12 t compacts the soil less than wheels at 10.5 t load in both weak uniform and stratified soil. Towed implement wheels with 4.5 t load caused similar soil displacement to the track with a load of 12 t. Inflation pressure had a significant influence on soil parameters and a larger overall diameter is more beneficial than a wider tyre. The study emphasises the importance of contact pressure and its distribution with respect to soil density changes. Total axle loads are less important than how these are distributed on the ground.

1. Introduction

This paper is the first in a series of three; it describes an investigation into the effect of different drive systems on soil compaction in a controlled laboratory environment. The second paper deals with the effect of machine configurations on soil compaction and explains track behaviour. The final paper extends and develops prediction models to estimate the increase in soil density from both tyres and rubber tracks and relates these to the experimental results in the earlier two papers.

Cereal farmers are under significant pressure due to a reduction in product related subsidies and a low world market price for cereals. Farmers must either grow in size and raise productivity or cease operation. In order to gain income with a given amount of produce, productivity has to increase.

Productivity can either be enhanced by more efficient machinery using more sophisticated technology or as a result of economies of scale. The current tendency is clearly towards larger machinery (Kutzbach, 2000), but larger machinery tends to imply heavier machinery and the threat of soil compaction increases. Raper (2005) has reported that there were no laboratory investigations published concerning axle loads significantly higher than 10 t and the comparison of wheels and tracks was limited to in - field investigations.

The aim of this study was to conduct a fundamental study in a controlled laboratory environment into the relative effects of a track and self propelled wheels with axle loads of 9-24 t on soil physical parameters. The effect of soil compaction was assessed by measuring soil displacement, changes to soil density and cone penetrometer resistance. The same type of tyre and track as used for the study is shown in *Fig. 1* in a field situation.

2. Literature Review

In general, tracks are better than wheels at limiting soil compaction (Erbach, 1994). However, according to Culshaw (1986) and Erbach (1994) they can have detrimental effects upon soil for several reasons: a) although the calculated mean contact pressure is smaller than for a wheel, it is applied for longer; b) the idler wheel configuration and track belts with inadequate tension may result in a non uniform pressure distribution, and c) vibrations from the engine and other machine parts are more readily transmitted into the soil on tracks because of the reduced suspension effect.

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Investigations showing the advantage of steel tracks were published by Reaves and Cooper (1960), Soane (1973), Taylor and Burt (1975), Janzen *et al.* (1985), Erbach *et al.* (1988), Erbach *et al.* (1991), and Kinney *et al.* (1992). For a 40 t steel tracked excavator changes in pre-compression stress in the topsoil could only be detected in very wet conditions with no detectable change in the subsoil conditions irrespective of moisture status (Berli *et al.,* 2003). Steel bogie tracks on a trailer are beneficial compared to wheels according to Bygden *et al.* (2004). However, no differences between a steel tracked and a rubber tyred tractor could be detected by Burger *et al.* (1983) and Burger *et al.* (1985). These authors conclude that machine related factors other than contact pressure had an influence on the results.

The less rigid belt of rubber tracks, whilst an advantage for highway travel, is a disadvantage compared with traditional steel track belts on soft surfaces due to the problem of an uneven weight distribution below the rubber belt due to the idler configurations and belt tension effects referred to earlier by Brown *et al.* (1992). Their results showed that rubber tracks performed in an intermediate manner between those of wheels and steel tracks and were not significantly different from either.

Campbell *et al.* (1988) found a greater cone penetrometer resistance after using a wheeled tractor even though the rubber - tracked machine had a 24% greater total mass. Comparisons between a wheeled and a rubber tracked tractor by Pagliai *et al.* (2003) showed less soil density change and penetrometer resistance increase in the top 100 mm for the wheeled tractor, less for the tracked vehicle between 100 – 200 mm depth and no difference between either at a depth of 200 – 400 mm. This was supported by the results of Servadio *et al*. (2001) and Brown *et al.* (1992). Servadio *et al.* (2001) found lower penetrometer resistance in the top 200 mm and a greater resistance between 200 – 400 mm depth for a wheeled tractor in comparison to a rubber tracked tractor. Brown *et al.* (1992) found more compaction in the top 125 mm for wheeled tractors, but below 125 mm differences were minimal between wheeled and tracked tractors.

Blunden *et al.* (1994) could not detect significant penetrometer resistance differences at 500 mm depth between a wheeled and a rubber belted tractor. Between 400 and 500 mm the wheeled tractor produced 0.03 MPa less penetrometer resistance. These results are interesting as the wheeled tractor weighed 18 t and the tracked one 15 t with a mean contact pressure below the tracked one which was 25% lower. From this work it is not evident why the differences in penetrometer resistance were small but this could be due to unequal pressure distribution below the track as reported by Weissbach, (2003), Keller *et al.* (2002) and Tijink, (1994).

All the above results cannot be generalized but they show the importance of designing the track frame carrying the rubber belts and transferring the weight whereas the frame is less crucial for steel tracks. A summary of papers reporting advantages (Bashford *et al.,* 1988 and Rusanov, 1991) or disadvantages (Blunden *et al.,* 1994) of tracks on soil compaction is given by Alakukku *et al.* (2003).

3. Methods

The rubber track, harvester tyres and implement tyres used in this study are specified in Table 1. The track was loaded to both 10.5 t and 12 t enabling the comparison of the tyre and the track under the same overall load and under the same working conditions. The additional weight of the track system for a given combine harvester is 1.5 t per track unit. Three different harvester tyre sizes were selected at the recommended inflation pressure for a 10.5 t load. The medium section width tyre was chosen to be operated at half the recommended inflation pressure to investigate the effect of a lower inflation pressure. The four implement tyres were laden to 4.5 t and inflated to the recommended inflation pressures. These implement tyres are typical rear tyres of a combine harvester and will be used to mimic whole machines in the second paper of this series.

The study was conducted in the 20 m long, 1 m deep, and 1.8 m wide soil bin laboratory at Cranfield University, Silsoe. The laboratory has been described in detail by Alexandrou and Earl (1998). The soil used was a sandy loam (Cotterham series) with 17% clay, 17% sand and 66% sand and water content was maintained at 10% dry base during the studies. Both a uniform and a stratified soil condition were prepared. The uniform soil condition with a dry bulk density of 1.4 g/cm^3 was chosen to imitate soil conditions with a low bearing capacity and to enhance the differences between the single treatments. Under these conditions the benefit of tracks would be expected to be greatest. The initial penetrometer resistance is shown in *Fig. 2* for both the uniform and stratified soil conditions. The stratified soil condition replicated a real in-field situation with a subsoil, a dense ‘plough layer’ and a soft working depth, with dry bulk densities of 1.5 g/cm^3, 1.6 g/cm^3, and 1.4 g/cm^3, respectively. The 900mm/10.5t/1.9bar tyre was compared to the T12t type to simulate field loading conditions on the stratified soil.

In addition to the initial values for the stratified soil conditions in the soil bin, *Fig. 2* also includes the penetrometer resistance of a real field condition with a ‘plough layer’. The close agreement of the field and soil bin conditions show that it was possible to replicate these field strength conditions in the soil bin. The working depth from 0 – 200 mm shows the least resistance, followed by the compacted ‘plough layer’ between 200 – 300 mm, below which, in the subsoil from 300 – 700 mm, the depth penetrometer resistance reduces. The only difference between field and soil bin conditions is that the plough layer was situated 30 – 40 mm deeper in the field.

3.1. *Track and tyre test apparatus*

To test the harvester tyres and the track, a test apparatus was designed and built in accordance with the requirements of the study and the soil bin (Godwin *et al.*, 2006). The apparatus, shown in *Fig. 3* with a track unit before a run (left hand side) and a 900 mm section width tyre after a run (right hand side), allowed the application of 0 to 14 t on to a self propelled wheel or track mounted on a standard Claas Lexion axle using a hydraulic cylinder. The test apparatus was self propelled in a similar manner to the single wheel tester built by Billington (1973). However, the load was applied indirectly on to the wheel/track which simplified the handling of the rig because the loading weights supplying the counterforce of the cylinder were spread over the frame of the test rig and remained in place during the change of drive systems.

Wheel or track loads could easily be adjusted as the applied load was a function of the pressure in the hydraulic cylinder for which the pressure was set using a pressure maintaining valve. The hydraulic cylinder was also used for lowering the wheel and track onto the surface of the soil and raising it up again. All the forces, except the vertical component, and the torques developing from both the weight application to and the movement of the wheel and track were removed by the use of linear bearings to prevent weight transfer from the axle. The axle was a standard Claas – Lexion combine axle which included the 300 kW hydraulic motor and gear box with the differential locked. The hydraulic power to drive the self propelled wheels and the track using the hydraulic motor on the axle was supplied from a PM1000 hydraulic pump which was able to supply 60 kW. This, in turn, was driven by a Perkins 6354 88 kW combustion engine.

Additionally, a fifth wheel could be mounted to the frame to measure the true speed during an investigation using a digital encoder. The speed of the tyre/track was measured via a second digital encoder mounted to the axle. The investigations were carried out at a speed of 0.8 m/s and a slip of 0.14 for the tyres and 0.05 for the track.

The implement tyres were placed in a test rig towed by the soil processor of the soil bin. The tyre was mounted on a continuous axle supporting the frame which accommodated up to 14 t of additional load.

3.2. *Soil displacement measurement*

A novel “non - invasive” procedure inspired by a technique of Trein (1995) was used to determine soil displacement (strain) and effective density change. This was achieved by placing talcum powder lines into the soil during preparation of the 20 m long, 1.7 m wide and 0.7 m deep soil bin and measuring the change in their relative position following each passage of a tyre or track. Three sets of talcum powder lines were placed along the length of the soil bin. The position of the talcum powder lines was located from the digitized output of two drawstring transducers connected to a pin drawn to each talcum line appearing in the profile as a point, when the length of each draw string was recorded. From the length of each drawstring and the distance between the drawstring transducers, the vertical and horizontal coordinates of each point were calculated. *Figure 4* shows the two points on either side of the soil bin in the areas undisturbed by the tyre/track which were taken as both depth and lateral position reference points. The initial positions of the other (central) talcum powder points were located at equal spacing along these lines from knowledge of their initial relative positions. Compared to the approach taken by Trein (1995) visualization had been enhanced as the talcum powder was much easier and hence faster to locate than the dye used earlier while maintaining accuracy.

The mechanical accuracy of the measurements was assessed by printing an imaginary cut through the soil bin profile with a large CAD plotter and measuring the position of the points with the drawstring transducers. Hence the true position of every single point was known and then compared to its measured position. This comparison showed that the individual position of a single point could be measured to an accuracy of +/- 2 mm, and the depth of a layer could be measured to within +/- 0.5 mm with repeated measurements. Having gained the initial and the final positions of the talcum powder points, it was possible to draw a vector diagram of the soil movement from the initial coordinate to the final. Such a vector diagram is shown in *Fig. 5* for the 800mm/10.5t/2.5bar tyre.

The vectors in *Fig. 5* exhibit near vertical soil displacement with little sideways movement which is independent of section width. Hence, it was concluded that the effect of the wall friction affecting the soil displacement was of little significance.

To compare the different treatments in one diagram the length of the central four vectors was averaged for each depth. This average vector length representing the soil displacement of the central 300 mm for the rut is plotted against depth in *Fig. 6* for the 800mm/10.5t/2.5bar tyre. Vectors with greater displacement, as shown by the solid line, show a greater change in soil density and a smaller displacement as shown by the broken line indicate smaller changes in soil density. *Figure 6* shows soil displacement as a function of depth, which can be described by the following equation fitted to the top 500 mm (with $d(z)$ being positive with depth):

$$d(z) = d_0 - s \times z \quad (1)$$

where: d is the soil displacement in mm at a given depth z; d_0 is the displacement at the surface in mm; s is the change in vector length per unit of depth in mm/mm; and z is the depth in mm.

When Eqn (1) is differentiated with respect to depth, the displacement change, *i.e.* the average increase in soil density is derived:

$$d'(z) = -s \quad (2)$$

Thus $|s|$ is a direct measure of the relative increase in soil density caused by vertical soil movement and will be used to compare the treatments. As stated earlier, the maximum error in measuring the depth of a layer was +/- 0.5 mm which would result in 1% error of $|s|$ in the worst case, i.e. all points line up in such a way that the top has a larger displacement of + 0.5 mm than in reality and the bottom has 0.5 mm less than in reality. This is unlikely due to the large amount of measurements and handling errors do not exist with the drawstring method.

3.3. *Cone penetrometer resistance*

Cone penetrometer resistance was determined by measuring the force necessary to push a 125 mm^2, 30^o cone into the soil. The data were automatically digitally recorded in 10 mm depth increments and plotted as penetrometer resistance with respect to depth. Cone penetrometer resistance was measured across the soil bin in ten places (1- 10) at 120 mm spacing for both the initial control and the three replicated positions of the wheel/track passage. This resulted in diagrams such as *Fig. 7*. The increase in measured penetrometer resistance at 700 mm depth was due to the penetrometer sensing the bottom of the soil bin. Consequently, the last five readings were always disregarded for statistical analysis. As *Fig. 7* indicates the central four readings were similar and thus averaged.

3.4. *Dry bulk density*

Dry bulk density (DBD) and moisture content were measured at depths of 0, 250, and 500 mm, with three replicates before and after each run, at the centre of the track mark in the soil bin by sampling using a cylindrical ring (60 mm diameter and 51.5 mm deep).

3.5. *Statistical analysis*

Before the statistical analyses were conducted, the normal distribution of the data was always verified. All parameters were analyzed using generalized linear models to determine whether there were significant differences between the initial values and the treatment values, between single treatments, and for interactions over the depth of measurement collections at the 95% - level. Variances within the process of taking measurements were accounted for by identifying appropriate covariance parameters on the level of measurement and replication. As measurements were taken in the same soil bin several times per run, they have to be treated as repeated unpaired measurements (Piepho *et al.*, 2004). Normal probabilities were used for multiple comparisons because the standard errors of the different treatments were similar in magnitude and differences are implied by analyzing the data as suggested by Nelder (1985).

3.6. *Repeatability of soil bin preparations*

Due to the time consuming preparation and data collection procedure, each treatment was usually only carried out once and repeated measurements taken which was taken into account in the statistical analysis. To show repeatability of the results in the soil bin, one treatment was carried out twice. As *Fig. 8* shows, results were repeatable if the soil bin was prepared to the same initial conditions and the same treatment was applied.

4. **Results**

4.1. *Uniform soil conditions*

4.1.1. *Soil displacement*

In weak uniform soil conditions vertical soil displacement and strain were significantly smaller for the track compared to the wheels at both normal and half inflation pressures as shown in *Fig. 9*. This figure shows that there was an expected gradual increase in the slope of the line with depth which corresponded to a reduction in the density increase with depth. However, if the data for depths of 500 mm and less were considered, this effectively gave rise to a near constant slope and thus a uniform change in soil density. Applying this criterion showed that all treatments were statistically significantly different at the 95% - probability level except for the two track loads and the 800mm/10.5t/2.5bar tyre from the 680mm/10.5t/2.2bar tyre.

The nearly identical soil displacement caused by these two tyres shown in *Fig. 9* was unexpected as the larger section width was expected to cause less soil displacement than the 680mm/10.5t/2.2bar. However, the larger diameter of the 680mm/10.5t/2.2bar tyre (1.94 m diameter) gave rise to a larger contact patch than the 800mm/10.5t/2.5bar tyre (1.82 m) diameter (an area of 0.69 m^2 compared to 0.62 m^2) and hence to the lower contact pressure. The 900mm/10.5t/1.9bar tyre due to its width and inflation pressure produced the least soil displacement at the recommended inflation pressure. The effect of reducing inflation pressure from 2.5 bar to 1.25 bar for the 800mm/10.5t tyre produced a significant decrease in soil displacement.

Figure 9 also shows that the displacement of the soil caused by the tracks was approximately 60 mm at the soil surface and decreased to zero mm displacement at 500 mm depth. The track at a 12 t load caused 8% more displacement than the track at a 10.5 t load, but the difference was not statistically significant.

From Eqn (2) the tyres at a normal inflation pressure increased soil density by 18%, the tyre at half inflation pressure by 12% and the track by 13%. The data for the increase in density of individual treatments including the correlation coefficient for the regression lines is shown in Table 2. The higher increase in soil density caused by the tracks was due to their soil displacement being reduced to zero at 500 mm depth whereas all tyres showed a residual soil displacement between 8 – 14 mm.

Figure 10 shows the soil displacement for the range of implement tyres tested. Larger contact areas and lower inflation pressure reduced soil displacement. Statistically all combinations were similar to each other with the exception of the 500-70mm/4.5t/2.3bar tyre. The similarity of the 500-85mm/4.5t/1.4bar and 600mm/4.5t/1.4bar, with contact areas of

0.41 and 0.39 m^2, respectively, is similar to the case of the 680mm/10.5t/2.2bar and the 800mm/10.5t/2.5bar. Again the higher section width of the tyre combined with an identical inflation pressure created identical soil displacement as the wider tyre. Despite the potential difference in carcass stiffness of cross ply vs. radial tyres, the two tyres produced near identical footprints although with different geometries. The 700mm/4.5t/1.0bar tyre was not able to utilize its large section width and low inflation pressure to create a significantly smaller soil displacement although having the largest contact area of 0.47 m^2.

The track at 12 t load in this context caused similar soil displacement to the three lower pressure implement tyres at 4.5 t; although the track carried 2.67 times the load. Additionally the tyres caused a residual soil displacement of 3 – 7 mm at 500 mm depth. The average increase in soil density caused by the implement tires was similar to the 800mm/10.5t/1.25bar tyre, both increasing soil density by 12%. Thus approximately half the load on a smaller tyre increased density by a similar amount to the total load at half the recommended inflation pressure. The individual increases in soil density are listed in Table 2.

4.1.2. *Penetrometer resistance*

The average of the central four penetrometer resistance readings over depth is shown in *Fig. 11*, including both the undisturbed initial readings as a mean over all experiments and the LSD with 5% error probability. This demonstrates that tracks caused a higher penetrometer resistance than tyres at depths close to the surface where the increase in strength can be more easily alleviated. All the tyres had higher penetrometer resistance in the subsoil (below 250 – 300 mm) than the tracks.

The grouping of the tyre configurations (680mm/10.5t/2.2bar and 800mm/10.5t/2.5bar against the 900mm/10.5t/1.9bar and 800mm/10.5t/1.25bar) indicates a relationship between inflation pressure and penetrometer resistance as the tyres with lower inflation pressures created less penetrometer resistance. Again, all comparisons were significantly different with the exception of the 680mm/10.5t/2.2bar from the 800mm/10.5t/2.5bar and the two track loads from each other.

From *Fig. 11* it can be seen that the shape and the values of the penetration resistance curves for the track at both loads of 12 t and 10.5 t were not significantly different, except at depths between 100 and 200 mm. Below 350 to 400 mm depth the penetration resistance approached that of the initial condition for T10.5t and the difference between the final and initial conditions was only significant for the T12t. The LSD shown in *Fig. 11* did not vary with depth as the depth factor was accounted for as covariance parameter.

The tracks exhibited a major change in penetrometer resistance close to the surface. For the wheels, the peak penetrometer resistance was smaller near the surface, with the penetrometer resistance in deeper layers being significantly higher than for tracks. Thus the advantage of tracks was that while there was a greater increase in penetrometer resistance this was close to the surface, where it could be alleviated with shallower tillage operations. The origin and implications of the peak in penetrometer resistance for the tracks will be discussed in detail in Part II, Multi-Axle Machine Studies.

Penetrometer resistance for the implement tyres is shown in *Fig. 12* and the values were not significantly different at the 5% level. The penetration resistance of these tyres were all significantly smaller than those of larger harvester tyres.

4.1.3. *Dry bulk density*

The final measured dry bulk density (DBD) for both tyres and tracks was significantly higher than initial DBD over all depths. The differences were in the range of 0.11 – 0.15 g/cm^3 and the least significant difference at the 95 % level was 0.046 g/cm^3. The data including the least significant difference bars is shown in *Fig. 13*. The difference between the tyre and track was just significant, whereas the statistical analysis of individual tyres and tracks showed no significant differences. The implement tyres show the same soil density as the track. In addition the final DBD was estimated from the initial DBD and the slope of the soil displacement lines and did not show significant differences except for the tyre.

From these results the conclusion could be drawn that the soil displacement analysis was more sensitive in determining differences between the single treatments, but the overall trends followed a similar pattern.

Campell (1994) discussed the difficulty in assessing soil compaction using dry bulk density. The soil displacement data had a finer resolution than the dry bulk density. The measured increase in DBD for the tyres was on average 11% and for both the tracks and the implement tyres it was 8%.

4.2. *Stratified soil conditions*

4.2.1. *Soil displacement*

Figure 14 compares the soil displacement in the stratified soil conditions with a simulated ‘plough layer’ at a depth between 200 – 300 mm. This figure shows that due to the stronger soil conditions of the stratified soil, the displacement was reduced to 20 % rut depth and hence soil displacement of that in uniform soil conditions which was included as reference.

The displacement by the track was less than by the tyre over the entire depth and was reduced to zero at 300 mm. The 900mm/10.5t/1.9bar, however, pushed the ‘plough layer’ with a small increase in density down into the weaker subsoil. Soil displacement for the tyre approached zero at a depth between 500 – 600 mm.

4.2.2. *Penetrometer resistance*

After the pass of the 900mm/10.5t/1.9bar tyre the penetrometer resistance increased significantly as shown in *Fig. 15 (a)* which exhibits that the tyre increased penetrometer resistance over the whole profile except for the ‘plough layer’. The shape of the penetrometer resistance curve for the tyre was similar for the stratified and uniform soil. The final penetrometer resistance below 130 mm was constant at 2 MPa excluding the ‘plough layer’. The plough layer did not become stronger, but its thickness was increased by about 20 mm. *Figure 14* confirms this as it shows that the ‘plough layer’ was pushed down into the weaker subsoil increasing the thickness of the ‘plough layer’.

The initial and final penetrometer resistance for the track in stratified soil conditions is shown in *Fig. 15 (b).* As with the tyre, the final curve was similar to that in uniform soil conditions with a pronounced peak close to the soil surface followed by a reduction in penetrometer resistance. The penetrometer resistance for the final condition merged with that for the initial condition above the plough layer. No soil compaction occurred below the ‘plough layer’.

The benefit for soil physical conditions after the pass of the rubber track compared to wheel/tyre systems was clearly shown in uniform and stratified soil conditions. The most significant effect of the study was to record how close to the surface the maximum penetrometer resistance can be kept using tracks compared to tyres and that with a ‘plough layer’ below 200 mm there was no change in penetrometer resistance and hence apparent soil strength.

5. Discussion

The results of this work have shown that soil displacement measurements are a sensitive method to determine differences between treatments. The penetrometer resistance could not detect any differences for the implement tyres, but measuring soil displacement differences could be detected. Stranks (2006) found similar results during an investigation with pea harvester tyres loaded to 4.5 t.

The rubber track used in this study weighed 1.5 t more, but caused a significantly smaller increase in soil displacement and penetration resistance than wheels in controlled laboratory conditions. Therefore the overall finding is that rubber belted tracks have significant benefits over the currently available tyre choices, corroborating the work of Erbach (1994). However, it is in contrast to the results by Brown *et al.* (1992) where rubber tracked vehicles were intermediate to steel tracked and wheeled vehicles but not significantly different from either. The reason for this may be due to improved frame and belt tension for this track system compared with those used by Brown *et al.* (1992) and the controlled conditions. The significantly reduced penetrometer resistance in the subsoil was not detected by Blunden *et al.* (1994), Pagliai *et al.* (2003) and Brown *et al.* (1992) when using rubber tracks. Servadio *et al.* (2001) only found a lower penetrometer resistance below a rubber belted tractor in the range of 200 to 400 mm depth than for a wheeled tractor. The large natural variation in field data might be a possible reason for this. Research could not be found indicating the reduced penetrometer resistance down to 650 – 700 mm.

These results confirm the results from Bekker (1956) and Hakanson (1988) who state that tyres with a smaller section width can reduce soil compaction when the contact area is maintained or increased with a longer contact patch resulting from a larger wheel diameter. The track can achieve this whilst confined to a much smaller vertical envelope.

Tracked vehicles equipped with such a belt and frame system as those used in this investigation may be the answer to the requirement of highly efficient farm machinery simultaneously protecting the soil as postulated by Hamza and Anderson (2005). Taking the reduced soil compaction in deeper soil areas into account and ignoring the higher soil compaction close to the surface, where it can easily be alleviated, tracks may be the answer to maintain high yields in agricultural systems relying on heavy farm machinery in order to maintain or increase productivity.

With stratified soil conditions the ‘plough layer’ was able to protect the subsoil for the tracked treatment. Brandhuber *et al.* (2006) were able to show in field measurements the benefit of tracked sugar beet harvesters. Our results of the 900mm/10.5t/1.9bar on the same soil conditions agree with the findings from Arvidsson *et al.* (2001), Trautner & Arvidsson (2003) and Yavuzcan *et al.* (2004) who detected increases in soil density to 0.3-0.4 m for wheeled sugar beet harvesters in field measurements. The subsoil conditions in the soil bin were insufficiently strong to resist the load without density change as found in field by Dickson (1994) on a previously compacted soil after passes with a combine harvester.

The benefit of constant tramlines for all field work shown by Chamen *et al.* (1994) will work very well with the track especially as it creates a high penetration resistance close to the surface which can act as a pathway.

The results of this investigation add to the evidence to support the conclusions for the tyre data given in Alakukku *et al.* (2003) and Keller and Arvidsson (2004) and contradiction to the establishment of an axle load limitation as suggested in Ericsson *et al.* (1974), Carpenter *et al.* (1985) and van der Ploeg *et al.* (2006).

6. Conclusions

(1) The change in soil physical properties commonly referred to as soil compaction is not a function which only is influenced by load; it is also influenced by the spreading of the load over a large contact area. With the same load this study found a range of responses for different under carriage systems, whereby some caused significantly less soil compaction than others.

(2) The major benefits of 'Terra Trac' drive systems over conventional tyre systems were:

   (a) a reduction in the surface rut depth and the sub-surface soil displacement of approximately 40% compared to that of a tyre system with substantial reductions in the increase in soil bulk density (*i.e.* a 13% rather than a 18% increase).

   (b) a smaller increase in penetrometer resistance in the subsoil layers, albeit with a greater increase in penetrometer resistance in the surface layers which can be more easily and more cheaply removed with subsequent shallower tillage operations.

(3) The effect on soil displacement and penetrometer resistance from a ‘Terra Trac’ loaded to 12 t, whilst higher, is not significantly greater compared to 10.5 t load.

(4) Track loads of 10.5 t and 12 t caused similar soil displacement as smaller tyres with 4.5 t of load.

(5) Reducing the inflation pressure from 2.5 bar to 1.25 bar for the 800 mm section width tyre significantly reduced the penetrometer resistance, surface rut depth, and sub surface soil displacement. This effect reduced the increase in dry bulk density from 18% to 12%.

(6) Soil compaction in a stratified soil (to simulate a dense layer situated 200/300 mm deep as in field conditions) in the laboratory stopped at the ‘plough layer’ for the ‘Terra Trac’ whereas the tyre pushed the hard pan into the weaker subsoil below.

(7) The results from the layered soil conditions show the benefit in managing hard pans effectively in the intended traffic lanes as they can protect the underlying soil from compaction.

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Table 1

Tyre and Track Specifications

Undercarriage System	*Load (t)*	*Inflation Pressure (bar)*	*Abbreviation Section Width/Load/Inflation Pressure*
680/85 R32	10.5	2.2	680mm/10.5t/2.2bar
800/65 R32	10.5	2.5	800mm/10.5t/2.5bar
900/65 R32	10.5	1.9	900mm/10.5t/1.9bar
800/65 R32	10.5	1.25	800mm/10.5t/1.25bar
Claas Terra Trac	10.5	0.75(1)	T10.5t
Claas Terra Trac	12	0.86(1)	T12t
500/70 R24	4.5	2.3	500-70mm/4.5t/2.3bar
500/85 R24	4.5	1.4	500-85mm/4.5t/1.4bar
600/55 – 26.5	4.5	1.4	600mm/4.5t/1.4bar
710/45 – 26.5	4.5	1.0	700mm/4.5t/1.0bar

(1) mean pressure assuming a contact patch of 1.4 m^2

Table 2

Average Increase in Soil Density for Tyre and Track Specifications

Undercarriage System (Section Width/Load/Inflation Pressure)	*Average Increase in Soil Density (%)*	*Regression Coefficient of regression line*	*Least Significant Difference*
680mm/10.5t/2.2bar	17.7	0.989	0.1
800mm/10.5t/2.5bar	17.6	0.999	0.1
900mm/10.5t/1.9bar	17.3	0.994	0.1
800mm/10.5t/1.25bar	11.6	0.997	0.1
T10.5t	12.4	0.952	1.5
T12t	13.4	0.968	1.5
500-70mm/4.5t/2.3bar	14.3	0.989	0.8
500-85mm/4.5t/1.4bar	11.1	0.968	0.8
600mm/4.5t/1.4bar	11.0	0.985	0.8
700mm/4.5t/1.0bar	10.6	0.995	0.8

Fig. 1. During harvest a track and a tire identical to the ones used in the study

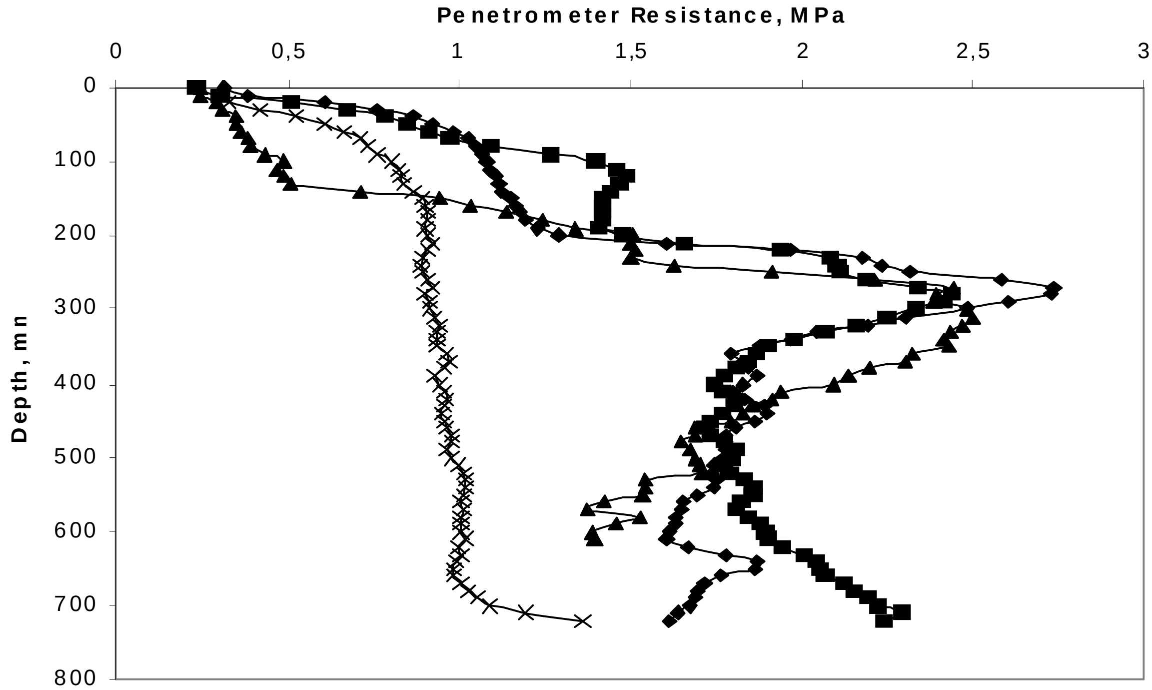

Fig. 2. Initial penetrometer resistance profiles in the soil bin of uniform and stratified soil conditions and including a field condition: ×*, uniform;* ■, ♦*, stratified one and two;* ▲*, field condition*

Fig. 3. Single Wheel/Track test apparatus with a track (left hand side) and a tyre (right hand side)

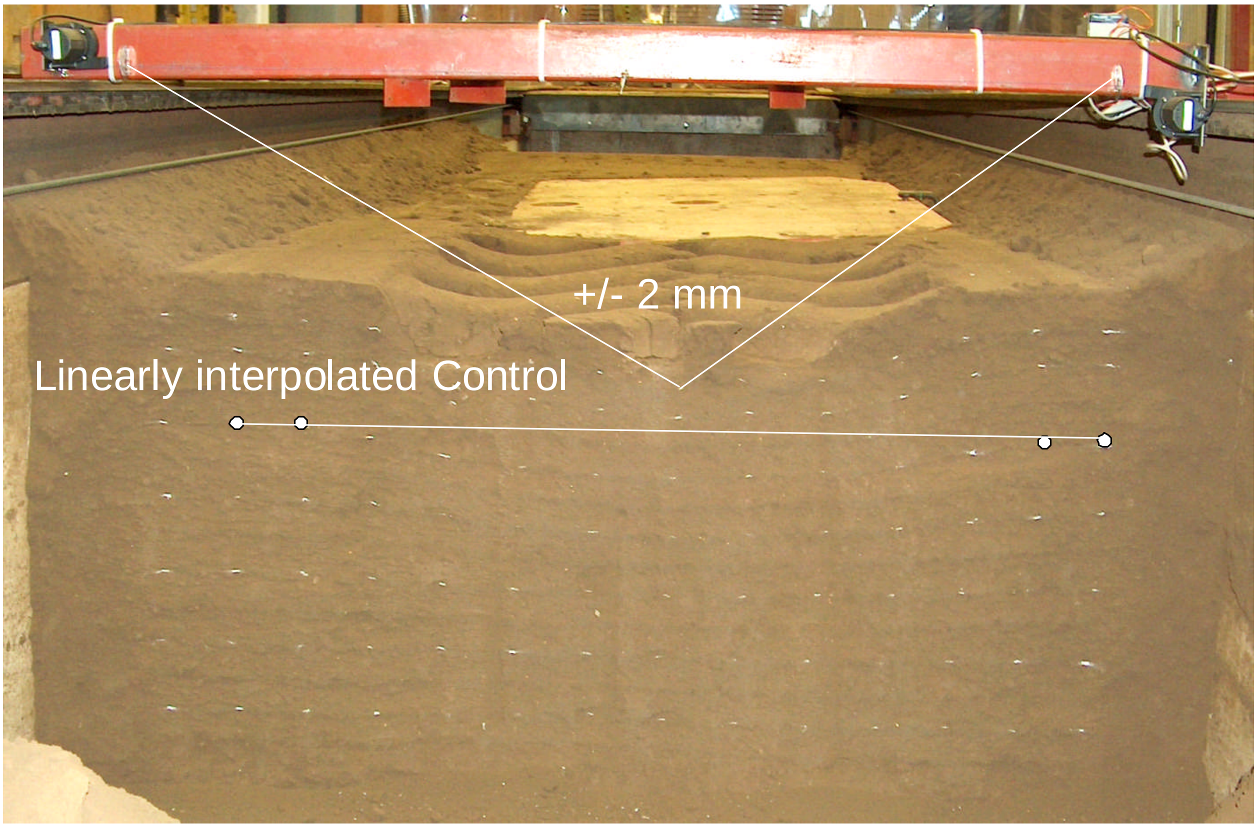

Fig. 4. Vertical cut through soil with points of talcum powder and the drawstring transducers in the initial condition

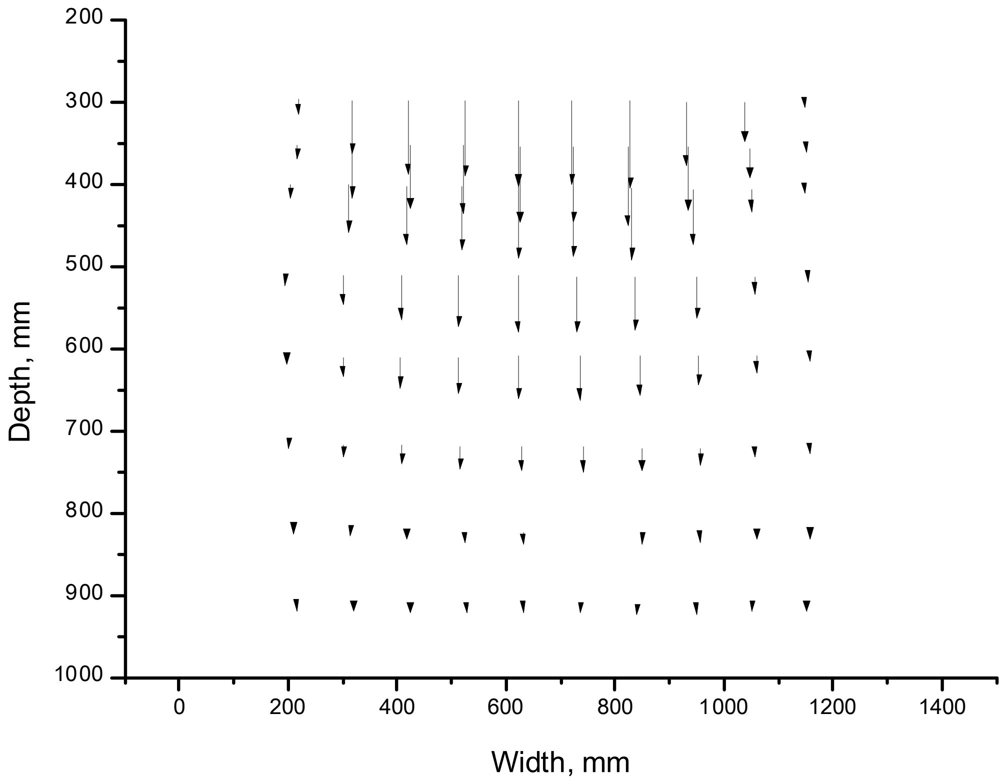

Fig. 5. Vector diagram of soil movement after the pass of an 800mm/10.5t/2.5bar tyre

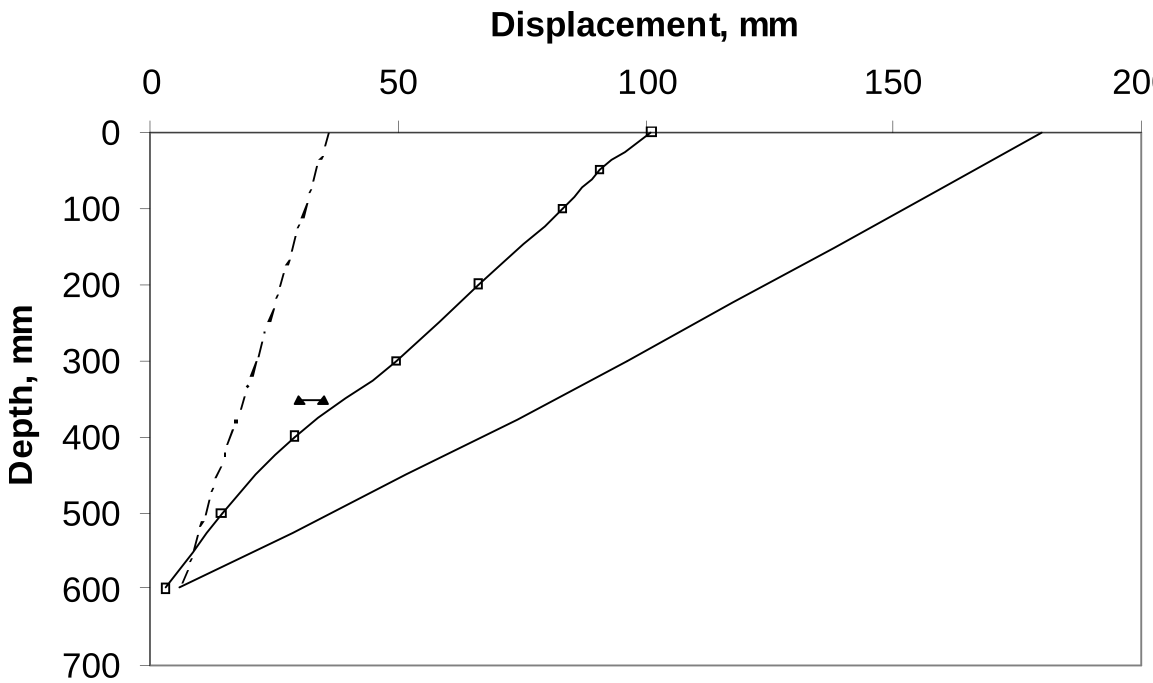

Fig. 6. Soil displacement vs. depth after a pass of an 800mm/10.5t/2.5bar: □, 800mm/10.5t/2.5bar; - - ,5% increase; - ,30% increase; and ▲ ,LSD

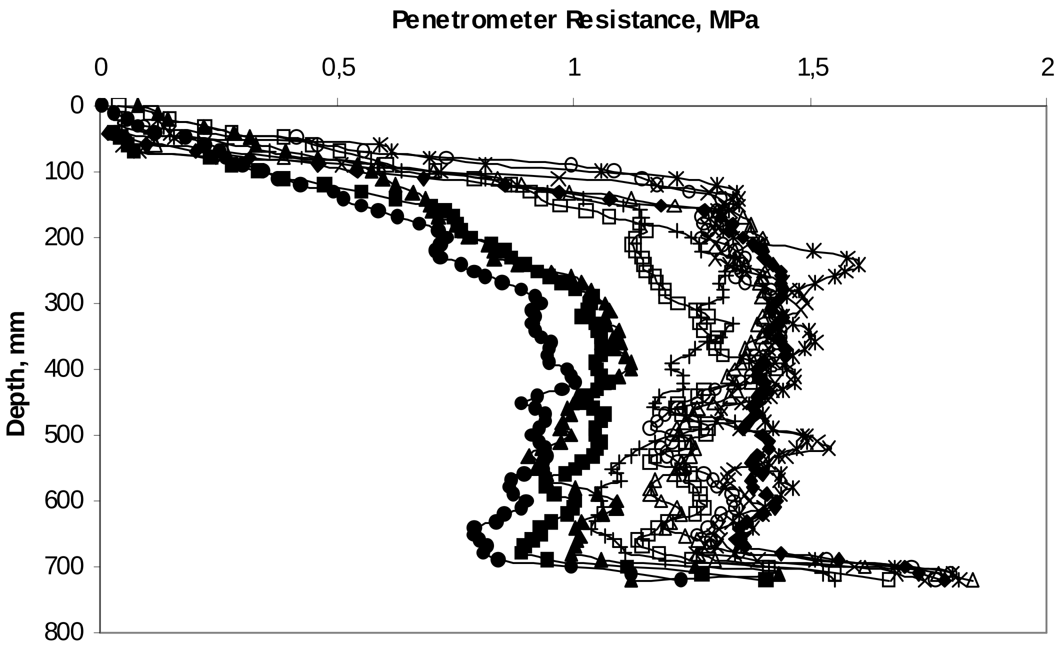

Fig. 7. Penetrometer resistance across the soil bin for the 900mm/10.5t/1.9bar tyre with ten readings: •, 1; ■, 2; +, 3; Δ, 4; ×, 5; ♦, 6; ⁎, 7; ○, 8; □, 9; and ▲, 10

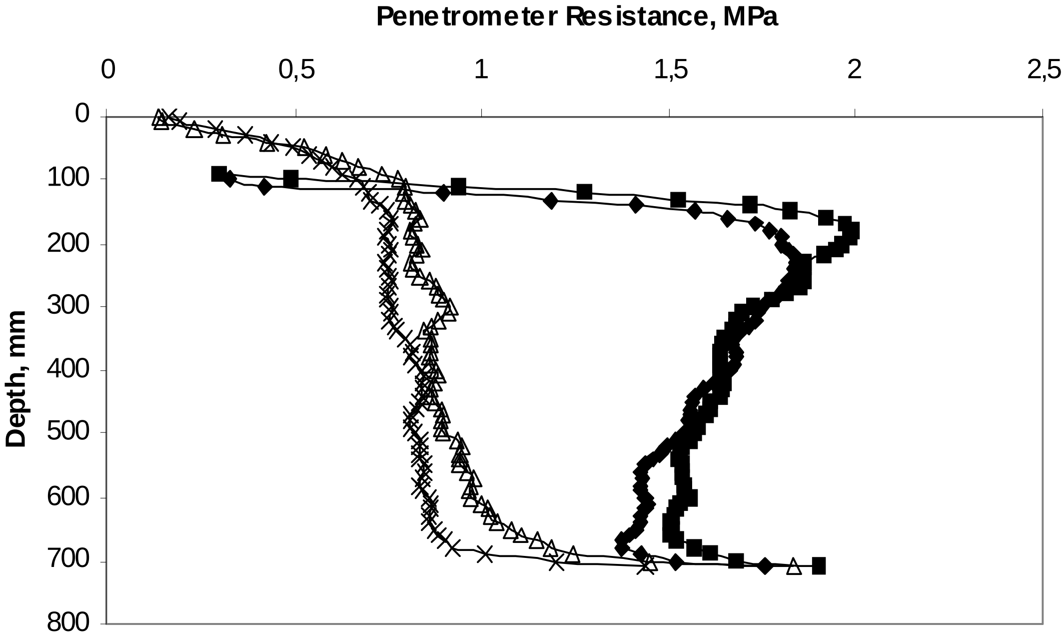

Fig. 8. Repeated treatments with near identical initials and results: ♦, 680mm/10.5t/2.2bar Test 1; ■, 680mm/10.5t/2.2bar Test 1; ▲, Initial Test 1; and ×, Initial Test 2

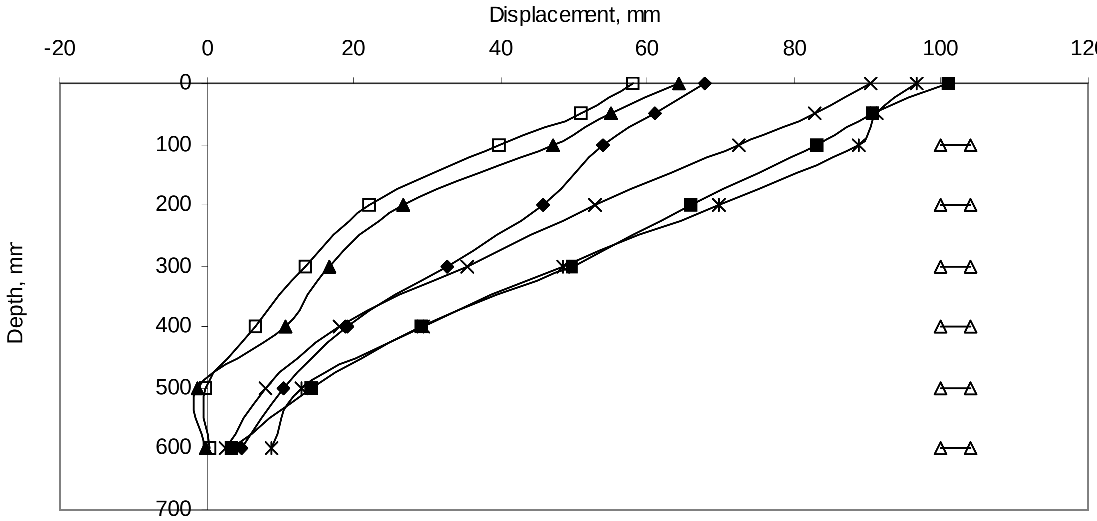

Fig. 9. Vertical soil displacement caused by harvester tyres at recommended and reduced inflation pressure and tracks: ∗, 680mm/10.5t/2.2bar; ■, 800mm/10.5t/2.5bar; ×, 900mm/10.5t/1.9bar; ♦, 800mm/10.5t/1.25bar; □, T10.5t; ▲, T12t; and Δ, least significant difference at 95% confidence level at given depth

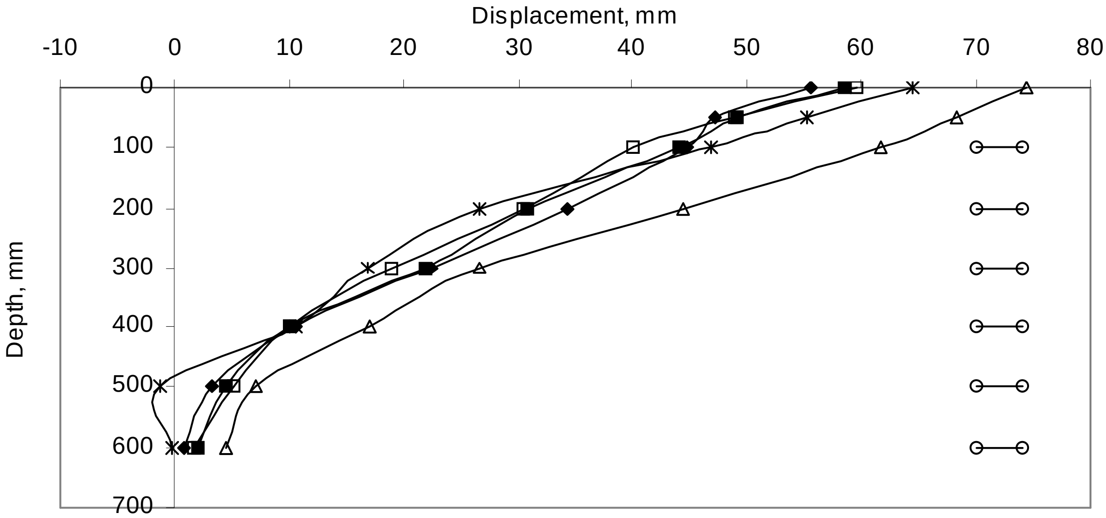

Fig. 10. Soil displacement vs. depth for the implement tyres including a track: ♦, 700mm/4.5t/1.0bar; ■, 600mm/4.5t/1.4bar; □, 500-85mm/4.5t/1.4bar; Δ, 500-70mm/4.5t/2.3bar; ✳, T12t; and ○, least significant difference at 95% confidence level

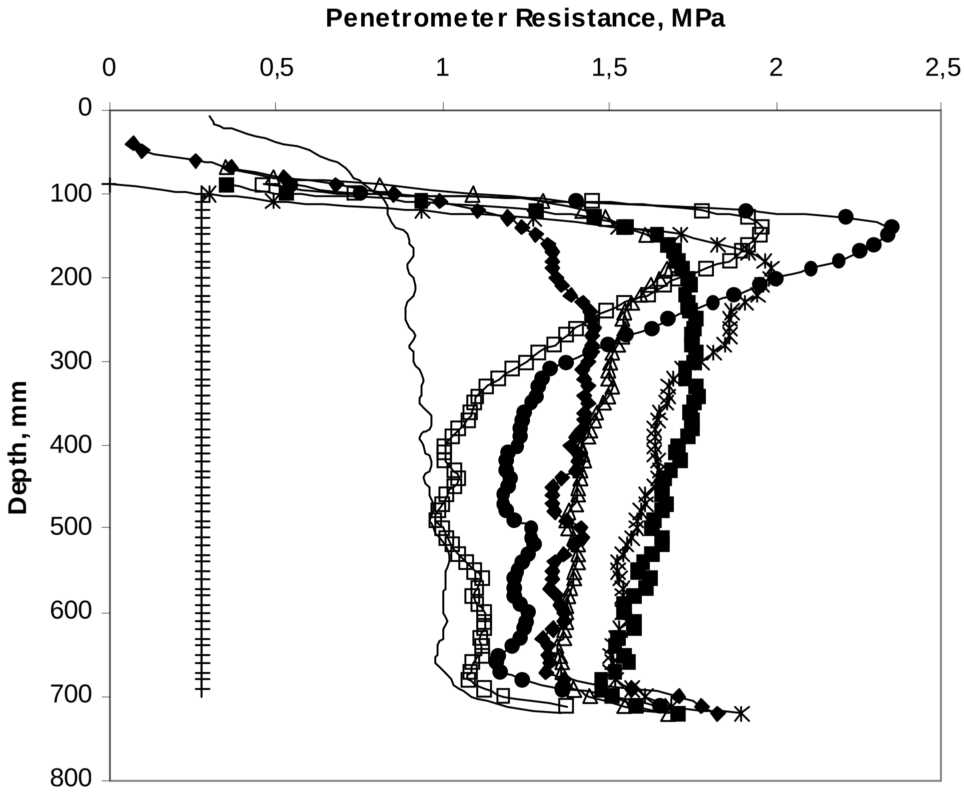

Fig. 11. Penetration resistance vs. depth initial and after the pass of the front tyres and the track: - , initial; ∗, 680mm/10.5t/2.2bar; ■, 800mm/10.5t/2.5bar; ♦, 900mm/10.5t/1.9bar; Δ, 800mm/10.5t/1.25bar; □, T10.5t; •, T12t; and +, least significant difference at 95% confidence level

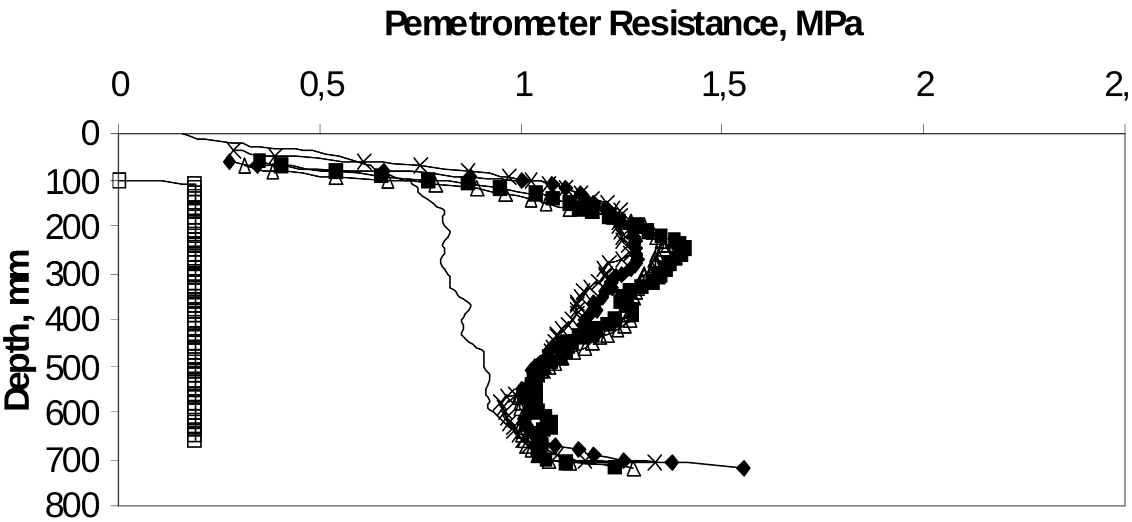

Fig. 12. Penetrometer resistance for the implement tyres: -, initial; ♦, 700mm/4.5t/1.0bar; ■, 600mm/4.5t/1.4bar; ⚹, 500-85mm/4.5t/1.4bar; Δ, 500-70mm/4.5t/2.3bar; and □, least significant difference at 95% confidence level

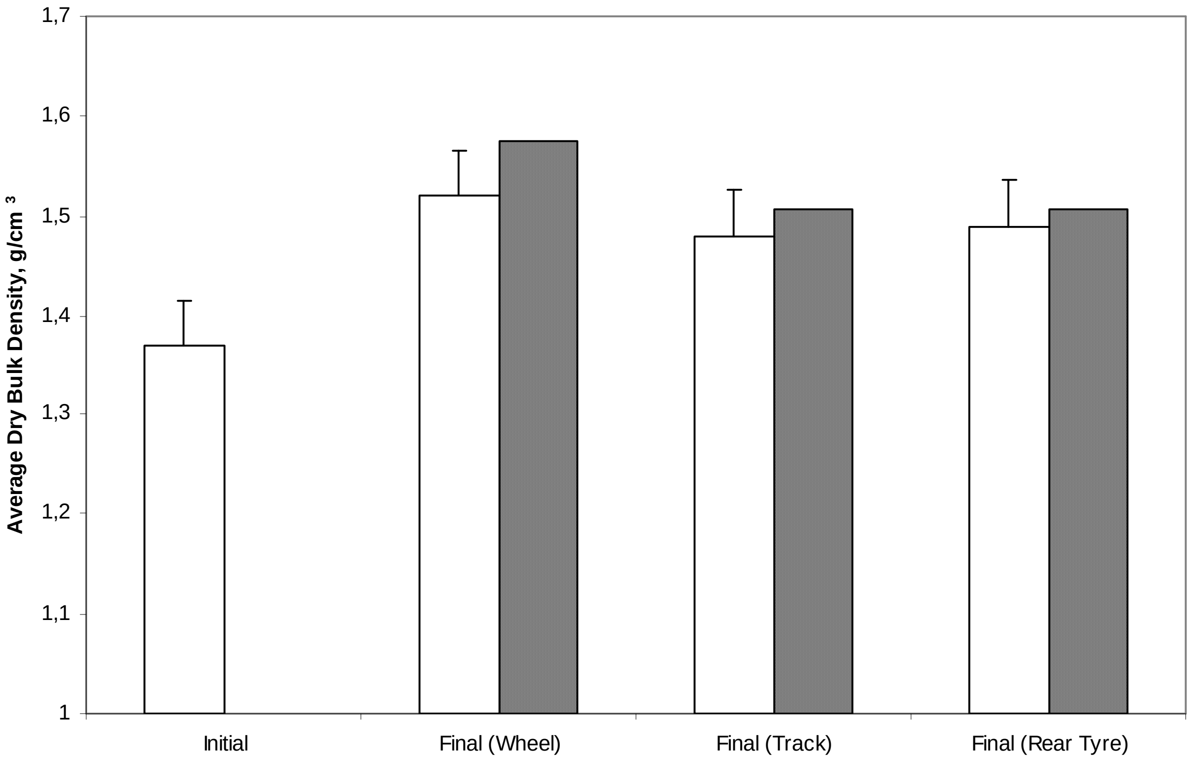

Fig. 13. Overall dry bulk density initially and finally measured (white bars) and calculated from soil displacement (shaded bars) for wheels and for tracks including least significant difference bar at 95%-probability

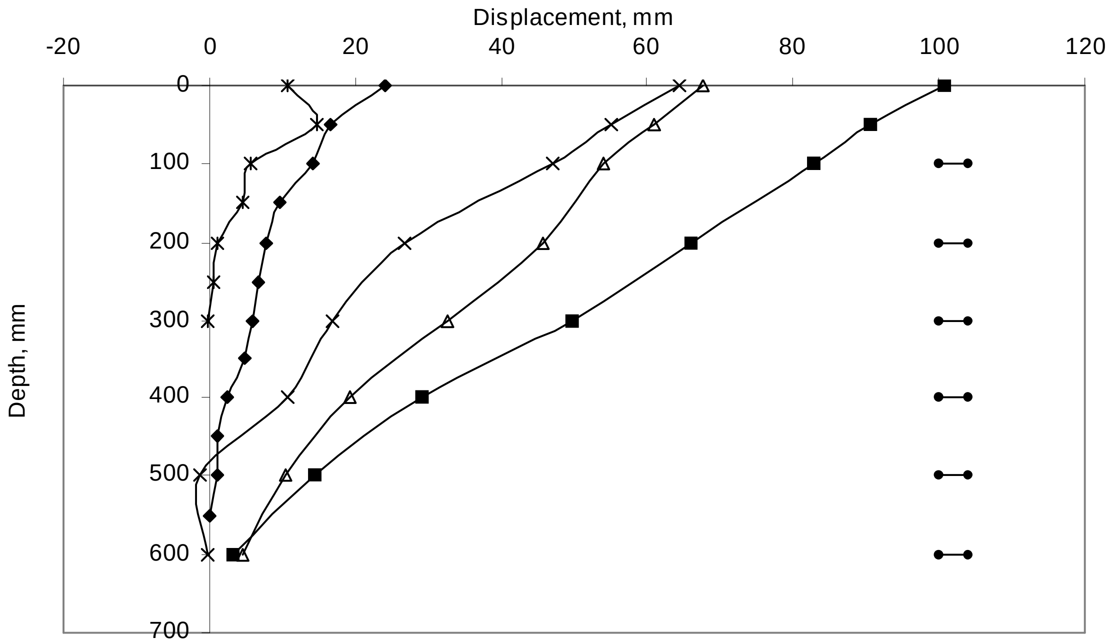

Fig. 14. Soil displacement over depth for stratified soil conditions and uniform conditions as reference: ∗, T12t stratified; ♦, 900mm/10.5t/1.9bar stratified; ×, T12t; Δ, 800mm/10.5t/1.25bar; ■, 800mm/10.5t/2.5bar; +, 900mm/10.5t/1.9bar; •, least significant difference at 95% confidence level

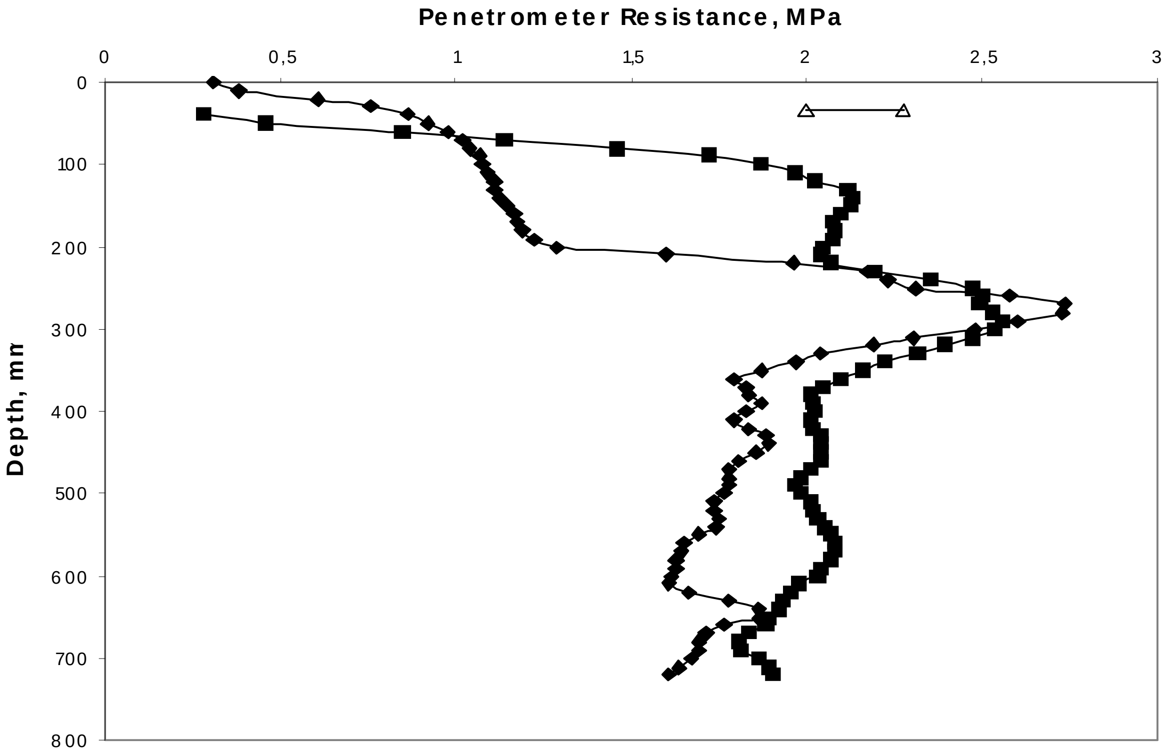

Fig. 15 a. Stratified soil conditions for the 900mm/10.5t/1.9bar: initial, ♦, and final, ■, including a least significant difference, Δ, at 95% confidence level

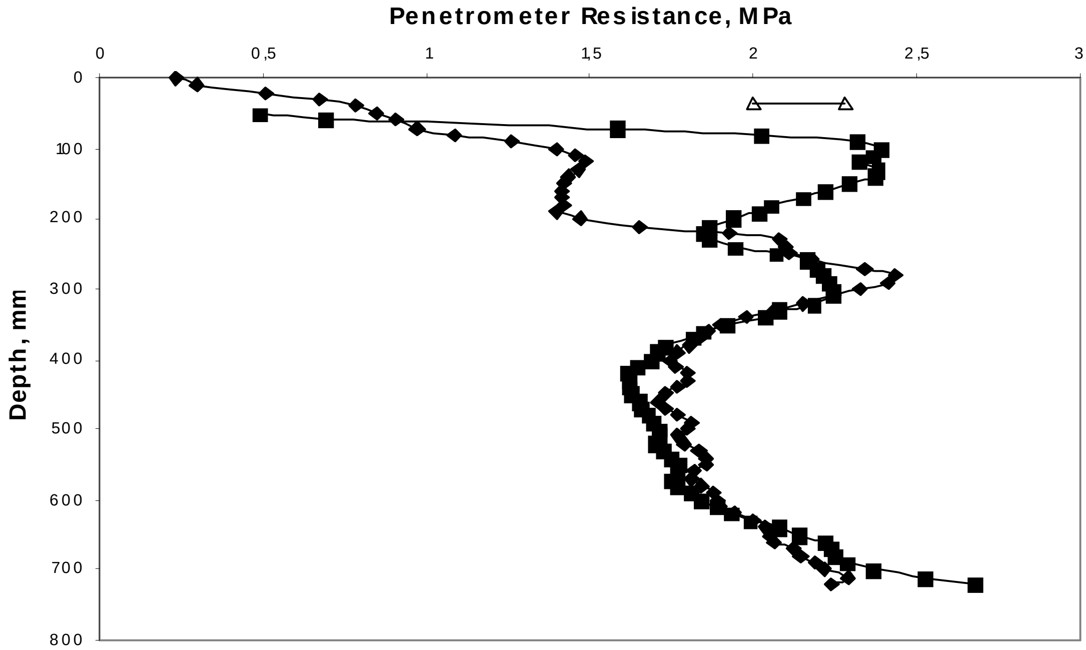

Fig. 15 b. Stratified soil conditions for the T12t: initial, ♦, and final, ■, including a least significant difference, Δ, at 95% confidence level