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The effects of tyre systems on the depth and severity of compaction

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The effects of tyre systems on the depth and severity of compaction (2006)

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Abstract

High value crops such as peas for the frozen vegetable market have to be harvested at the optimum point for quality, regardless of field conditions. Six wheeled pea harvesters with a gross weight of 27 t, giving a wheel load of 4.5 t are required to move from field to field with optimum timeliness. In order to achieve road speeds of 25 km/h an inflation pressure of 2.2 bar is required for the specific tyre load speed rating. Typically, in field conditions, this inflation pressure is not reduced and therefore the likelihood of soil damage is increased.

This study was undertaken to examine the effects of tyre section width and inflation pressure on rolling resistance, rut depth and sub-surface soil deformation. Under controlled laboratory conditions three tyres, at three inflation pressures, with a load of 4.5 t were passed over a soil at three different initial bulk densities. Measurements of dry bulk density, rut depth, rolling resistance, cone penetrometer resistance and soil deformation through the profile were taken before and after the passage of the tyres.

The results show that by increasing the tyre size and reducing the inflation pressure the depth at which compaction occurs and rut depth decrease by 44%. The 800 mm section tyre causes less compaction than any of the other tyres tested especially when inflated to 1.6 bar. Rolling resistance is reduced when the tyre is inflated to the optimum for each tyre.

The change in bulk density when plotted against either initial bulk density or penetration resistance results in a set of curves which can be used by the manufacturer, farmer or operator to select the correct tyre section width and inflation pressure for field conditions.

As a result of this study the harvester manufacturers are investigating the engineering requirements of increasing tyre section width to 800 mm and are now equipping pea harvesters with central tyre inflation systems. The benefits of which would be to significantly reduce the amount of soil compaction, reduce rolling resistance and save the operator £455 000 per annum in fuel costs.

Acknowledgements

I would like to acknowledge the support of Unilever Frozen Foods and Ice Cream, without their financial support this study would not have been possible; Trelleborg Wheel Systems (UK) Ltd. for the loan of tyres for the experimentation and PMC Harvesters Ltd. also for their financial support.

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1 Introduction

1.1 Background

Since the advent of mechanisation in farming soil compaction has been a problem to a greater or lesser extent. Post Second World War this was first seriously acknowledged in the United Kingdom following a wet harvest in 1968 by the Agricultural Advisory Council report (1970) "Modern Farming and the Soil". More recently as the size of the machinery has increased and its weight has increased so compaction has become a bigger problem. The main cause of compaction is the prime movers, the wheeled and tracked power sources, and harvesting machinery. These have the greatest weight and have the most potential to cause damage because all of their weight is transferred to the soil on tyres which, in comparison to the machine, have a small contact area.

It has been shown through yield data that field compaction causes a loss in yield, especially on the headlands but the impact that compaction has on a field grown crop has until recently not been quantified. Studies carried out in the United States by Erbach et al (1988) demonstrated that in heavy clay soils there can be a decrease in emergence rate of up to 10% in trafficked soil when compared with non trafficked soil. The effect such trafficking has is dependant on the field conditions, the previous field history in terms of operations, the weight of the machine travelling over the soil and its tyre size and inflation pressure. The depth of compaction caused by heavy axle load (greater than 10 Mg) has been recorded to a depth of 1 m (Håkansson and Reeder, 1994) where the clay content of the soil has been high and typically to a depth of 0.5 m with axle loads of 10 Mg.

The research undertaken for this report was influenced by the need to quantify what happens when pea harvesters with a total load of 27 tonnes pass over the soil. Typically these six wheeled machines have an axle load of 9 tonnes when fully laden and need to be operated in the field when the crop is ready to be harvested, readiness of the crop being determined in field by sweetness and hardness tests. Timeliness of harvest is imperative to ensure that the crop reaches the processing factory within 150 minutes of picking to retain optimum quality. This was highlighted by Chamen et al (2000) and

Alakukku et al (2003) who identified the critical operations that were likely to cause compaction to the subsoil because of the soil moisture content.

In the UK with its unpredictable weather the crop may be ready to harvest when the soil has a high moisture saturation after heavy rain or after a prolonged dry spell and the soil is very hard. The crop is typically grown in the eastern regions of the UK on a range of soils which are susceptible to these weather variations and thus are susceptible to compaction.

The need to harvest the crop when it is at its optimum can lead to the harvesters being used in unsuitable conditions. This could lead to residual compaction at depth which the land owner then has to remediate. The cost of this remediation is expensive in terms of fuel used to loosen the soil at depth and the time taken to carry the operation out, typically £48.50 ha^{-1} if a contractor is used and £38 ha^{-1} if carried out by the farmer (Nix, 2005). It is often impractical and not possible to remove the compaction caused at depths greater than 500 mm which leads to long term subsoil compaction and reduced future yields.

1.2 Aim and Objectives

The aim of this research was to reduce the effect of tyre systems on compaction and rut depth.

To allow this to be carried out the following objectives were set:

1. To determine the effect of tyre size and inflation pressure at a given load on rolling resistance, rut depth, and sub-surface compaction deformation and compaction for selected tyre systems.
2. To develop a protocol to enable the relative effects of tyre section width and inflation pressure on soil compaction (percentage change in bulk density) to be determined for a range of soil conditions.

To achieve this the methodology outlined below was used.

1.3 Outline Methodology

This section gives an overview of what measurements were taken and the conditions under which the experiments were performed. The methods used in the research are detailed in Section 3.

A 20 m long by 1 m deep by 1.8 m wide Soil Bin Laboratory as described by Alexandrou and Earl (1998) was used to produce a soil condition that can be consistently replicated. Three different soil bulk densities (1.57 t m^{-3}, 1.35 t m^{-3} and 1.25 t m^{-3}) were used to test three tyre section widths; 800 mm and 700 mm at three operating pressures, 0.9 bar, 1.6 bar and 2.3 bar, and a 500 mm section width tyre at 1.6 bar, 2.3 bar and 2.9 bar. Before each test was carried out a section profile of the undisturbed soil was examined and recorded in addition to measurements for dry bulk density and penetration resistance. The tyre was then loaded to 4.5 t and towed over the soil and rolling resistance recorded. After each test bulk density samples, penetration resistances, rut depth and disturbed soil section profiles, to determine soil deformation, were taken.

2 Literature Review

For a long time the effects of soil compaction have been acknowledged, (Gameda et al, 1994; Alakukku and Elonen, 1994; van den Akker et al, 1994) the reduction in crop yield and the cost of remediation being the most costly to farmers. In recent years there have been many papers produced that attempt to quantify the impact that soil compaction has on crop yield and to model the effect of soil compaction.

Work carried out by Söhne (1958) based on the initial theories identified by Boussinesq (1885) shows that an increase in the moisture content of a soil and the increase in payload on a tyre both increase the depth and severity of soil compaction. Söhne demonstrated that with a soil of 3.4% moisture content compacting it to 42% porosity required a surface pressure of 19 bar (285 psi). When the moisture content was increased to 14% the pressure at the surface required to achieve the same porosity was 3.25 bar (48 psi) and when the soil was in a 'wet' condition it required only 0.35 bar (5.6 psi). Söhne compared his results with a formula used in civil engineering for soil compaction and showed that there is a logarithmic relationship between porosity of the soil and pressure applied to the soil. Söhne concluded from the study that the soil compaction under a moving wheel was the same as that induced from a static compaction or kneading compaction that he used in his experimentation. Söhne also concluded that the amount of compaction occurring in different layers of the soil was dependent on different factors. Compaction in the top layers of the soil is dependent on the pressure in the tyre and the contact area but deeper in the soil profile the compaction is dependent on the load applied. The experimental equipment that Söhne used was designed to mimic the action of a tyre in the field. However, the soil sample was contained in a sleeve and this in effect constrained the soil movement sideways away from the applied pressure. The soil was also uniformly homogenised and not representative of a well structured field soil. The conclusion that agricultural machinery should be made lighter to lower the amount of compaction at depth in the soil profile is unrealistic, the increase in the size of the tyre to accommodate for the load increase, therefore increasing contact patch and reducing applied contact pressure is a more realistic option. Work conducted by Smith and Dickson (1990) indicates that this early work by Söhne was correct. They conducted a study using combinations of axle load and inflation pressure on two tyres. They concluded that the higher the axle load the greater the amount of compaction at depth with less effect on soil nearer the surface.

It was thought that with the development of agricultural practices and the increasing use of larger and therefore heavier machinery the use of dual tyres would be able to relieve some of the problems of soil compaction. Work conducted by Blackwell and Dickson (1978) showed that using a dual tyre system resulted in a greater area of compaction but its depth and severity was reduced. This system of load bearing would appear to be beneficial as the cost of remedial work to remove the effects of deep compaction can be costly in terms of time and fuel. The use of dual tyres as opposed to single tyres fitted to a standard agricultural tractor was investigated further by Makin (1989). The soil conditions Makin investigated were a shallow cultivation depth (100 mm to 120 mm) over compacted subsoil. Makin considered the difference in cone index to measure the effects of soil compaction and from his results he concluded that a single tyre produced less compaction than dual tyres when the volume of compacted soil was considered. The increase in weight applied to the tractor had little effect on the amount of resulting compaction from either the single or dual wheels. The results suggested that there is no advantage in using dual tyres; however the depth of the compaction through the profile was not reported. The results were taken one day later than the operation took place, this could have allowed a consolidation of the soil profile leading to a higher cone index. Makin relied only on the cone index results to base his findings on. Van den Akker et al (1994) concluded that the cone index was not reliable enough to give a true picture of what was occurring under the tyre when used on its own. When used in conjunction with measurements of dry bulk density and soil deformation a better indication of what happens under the tyre is more accurately determined.

The use of a dual tyre system could be considered to have some benefits but as has been shown, although it reduces the amount of deep compaction it also increases the amount of surface and sub-surface compaction. Raper (2005) cited work by Taylor et al (1986) which highlighted the fact that dual wheels, although reducing compaction under one wheel by increasing the contact area increase compaction from zero to above zero under the second tyre. This is supported by Keller and Arvidson (2004). They investigated the use of dual tyres by using load cells in the soil at three depths. Keller and Arvidson showed that soil stress is a function of surface stress and contact pressure. These are influenced by tyre size, inflation pressure, wheel arrangement, load and soil conditions. Their results showed that the inflation pressure has a significant effect on soil stress in the top soil and upper levels of the subsoil. The lower the inflation pressure the lower the soil stresses in these horizons.

The use of wider tyres having a larger contact patch and thus a greater ability to spread the load applied was investigated by Dickson (1994). The study used a combine harvester fitted with standard tyres (18.4/15-26 front at 180 kPa inflation pressure and 10.5/65-16 rear at 220 kPa inflation pressure). A set of alternative tyres (23.1/18-26 front at 140 kPa inflation pressure and 12.0/75-18 rear at 190 kPa inflation pressure) were used in the Scottish Centre of Agricultural Engineering model developed by Smith (1985), to compare with the predicted increase in bulk density. The results showed that there was a significant increase in dry bulk density measured with a gamma ray probe under the harvester tyres compared with the un-trafficked soil. The measurements were taken to a depth of 390 mm and showed a significant increase in dry bulk density between 180 and 240 mm only. This was attributed to the undisturbed subsoil below the cultivated layer not deforming under the tyre. When compared with the model the results were similar below a depth of 210 mm but the model considerably over estimated above this. From this work Dickson concluded that the only way to reduce soil compaction was to decrease the gross weight of combine harvesters. There is no data for the compaction caused by field operations prior to sowing. Even though there was no traffic after sowing, measurements could have been taken on previously wheeled soil and compared with previously un-wheeled results. The use of larger section tyres to support more axle load without an increase in soil compaction was investigated by Danfors (1994). By observing the porosity of the soil to a depth of between 300 mm and 400 mm he found that there was no difference between tyres tested. Danfors concluded that there was no reason to increase the previously recommended maximum axle loadings of 6 Mg for a single axle and 8 to 10 Mg for a tandem axle. Danfors also concluded that the amount of compaction was decreased if lower than standard inflation pressures were used.

The use of available pore space as a method for determining soil compaction was investigated by Richard et al (1999). Their study, over a period of five years, used pore space in conjunction with morphological analysis. They were able to show that as soil moisture increased the depth and severity of compaction increased. The morphological change observed could, they state, be described as a half ellipse. This is in line with the formation of pressure curves as described by Söhne (1958).

Van den Akker et al (1994) during tests on two tyres (SR 20.0/70 and SR 16.0/70) fitted to an agricultural trailer at two operating pressures (80 kPa and 240 kPa) found that penetration resistance (cone index) was not a good indication of increased compaction on its own, they also used a cross section of the wheel rut and measured the relative displacement of the soil. When their tyres were run at low inflation pressures the effect of carcass stiffness seemed to be important, they were able to show this with the increase in penetration resistance. They showed that the compaction below the larger tyre was significantly (one half to one third) lower than that caused by the smaller tyre. They concluded that there was an advantage to using tyres of a wider section and at lower operating pressures to reduce soil compaction. It would be valuable to investigate what happens when significantly wider tyres are operated at the same pressures; the maximum tyre width used by van den Akker et al in this experiment was 500 mm.

This work was taken a stage further by Çarmen (2002) who showed that in a clay loam soil with an increase of 10% in soil / tyre contact area a corresponding decrease in soil compaction was recorded throughout the soil profile. Çarmen also showed that reducing the tyre lug height and increasing the lug area gave less compaction at the soil surface. The height of the tyre lugs was reduced by cutting them down. This, however, may not have given a realistic lug area when compared with ‘normal’ lug wear under operating conditions.

Wood and Wells (1985) used a sectionalised Soil Bin to be able to study the movement of soil under tyre loadings and measuring the change in volumetric strain. They used a silt-loam topsoil and laid lines of marble dust at pre determined layers during the construction of the soil profile. They were able to split their Soil Bin in sections and look at the resulting deformation after the tyre had passed. The density of the soil was assessed by using a gamma ray probe. The volumetric soil strain was calculated for each soil condition by measuring the area between four points on a vertical grid, assuming a unit depth into the profile, before and after trafficking. There was no significant difference between the measured and the calculated strains.

The axle load applied to a tyre has been found to be the dominant factor in affecting pressure in the soil profile, the higher the load the greater the effect (Taylor and Burt, 1987). In their research they state that if a traffic pan was present the pressures below the compacted layer were lower and the pressures above the compacted layer were higher than in a soil with uniform density prior to trafficking. They concluded that there was no significant difference between the two tyres they tested, one a standard width tyre (24.5-32: 10 ply) and one of a size similar to a flotation tyre (67 x 34.00-30 12 ply). Taylor and Burt used pressure cells installed in the soil profile to measure the stresses caused by the passage of the tyre after tillage of the soil had been carried out. The tests were undertaken in two soil types, sandy loam and clay loam. The re-compaction of the clay soil may have been significantly more difficult than the sandy loam soil because of the nature of clay soils. The size of the clay particles might have led to over compaction of the replaced soil and thus the soil above the cells may have been of a different density to the rest of the soil and could have had an influence on the results.

Çarmen (1994) looked at the effect of tyre load and forward speed on soil compaction. He measured compaction using a cone penetrometer giving a cone index and bulk density. From his studies he concluded that the tyre carrying the highest load and operating at the slowest speed produced the greatest compaction. Çarmen also concluded that the load on a tyre had more effect on tyre sinkage, bulk density and cone index than forward speed. His results showed that the cone index increased more in the 0 – 100 mm depth range than below 100 mm. These experiments were carried out in the field and no account for in field variation of soil conditions was made. The soil was tilled to a depth of 150 mm before the experiments were undertaken but it is not noted in the paper where the experiments were carried out, i.e., in the wheeled or un-wheeled soil. Soil bulk density was measured before and after the tyre passage but only to a depth of 100 mm. Although the cone index was recorded there was nothing to relate these measurements to. As has been noted before the use of cone index alone could be considered misleading.

The long term effects of a compaction event have been studied by Gameda et al (1994) and Alakukku and Elonen (1994). Both studies were carried out over a six year period and reported a yield loss in the first three years. Gameda et al also found that the yield reduction carried on into year six whereas Alakukku and Elonen found there was only a difference in year six. They attributed this loss to the growing season being wet. Gameda et al found that the soil density throughout the study period increased as well as the crop yield. They attributed this to the freeze/thaw effect re-establishing macro pores and thus allowing the roots to grow down through the compacted soil. Freezing of a saturated soil allows the water contained in the soil to expand as it freezes and thus when thawing occurs the pore structure is opened out. Despite the increasing crop yield both studies recommended that the use of highly loaded axles should be avoided. Contrary to these findings Schäfer-Landefeld et al (2004) found no evidence of subsoil compaction under a 20 Mg load, even in wet conditions, where a plough pan existed. They did report that on their trials site where subsoiling had taken place the risk of re-compaction was greatly increased if the in-field trafficking was not reduced.

2.1 Soil compaction models

The modelling of soil behaviour under wheeled or tracked loads has become a useful tool in the prediction of soil compaction. Many models have been developed using a number of different computer based packages. These are outlined below.

Most of the modelling solutions use the computer programming language Fortran as the basis for their models. Blackwell and Soane (1981) found from their work on a simple model to predict soil compaction that the decrease in load on a tyre was the most important factor affecting soil compaction. It had a greater influence than the contact pressure. They concluded that an increase in contact area could not significantly decrease the amount of compaction in the soil particularly below the cultivated depth. The model was effective only for a sandy loam soil which needed to have a dry bulk density of greater than 1.1 t m^{-3} to give a close prediction of the final measured dry bulk density. The model therefore has limited use as the soils that are liable to be damaged most by traffic tend to have lower dry bulk densities. Smith (1985) used a high level language, FORTRAN 77, to develop the Blackwell and Soane model to predict the change in dry bulk density of the soil, this model is also able to model what happens under multiple passes. During testing the model was found not to be accurate in predicting the change in dry bulk density but it was able to give an indication of the differences between the effects of applied load, tyre types and wheel arrangements. The model was found to under predict the soil compaction in a layered soil as the equation used was for uniform soil, it also failed to predict the depth of wheel rut accurately.

The SOCOMO model developed by Van den Akker (2004) is based on the theory by Boussinesq (1885). With modifications to these equations the model predicted soil stress well when compared with results from field experiments carried out in a sandy soil. Van den Akker reported that the plastic deformation in the model fitted well with that experienced in the field, he also stated that the model was still being modified to give a better stress – compaction relationship.

A model developed by Jakobsen and Dexter (1989) highlighted many factors that influence soil compaction under tyres. Firstly, the formation of a wheel rut increases the soil contact area and therefore decreases the contact pressure resulting in a lesser increase in bulk density. If there is more than one pass of the wheel then this effect becomes less and the inflation pressure plays a more influential role. Secondly the critical state conditions depend on wheel slip and horizontal soil displacement. Their model may have been inaccurate by overestimating the amount of soil compaction at shallow depths in consolidated soils. The model results were compared with results obtained in previous experiments by the author and from Gupta et al (1985). The model over predicted the depth of wheel rut and the maximum bulk density, this would lead the user of the model to think that more damage to the soil was occurring than in reality. Gassman et al (1989) developed a model using a finite element modelling computer programme. They found that the model was accurate to within 2.5% below a depth of 150 mm but underestimated above this. They found that for layered soils the depth of compaction was not significantly different for all wheels tested but in a uniform soil the strain was more evenly distributed and went deeper into the profile than the layered soil.

O'Sullivan et al (1999) produced a model to run in excel for use by consultants and students. The model uses excel to input the data of contact area, tyre pressure and soil conditions and uses an embedded Visual Basic macro to analyse the inputted data and produces results for bulk density after the tyre has passed in tabular and graphic format. The graph plots the change in density against depth through the profile. The results obtained from the model were compared with physical results from the field. It was found that the model over estimated the amount of compaction in the soil under a low inflation pressure tyre carrying a low load but was more accurate when a heavier load and higher inflation pressure were used. The model is only good at giving accurate results at the extreme of loading and is variable at low inflation pressures. In today's agricultural systems where the trend is to go for wider tyres than those tested and at lower operating pressures the model will indicate what not to do but is unlikely to be able to determine the best possible solution.

3 Methodology

The effects of tyre size, inflation pressure and load were investigated to determine their effect on rut depth, compaction and the depth at which compaction occurs in the soil profile. The study was carried out using three tyres of different section widths and three different operating pressures under a load of 4.5 tonnes (t). The load of 4.5 t was decided upon as the tyres under investigation are typically fitted to a pea harvester with a total weight of 27 t. The investigations were based on pea harvesters that have a six wheel configuration giving a gross weight on each wheel of 4.5 t.

Figure 1 Pea harvester in operation

To reduce the effect of soil variability in the field this study was undertaken in the controlled environment of the Soil Bin Laboratory, Cranfield University at Silsoe where simulated soil conditions can be replicated to within 5% with respect to dry bulk density.

3.1 Soil Bin Laboratory and soil conditions

A sandy loam soil (66% sand, 17% silt, 17% clay) in the Soil Bin, a 1.5 m wide, 1.0 m deep and 20 m long concrete lined hole in the ground was initially prepared to a dry bulk density of 1.57 t m^{-3}. The Soil Bin was prepared by moving the soil to one end and replacing it in uniform layers compacted with six passes of a 750 kg roller. This is achievable because the soil processing unit runs on fixed rails enabling it to prepare homogeneous soil conditions to the full depth of the Soil Bin, each layer being of a consistent 50 mm depth. Wetting the soil before the next layer was applied changed the soil cohesion forming a distinctive 'wet' layer visible when a section through the profile was taken (Figure 2). This soil condition was used as the first bearing capacity, the other two soil bearing capacities on which the tyres were tested were obtained by altering the soil bulk density. These were achieved by using one pass of the roller which gave a dry bulk density of 1.35 t m^{-3} and a 'poured' soil with a dry bulk density of 1.25 t m^{-3}. Although these soil conditions do not relate directly to infield conditions they give an indication of what might happen in different soil moisture conditions in the field.

Figure 2 Soil profile showing visible wet layers used to determine soil deformation in medium and high density soil conditions

3.1.1 Profile measurement using wet layers

A section of soil was exposed to reveal the wet layers which were highlighted by carefully removing the soil between them using a stiff brush and palette knife. The surface and identified 'wet' layers were photographed and measurements were taken at the centre point and at five points either side of the centre, at 100 mm spacing. The recorded measurements were then entered into a spreadsheet and a plot of the soil profile produced.

3.1.2 Profile measurement using sand layers

The use of the ‘wet’ layer technique in the poured soil was not possible as the surface of each layer needs to be lightly compacted to prevent the water moving too far into the soil profile. Therefore thin layers of sand at 100 mm depth intervals were used to give an indication of before and after soil deformation (Figure 3). The sand was placed in three distinctive blocks along the Soil Bin each 300 mm long.

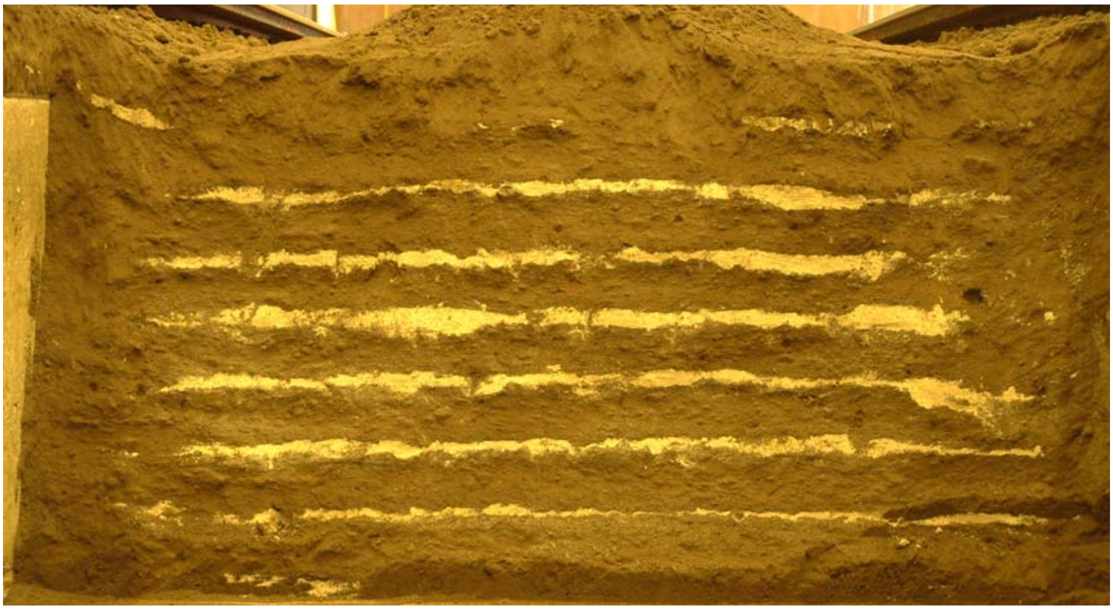


Figure 3 Soil profile showing visible sand layers used to determine soil deformation in the poured soil

This was done to prevent excess sand being added to the soil thus changing its characteristics. The inter layer spacing of 100 mm was adopted as it was anticipated that the penetration of the tyre through the low bearing capacity poured soil would be greater than the other two soil conditions. Measurement of the sand layers was carried out as described in Section 3.1.1.

3.1.3 Recording of soil bulk density

A sample of the soil was taken at three points; the surface, 250 mm and 500 mm depth using a density ring with a known volume; this was replicated three times at each point. Bulk density measurements were taken to identify any change in soil bulk density caused by the passage of the wheel. The soil samples were weighed and placed in an oven to dry for 48 hours at a temperature of 105°C. The samples were then reweighed and the dry bulk density calculated using the following formula.

$$\frac{w}{v} = dbd$$

where: w = weight of dry soil (g)

v = volume of density ring (cm^3)

dbd = dry bulk density ($g\ cm^{-3}$)

3.1.4 Soil moisture content

The samples taken for bulk density measurement were also used to determine the soil moisture content to ensure homogeneity throughout the experimental procedure. The soil was weighed before being placed in an oven at 105ºC for 48 hours. The soil was then weighed again and the soil moisture content calculated using the following formula

$$\left[\frac{wet - dry}{dry}\right] * 100 = mc$$

where: wet = weight of wet soil (g)

dry = weight of dry soil (g)

mc = moisture content (%)

3.1.5 Penetration resistance

Penetration resistance was measured using two different penetrometers; a Bush penetrometer which recorded through the profile at 35 mm depth intervals and an Eijkelkamp Penetrologger that recorded at 10 mm intervals through the profile. Both penetrometers were used to take measurements at ten points across the Soil Bin and three locations along the Soil Bin to a depth of 490 mm. Each of the penetrometers was fitted with 30º internal angle cone with a base area of 1.3 cm^2. Graphs of penetration resistance were then constructed.

3.1.6 Tyre selection

The tyres used for the experiments were selected around those typically fitted to a pea harvester. A pea harvester is currently fitted with a 700 mm section Trelleborg tyre on a 26.5 inch diameter rim. It was decided to use a tyre of the next largest section width, this being 800 mm. This tyre is the largest tyre that can be fitted to a pea harvester with the correct load speed rating and, with slight modifications to the harvester, would still be allowed to travel on the roads (3 m width limit for unescorted vehicles). It also has the correct load speed rating (Trelleborg Handbook) to allow it to carry 4.5 t at speeds of up to 25km h^{-1}. The smaller tyre with a 500 mm section width was one that the manufacturer previously fitted to the pea harvester (Figure 4).

Figure 4 The three tyres used during the study showing section width and tread pattern

3.1.7 Inflation pressures

The two larger tyres were each operated at three pressures, 2.2 bar (33 psi), 1.6 bar (23 psi) and 0.9 bar (13 psi). These inflation pressures were chosen because 2.2 bar is currently used as it is recommended by the tyre manufacturers for the correct load – speed rating, 0.9 bar is the lowest pressure at which both tyres are able to support the load of 4.5 t and 1.6 bar is the mid point. It was intended that all three tyres should be operated at the same pressures but after consulting the manufacturers' handbook the 500 mm section tyre was not capable of supporting the load of 4.5 t at the lower operating pressure of 0.9 bar. It was concluded that the lowest safe pressure at which the 500 mm tyre could operate was 1.6 bar. It was therefore decided to operate the 500 mm section tyre at three higher pressures, these being 1.6 bar, 2.2 bar and 2.9 bar (43 psi). The higher pressure of 2.9 bar was chosen as it represents an even increase in inflation pressure and is also capable of withstanding the 4.5 t load applied.

3.1.8 Experimental rig

The rig used during the experiment was a single wheel frame with the wheel mounted centrally and weights placed evenly either side resulting in a gross weight of 4.5 t (Figure 5). The frame was placed centrally in the Soil Bin and attached to the Soil Bin processor via an extended octagonal ring transducer (EORT) (Figure 6) as described by Godwin, 1975.

The EORT was instrumented and connected to a data logging system. The data logging system consisted of a Strainstall signal amplifier connected to a computer running DASYLab 5.6 software configured to record horizontal force.

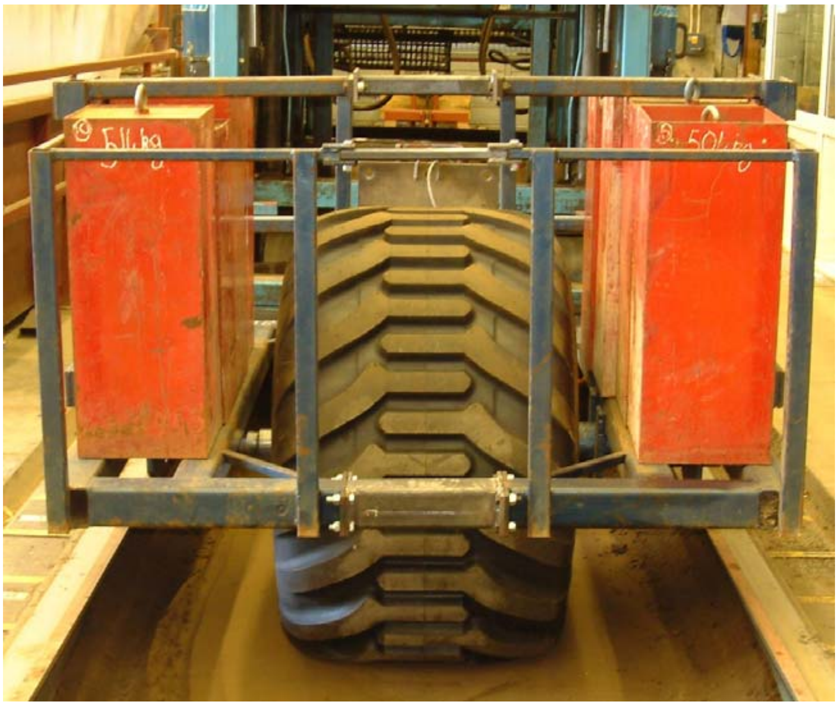


Figure 5 Experimental rig used during this study showing the applied load; with 800 mm section tyre fitted

Figure 6 The Extended Octagonal Ring Transducer used in this study to measure rolling resistance attached to the Soil Bin Processor

3.1.9 Experimental procedure

The soil was prepared to one of three known densities as described in section 3.1. Measurements of the penetration resistance were taken and a section at one end of the prepared soil was exposed. The position of the 'wet' layers was recorded and samples taken for calculating dry bulk density and moisture content. The processor was moved to one end of the Soil Bin Laboratory and a metal plate 25 mm thick was placed on the surface to prevent sinkage of the wheel and frame in to the prepared soil. The wheel and frame were attached to the processor via the EORT. The data logging system was started and weights added to give a gross wheel weight of 4.5 t (Figure 5). The system was then stopped. The resulting measurements were used to produce a calibration curve for calculating the rolling resistance. The data logging system was re-started and the processor moved along the Soil Bin pulling the wheel behind. The speed at which the processor moved was set and maintained at a typical field operating speed for a pea harvester of 1 m s^{-1}. The speed was set by timing the processor over a 10 m run and adjusted to give the desired forward speed. At the end of each section the wheel was stopped, the pressure adjusted according to the schedule (Table 1) and then continued along the next section. Three pressures were tested in each Soil Bin preparation.

Table 1 Experimental design used during this study showing Soil Bin Preparations, soil density and inflation pressure for each tyre tested

Soil Bin Preparation 1 Tyre 1 High density	Soil Bin Preparation 2 Tyre 1 Low density	Soil Bin Preparation 3 Tyre 1 Medium density	Soil Bin Preparation 4 Tyre 2 Low density	Soil Bin Preparation 5 Tyre 2 Medium density	Soil Bin Preparation 6 Tyre 2 High density	Soil Bin Preparation 7 Tyre 3 Medium density	Soil Bin Preparation 8 Tyre 3 High density	Soil Bin Preparation 9 Tyre 3 Low density
0.9 bar	2.2 bar	1.6 bar	2.2 bar	0.9 bar	1.6 bar	2.9 bar	2.2 bar	1.6 bar
2.2 bar	1.6 bar	0.9 bar	1.6 bar	2.2 bar	0.9 bar	2.2 bar	1.6 bar	2.9 bar
1.6 bar	0.9 bar	2.2 bar	0.9 bar	1.6 bar	2.2 bar	1.6 bar	2.9 bar	2.2 bar

After the completion of the run the weights, wheel and frame were removed and three sets of cone penetrometer readings taken. In addition surface profiles were obtained by using a profile meter placed centrally over the rut. The profile meter has multiple metal points that were lowered until they touched the surface of the soil. The profile meter was then removed and the resulting outline drawn onto a piece of paper and the rut cross sectional area was calculated using a planimeter.

The soil was removed to expose a section profile of the treated soil and the ‘wet layers’ or sand layers were measured. Bulk density samples were taken in each section at three depths, on the surface, 250 mm and 500 mm below the surface. This was repeated three times for each treatment.

Figure 7 Profile meter used to determine the soil deformation at the surface after each test during the study

As the bearing capacity of the poured soil was low it was decided that each of the tyres would be pulled the complete length of the Soil Bin at each pressure. A change in pressure partway along the Soil Bin would have allowed the tyre to be static on the poured soil giving it time to sink below the critical depth at which rolling stops and bulldozing occurs. This would not have allowed for realistic readings to be taken at subsequent inflation pressures as the distance allowed for each test was too short for the wheel to climb out of the rut caused by being stationary.

4 Results and discussion

4.1 Rolling resistance

The rolling resistance was calculated for each tyre at each inflation pressure at each soil dry bulk density by converting the measured voltage into force units using the calibration constant of 31.82 kN V^{-1} (see Appendix A)

Figure 8 shows a typical trace for rolling resistance versus time for the 800 mm section tyre. Three discrete sections from each trace were sampled (shown by dotted lines in the shaded area) and the mean calculated to provide figures for rolling resistance which were then used for the subsequent detailed analysis.

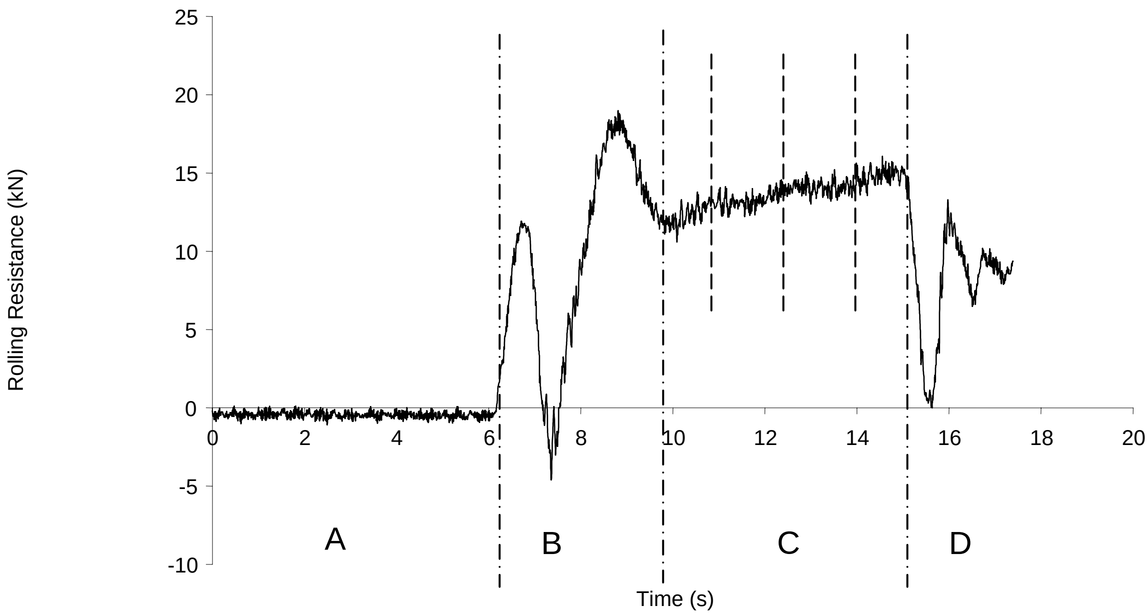
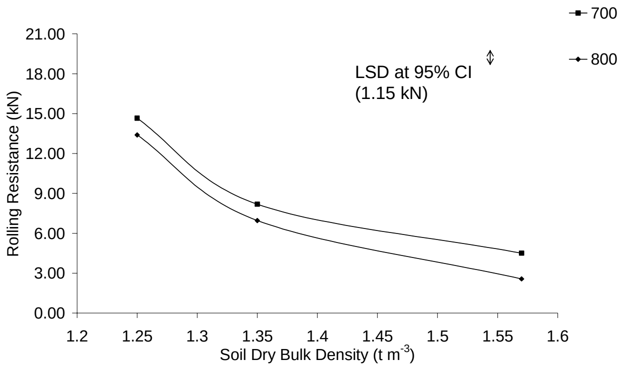


Figure 8 Plot of rolling resistance against time for 800 mm tyre at 2.2 bar inflation pressure on 1.25 t m^{-3} density soil showing four discrete phases of the processor operation (A,B,C and D)

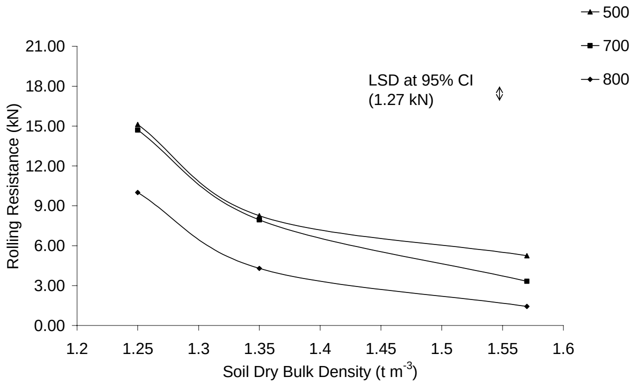
The plot in Figure 8 can be divided up into four elements. The first (A) being before the soil processor moves off, secondly (B) the forces through the EORT as the processor accelerates, the peaks are formed because the processor is driven using wire ropes which stretch as power from the engine is applied, thirdly (C) the length of the run and finally (D) forces through the EORT caused by the processor stopping abruptly. The increase in the rolling resistance shown in section (C) was caused by the tyre under load sinking into the soil as it passed over it, this led to an increase in rolling resistance because the amount of soil in front of the tyre increased along the run. All the plots of rolling resistance on the low bulk density soil show a similar trend. The plots for the other two bulk densities show a more linear trace with little or no increase in rolling resistance over the run as a result of the soil being able to withstand the applied load.

The effect of dry bulk density and inflation pressure on rolling resistance for the three tyre sizes are shown in Figures 9, 10 and 11 which express the same results in three different formats. A statistical analysis was undertaken of the original data and the least significant difference obtained to the 95% confidence interval (C I). The analysis studied the effects of dry bulk density and tyre size at each operating pressure on rolling resistance.

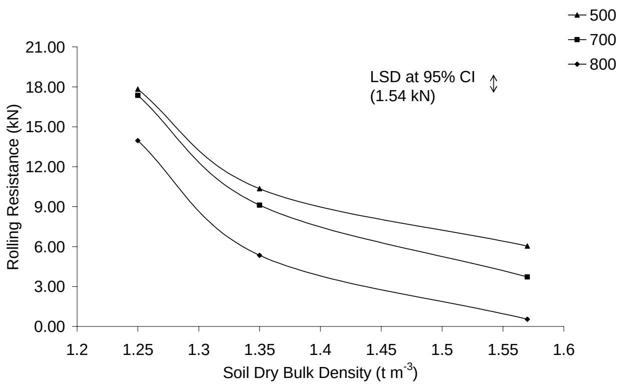
(a)



(b)



(c)



(b)

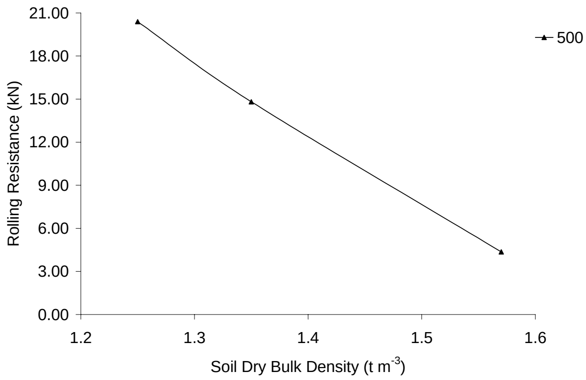


Figure 9 Effect of dry bulk density on rolling resistance for a range of tyre sizes (500 mm to 800 mm section width) at four inflation pressures 0.9 bar (a), 1.6 bar (b), 2.2 bar (c) and 2.9 bar (d)

(a)

(c)

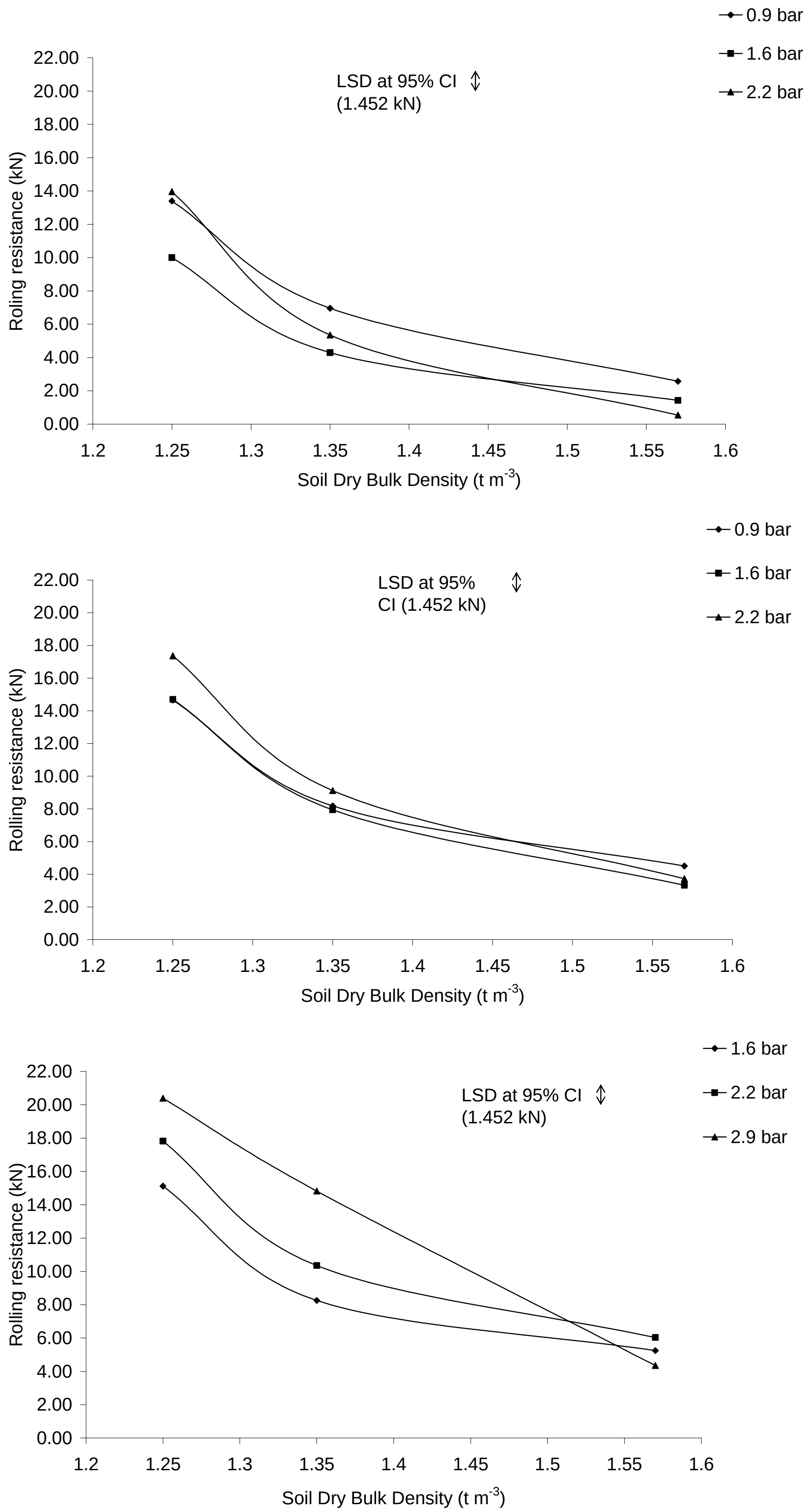


Figure 10 Effect of dry bulk density on rolling resistance for three tyre sizes 800 mm (a), 700 mm (b) and 500 mm (c)

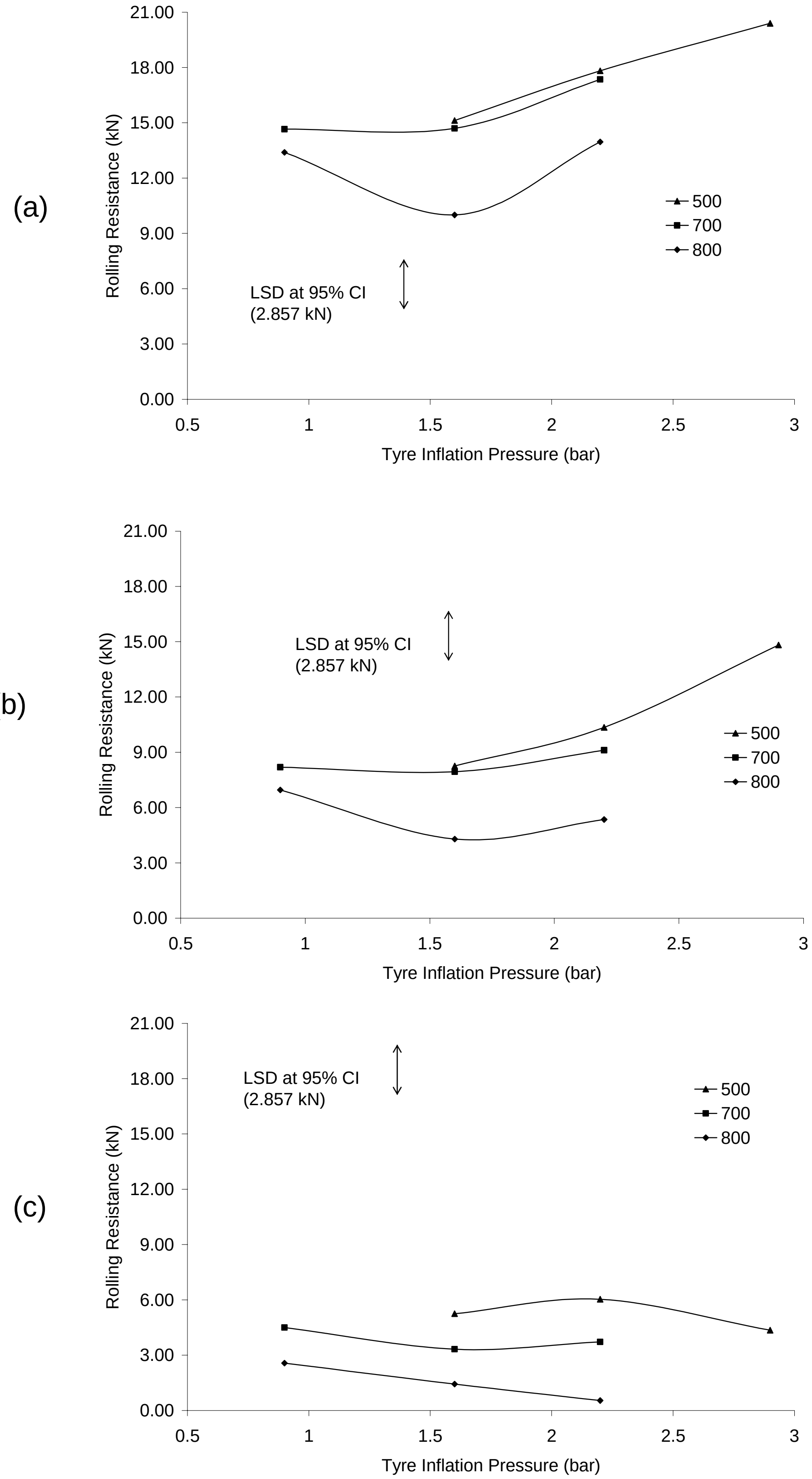


Figure 11 The effect of tyre inflation pressure on rolling resistance at three bulk densities 1.25 t m^{-3} (a), 1.35 t m^{-3} (b) and 1.57 t m^{-3} (c)

The effect of dry bulk density on rolling resistance shown in Figure 9 indicates that at 0.9 bar inflation pressure, Figure 9 (a), trends of both the 800 mm and 700 mm tyres are the similar. At 1.25 t m^{-3} dry bulk density there is a significant difference between them and this increases as the dry bulk density increases. An increase in inflation pressure to 1.6 bar, Figure 9(b), increases the difference between the 800 mm and 700 mm tyre on the low bulk density soil; as the soil density increases the rolling resistances tend to move towards each other but are still significantly different from each other. Considering the relationship between the 700 mm and 500 mm tyres, these two tyres are statistically similar on the 1.25 t m^{-3} and 1.35 t m^{-3} density soil but as the density increases so the lines diverge and on the 1.57 t m^{-3} density soil the rolling resistance is significantly different. Examining Figure 9 (c) rolling resistance for all tyres has increased on the low density soil and decreased on the hard soil this is especially true for the 800 mm section tyre. The rolling resistance for the 500 mm section tyre at 2.9 bar, Figure 9(d), is considerably greater than the others on the low bulk density soil. As expected, as the soil density increases the rolling resistance decreases. This is due to the smaller contact patch between tyre and soil. The high inflation pressure in the tyre increased the stiffness of the tyre not allowing it to deflect under the applied load; this caused the tyre to penetrate the low density soil creating more rolling resistance and on the dense soil the tyre sat on top of the soil producing a small contact patch.

The results shown in Figure 10 compare each tyre size at all inflation pressures. Considering the 800 mm section tyre (Figure 10 (a)), there is no significant difference in performance at both 1.25 t m^{-3} and 1.35 t m^{-3} soil densities when operating at either 0.9 bar or 2.2 bar inflation pressure. It can be seen that the tyre when inflated to 1.6 bar gives less rolling resistance on the two lower density soils than when it is inflated to 0.9 bar; this can be explained by examining the tyre manufacturers' literature for the 800 mm section tyre which shows that it is designed to withstand the applied load at 1.6 bar inflation pressure but not at 0.9 bar. This allowed the tyre to flex more (Figure 12) under the load and thus increase the contact area between the tyre and the low bulk density soil.

Figure 12 Tyre wall flexing of the 800 mm tyre inflated to 0.9 bar caused by the tyre operating below the manufacturers' recommended inflation pressure for the applied load

As the soil becomes denser the difference between these operating pressures increases, this is because when the soil is denser the tyre does not deform the soil and leave a rut. At low soil bulk densities rut formation becomes greater and the tyre forms a 'bow wave' which it has to overcome. The 'bow wave' was caused by the tyre operating below a critical depth at which it had the ability to climb out of the rut that it was forming. This can be seen in the rolling resistance results, as the tyre size increases and the operating pressure decreases the 'bow wave' becomes less, the tyre penetration into the soil decreases and the rolling resistance does likewise. This is also true for the 700 mm section and 500 mm section tyres. The high rolling resistance results for the 800 mm section tyre operating at 0.9 bar can be explained by considering the manufacturers' recommended inflation pressure.

Considering the other two tyres, as inflation pressure increases the general trend is for rolling resistance to increase at the lower soil dry bulk densities and to decrease at higher dry bulk densities. This is consistent with the explanation above of the 'bow wave' effect, tyre wall flexing on the two smaller tyres did not have an effect on rolling resistance as the tyre wall stiffness was greater in. The difference in rolling resistance can be explained by the change in soil – tyre contact area. As the tyre inflation pressure increases the contact area decreases so there is less soil tyre interface and hence less rolling resistance. The rolling resistance for the 700 mm tyre at 2.2 bar on the low bulk density soil is significantly different from the other treatments.

Each inflation pressure for the 500 mm tyre on both the 1.25 t m^{-3} and the 1.35 t m^{-3} soils are significantly different from each other. On the hardest soil the 2.9 bar inflation pressure is significantly different from the 2.2 bar inflation pressure.

Figure 11 (a) shows the effect of tyre inflation pressure on rolling resistance on the low bulk density soil, it can be seen that as inflation pressure increases above 1.6 bar there is an increase in rolling resistance for all tyres. There is some evidence that the increase in rolling resistance below 1.6 bar is caused by the flex in the tyre wall. This is substantiated when considering the tyre manufacturers' data which recommends the tyre be run at at least 1.6 bar for the applied load. As soil strength increases, Figure 11 (b), this trend persists. On the hard soil, Figure 11 (c), there is a significant difference between all tyres at 2.2 bar inflation pressure and between the 500 mm and 800 mm section tyres at 1.6 bar inflation pressure. There is a general trend that as inflation pressure decreases rolling resistance increases.

If the cost implications of these findings, in terms of fuel requirements, are considered and assuming the bulk density in field is 1.4 t m^{-3} for the first axle, 1.45 t m^{-3} for the second and 1.5 t m^{-3} for the final axle then the calculations shown in Table 2 can be used. The bulk densities assumed in Table 2 are based on in field measurements taken during harvesting, given that the harvester wheels are evenly loaded to 4.7 t and follow each other.

These show that by increasing the tyre section width to 800 mm and reducing the inflation pressure to 1.6 bar and comparing this with the current tyre system used a saving of £2.18 per hectare can be made. If the 800 mm section tyre is compared with the previous tyre used (500 mm at 2.2 bar) then a saving of £4.55 is made. This is a considerable saving in fuel over the whole area harvested by Unilever Frozen Foods of £455 000 at current market prices for diesel of 39.5 pence per litre.

Table 2 Costing for fuel used with increased rolling resistance using data obtained during this study

		1st tyre	2nd tyre	3rd tyre	For each side	For whole machine	Extra power required kW
Bulk density ($t\ m^{-3}$)		1.4	1.45	1.5			
Rolling Resistance (kN)	800 mm @ 1.6 bar	3.5	2.5	2	8	16	16
Rolling Resistance (kN)	700 mm @ 2.2 bar (current)	8	6	5	19	38	38
Rolling Resistance (kN)	500 mm @ 2.2 bar (previous)	13	10	8	31	62	62

Assuming 1 kN rolling resistance at a forward speed of 1 $m\ s^{-1}$ gives an increase in power required of 1 kW and fuel cost at £0.395 / litre then

Forward speed ($m\ s^{-1}$)	1
Distance covered (m)	3333.3
Time for 1 ha (s)	3333.3
Time for 1 ha (h)	0.93

Fuel used	Cost per ha
4.00 l for 16 kW	£1.58
9.51 l for 38 kW	£3.76
15.52 l for 62 kW	£6.13

These figures are based on an engine size of 275 kW using 220 g kWh^{-1}, the specific gravity of diesel as 814 g l^{-1} and a machine working width of 3 m.

4.2 Rut depth

The rut depth was measured on the centre line of the tyre track at three places along each run. Each set of three measurements was averaged and plotted into graphs shown in Figure 13 and Figure 14.

The results, when plotted show the effect of soil density on rut depth and inflation pressure (Figure 13). This shows that soil density has the greatest effect and is significant for all. The relationships for individual tyres are all similar with ruts of between 170 mm and 230 mm on the low density soil and no significant difference on the hard soil. The data show that there are differences between tyre sizes at lower bulk densities. For all tyres tested the rut depth decreased as the soil density increased.

When the results of the experiments are plotted to compare the effect of tyre inflation pressure at each soil dry bulk density (Figure 14) it can be seen that this has no significant effect on rut depth in the dense or medium soils. In the low density soil there is a significant difference between the 500 mm and 800 mm section tyres at 2.2 bar inflation pressure, these differences can be explained in as much as the rut depth reduces with an increase in tyre section width and are not due to the effects of inflation pressure. It does not demonstrate if there is any difference between each tyre at depth. This effect is described in Section 4.5.

(a)

(b)

(c)

(d)

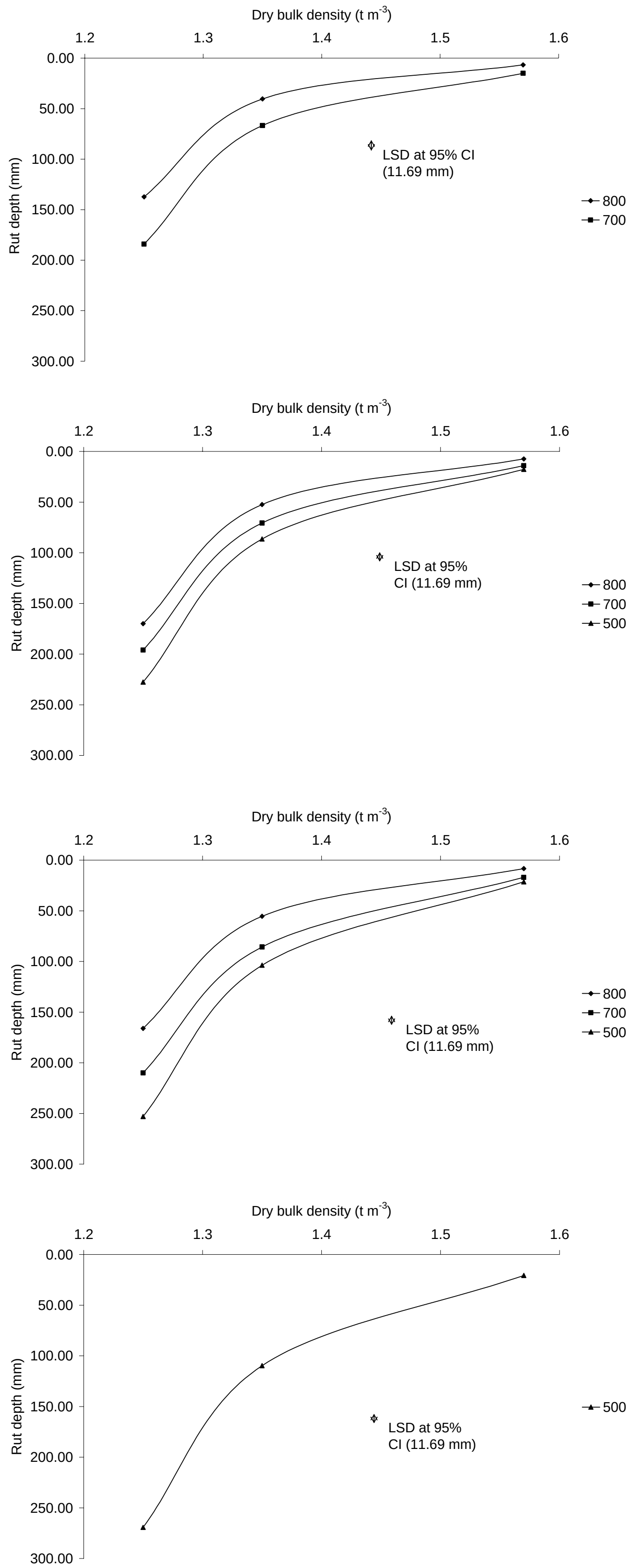


Figure 13 The influence of soil dry bulk density and tyre size on rut depth at a range of inflation pressures; 0.9 bar (a), 1.6 bar (b), 2.2 bar (c) and 2.4 bar (d); ◆ 800 mm section, ■ 700 mm section tyre and ⁂ 500 mm section tyre

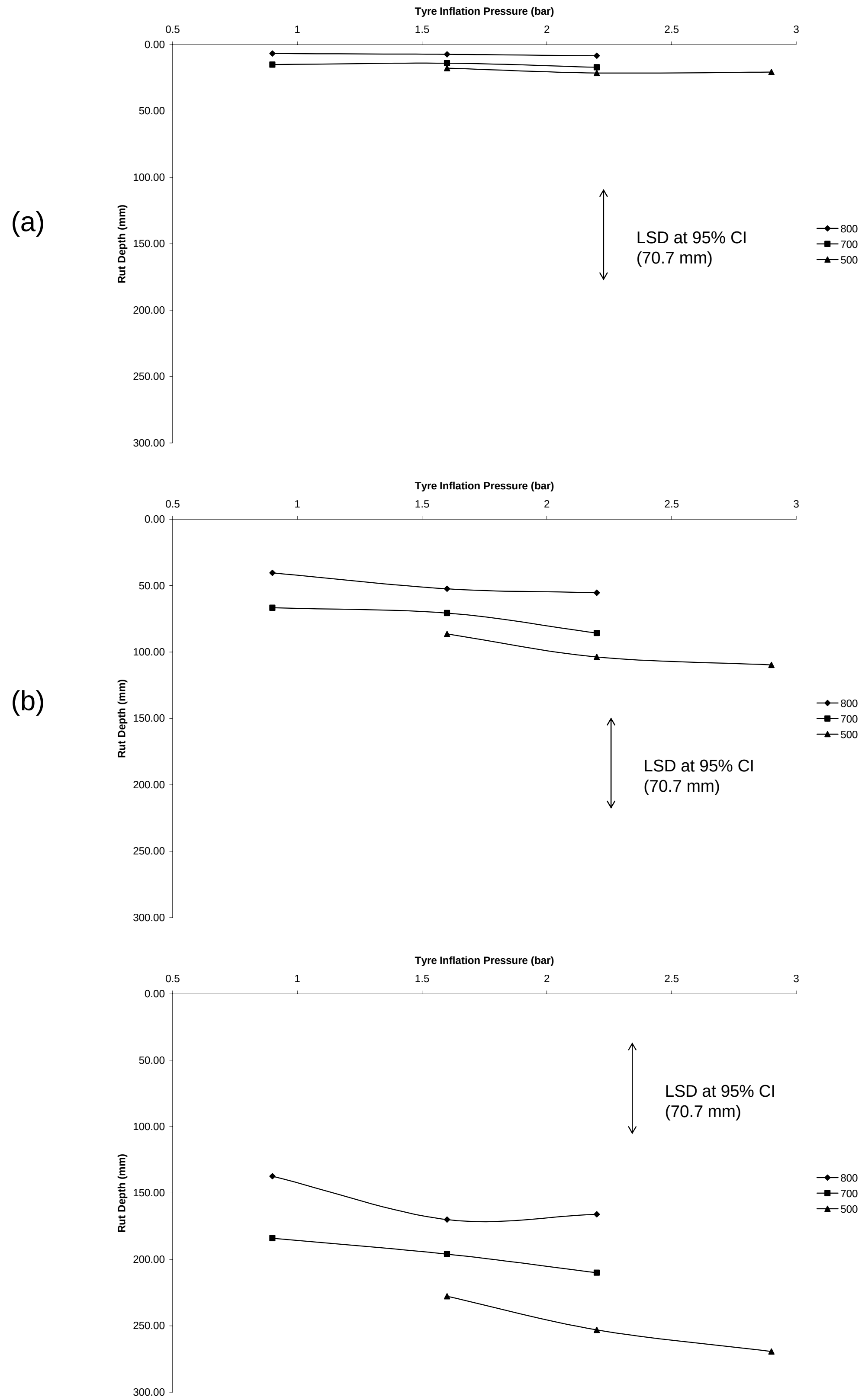


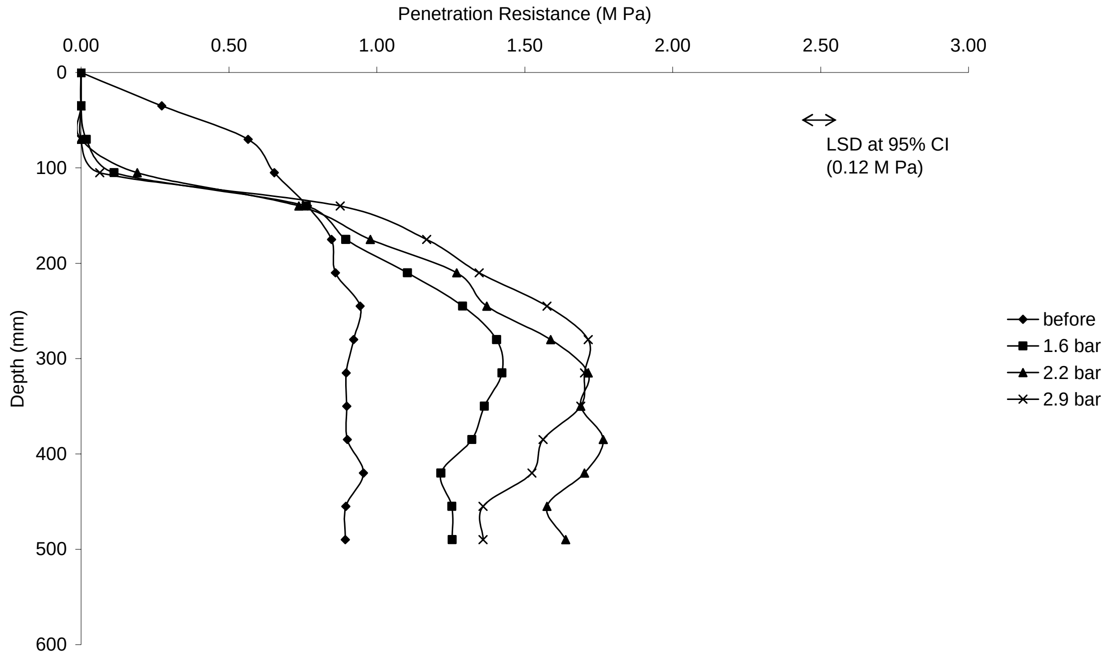
Figure 14 The effect of tyre size and inflation pressure on rut depth in a range of soil bulk densities; 1.57 t m^{-3} (a), 1.35 t m^{-3} (b) and 1.25 t m^{-3} (c); ◆ 800 mm section, ■ 700 mm section tyre and ⁂ 500 mm section tyre

4.3 Penetration resistance

The penetration resistance for each test was taken three times, both before and after the passage of the tyre, in a set of 10 recordings spaced equally about the centre line of the tyre. The results recorded were transcribed in to excel. To take account of any uneven loading on the tyre the average of pairs working on either side of the centre line were taken and an analysis of variance of the resultants for each tyre was carried out using Genstat. Graphs were plotted and are shown in full in Appendix B. The results for the centre penetration resistances are shown in Figures 15, 16 and 17.

Figure 15 shows plots for the 500 mm section tyre showing the penetration resistance for the 1.35 t m^{-3} and 1.57 t m^{-3} soils. The penetration resistance results for the soft (1.25 t m^{-3}) soil have been discounted because of irregularities in soil preparation and the use of two different penetrometers in recording the results. These differences do not affect the results for rolling resistance, rut depth, dry bulk density or soil deformation as each three replicates for each tyre and inflation pressure were taken from each Soil Bin preparation and so were able to be statistically analysed without the irregularities showing any effect.

The results for the medium density (Figure 15 upper) show that rut depth for all inflation pressures are the same and the residual penetration resistance is seen to increase with tyre inflation pressure. For the high density soil (Figure 15 lower) the effect of tyre pressure has minimal effect on rut depth and residual penetration resistance at depth. There is however some increase in penetration resistance between 50 mm and 200 mm depth.



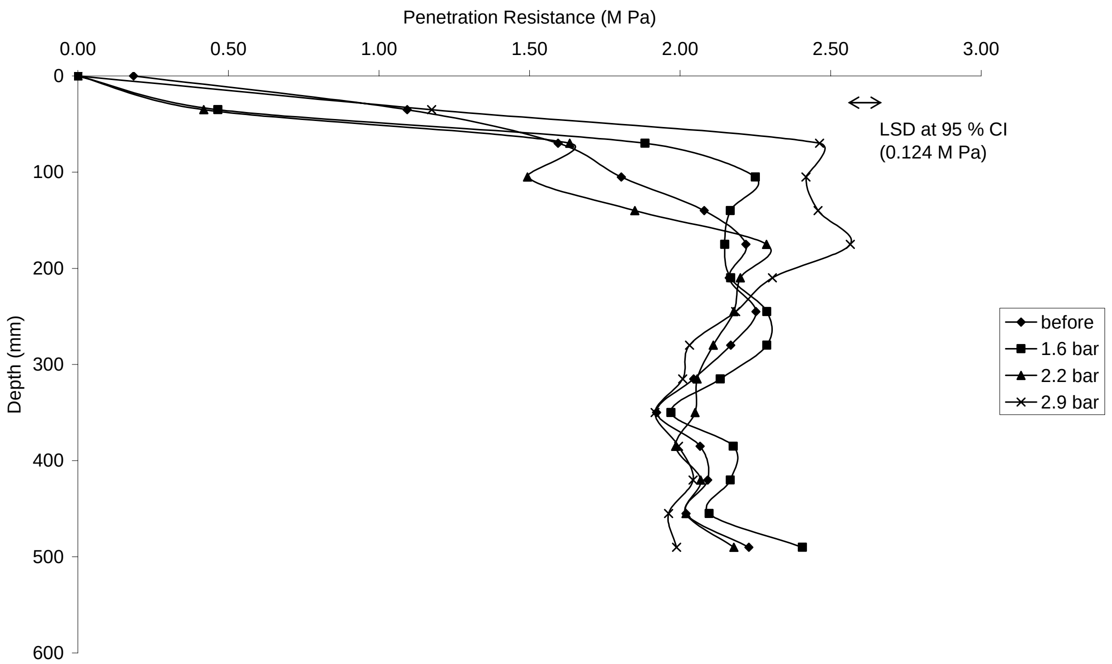


Figure 15 Change in penetration resistance for the 500 mm section tyre at 50 mm from the centreline of the tyre on 1.35 t m^{-3} (upper) and 1.57 t m^{-3} (lower) initial soil bulk densities

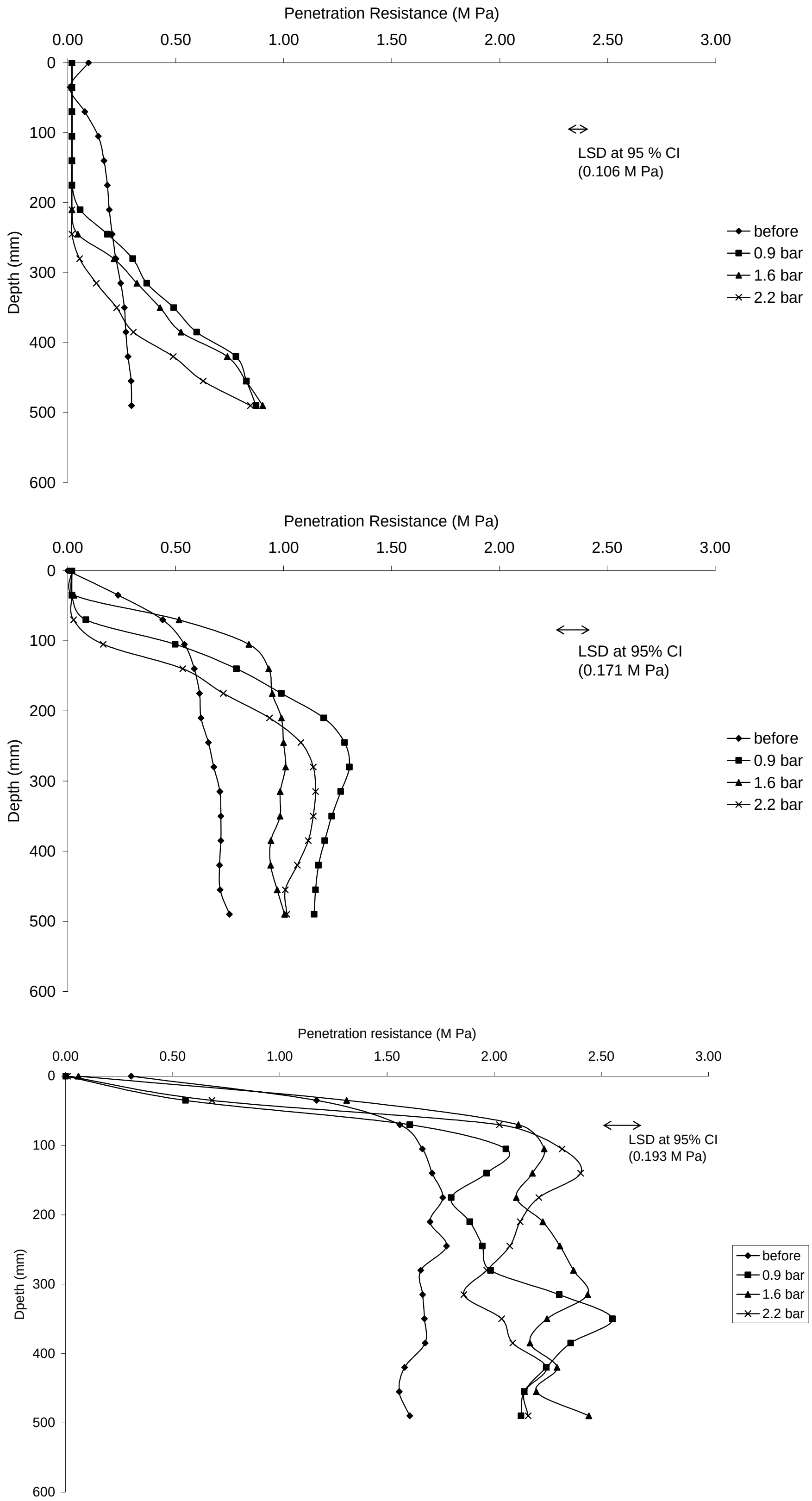


Figure 16 Change in penetration resistance for the 700 mm section tyre at 50 mm from the centreline of the tyre on 1.25 t m^{-3} (upper), 1.35 t m^{-3} (middle) and 1.57 t m^{-3} (lower) initial soil bulk densities

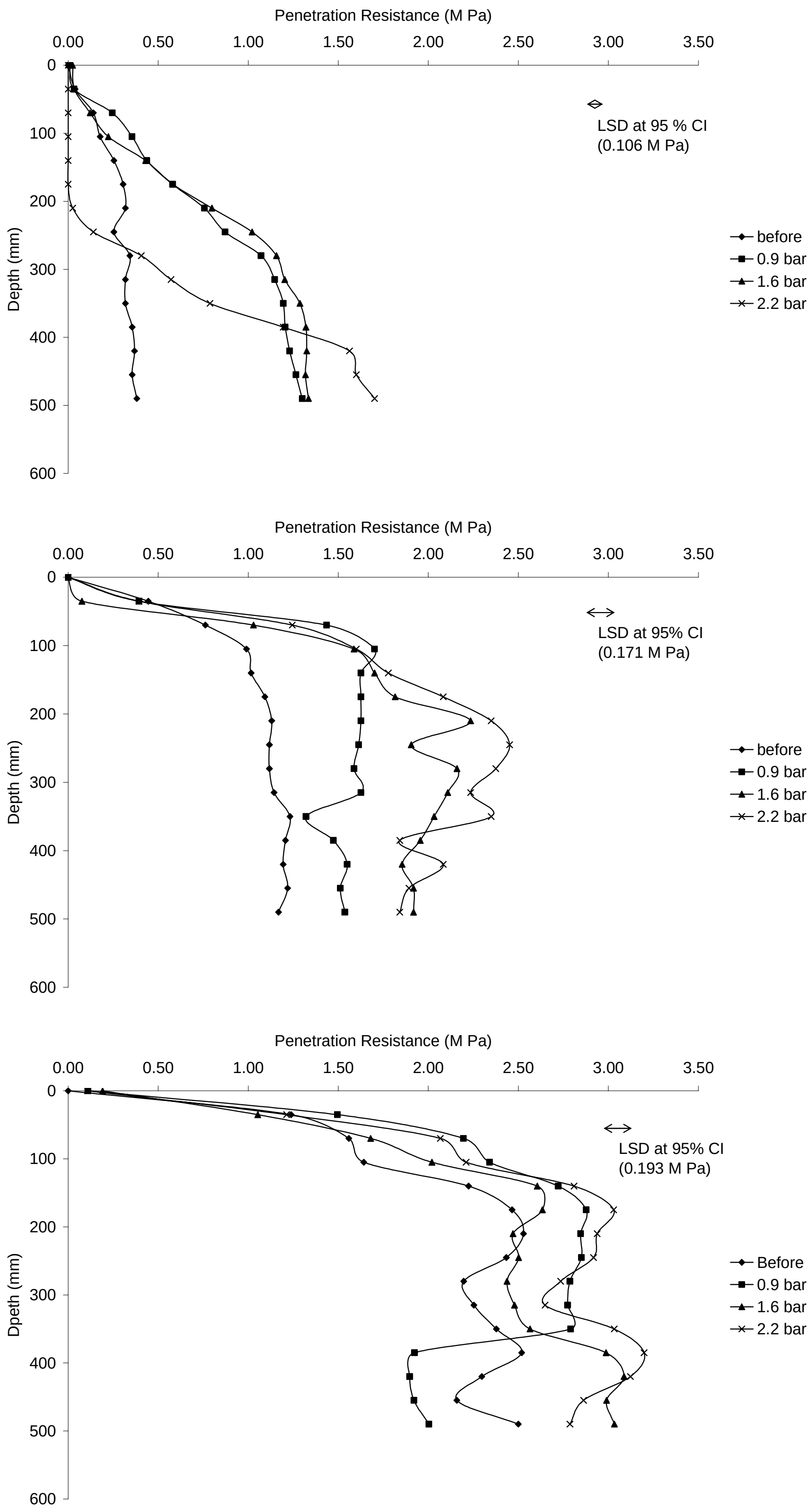


Figure 17 Change in penetration resistance for the 800 mm section tyre at 50 mm from the centreline of the tyre on 1.25 t m^{-3} (upper), 1.35 t m^{-3} (middle) and 1.57 t m^{-3} (lower) initial soil bulk densities

Figure 16 shows plots for the 700 mm section tyre at 50 mm from the centreline of the tyre. The penetration resistance increases significantly for all tyre inflation pressures on the 1.25 t m^{-3} density soil, however there is no significant difference between the 0.9 bar and 1.6 bar inflation pressures. Operating the tyre at 2.2 bar results in a deeper rut depth however all three inflation pressures give the same or comparable rates of increase in penetration resistance.

When the soil bulk density is increased to 1.35 t m^{-3} all three pressures produce an increase in penetration resistance that is significantly different to the control. The rate of increase is comparable, all three give an increase in residual penetration resistance. The maximum penetration resistance occurs at a depth of approximately 300 mm which is higher than on the 1.25 t m^{-3} soil and would be more easily removed in the field. The studies that were carried out on the 1.57 t m^{-3} density soil show that a small increase in rut depth for all tyres gives a relative increase in residual penetration resistance above the initial values which in the upper layers (between 100 mm and 200 mm) increases with inflation pressure.

The 800 mm tyre (Figure 17) on the 1.25 t m^{-3} soil shows a substantial increase in rut depth for the tyre at 2.2 bar inflation pressure it being greater than the other two inflation pressures but the rate of increase is comparable.

Studying the plots for this tyre on the soil with a bulk density of 1.35 t m^{-3} shows an increase in the control penetration resistance. It can be observed that there is very little difference in the resultant plots for all three inflation pressures to a depth of 100 mm. From this point down through the profile the plot for the tyre at 0.9 bar slightly decreases and then becomes steady indicating that there is a uniform increase in soil strength through the rest of the profile. There is an increase in residual penetration resistance with inflation pressure between 100 mm and 400 mm.

Considering the results for the hardest soil (1.57 t m^{-3}) they show that there is some difference between the treatments and the control, although the variability in the results could be caused by the very dense nature of the soil profile making recording with a cone penetrometer very difficult, in addition to the increased difficulty of homogeneous soil preparation for the complete length of the Soil Bin.

4.4 Dry bulk density

Dry bulk density measurements were taken and compared for statistical significance. The initial comparison shows that there was a difference between the control (initial) at the lower two dry bulk densities and the treatments (Figure 18). Further analysis shows that there is no effect of inflation pressure but there is a significant difference between the 500 section tyre and all other tyres (Table 3).

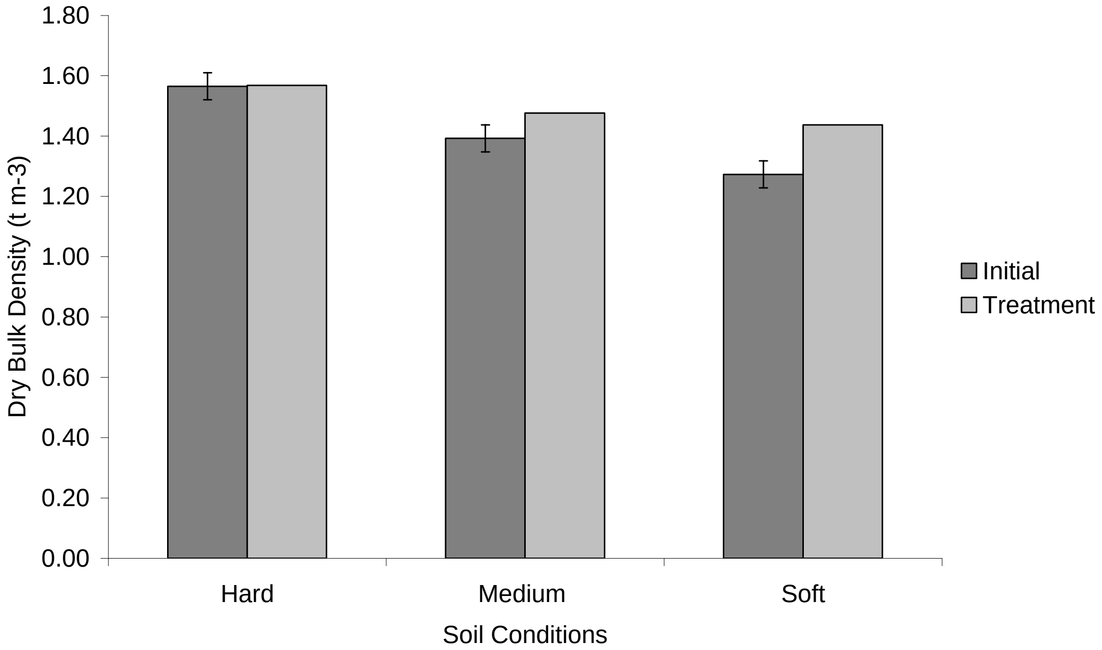


Figure 18 Comparison of initial resultant bulk densities for all soil conditions used in this study

Table 3 Statistical analysis for the effect of tyre size on dry bulk density for tyres used in this study

Tyre size v tyre size		Degrees of freedom	LSD	Pr (t)
500	700	84	0.031512	0.3912
500	800	84	0.031512	0.1873
700	800	84	0.028185	0.0164

4.5 Soil deformation

4.5.1 Soil deformation profiles

The soil deformation recorded during the experiments was transcribed into Microsoft Excel and graphs were produced, these are shown in Figures 20, 21 and 22. It can be seen that there is little difference in the soil surface deformation between the two larger tyres (Figures 20 and 21) when the soil had a high bulk density (1.57 t m^{-3}). With these two tyres it was observed that the soil deformation was caused by the tyre lugs with the carcase making little or no impression in the soil (Figure 19a).

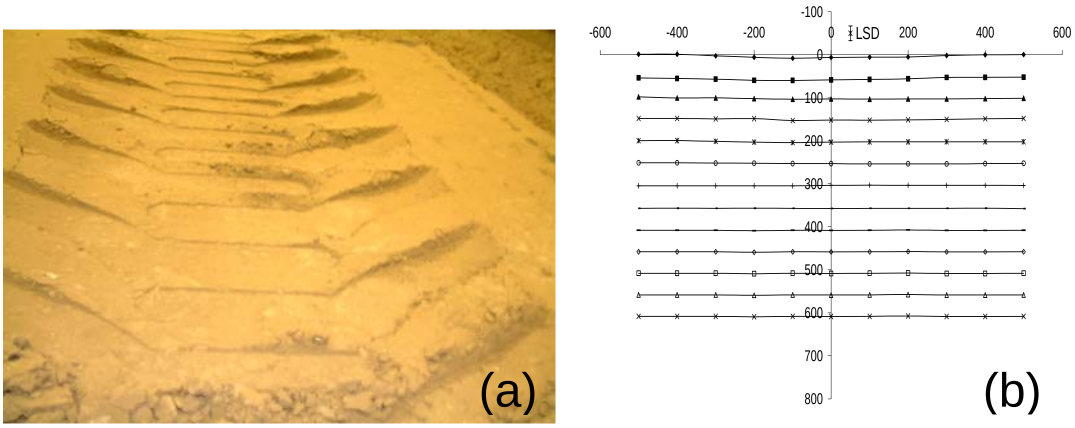


Figure 19 (a) Image of rut formation on high density soil by 800 mm section tyre at 2.2 bar inflation pressure and (b) soil deformation under the same tyre and operating conditions

Despite the small amount of surface deformation, soil deformation was observed in the profile to a depth of 250 mm (Figure 19b). The top 50 mm of the soil profile was uniformly moved down with no obvious compression of the soil. The next 50 mm layer was observed to have taken the majority of the deformation as below this the soil layers appear uniform across the profile. If the results for the 500 mm tyre, Figure 22, operating on soil with the same bulk density are examined it can be seen that as the tyre inflation pressure increased to 2.2 bar and then 2.9 bar the depth of compaction increase by approximately 50 mm for each; resulting in the depth of compaction under the 500 mm tyre inflated to 2.9 bar being 300 mm.

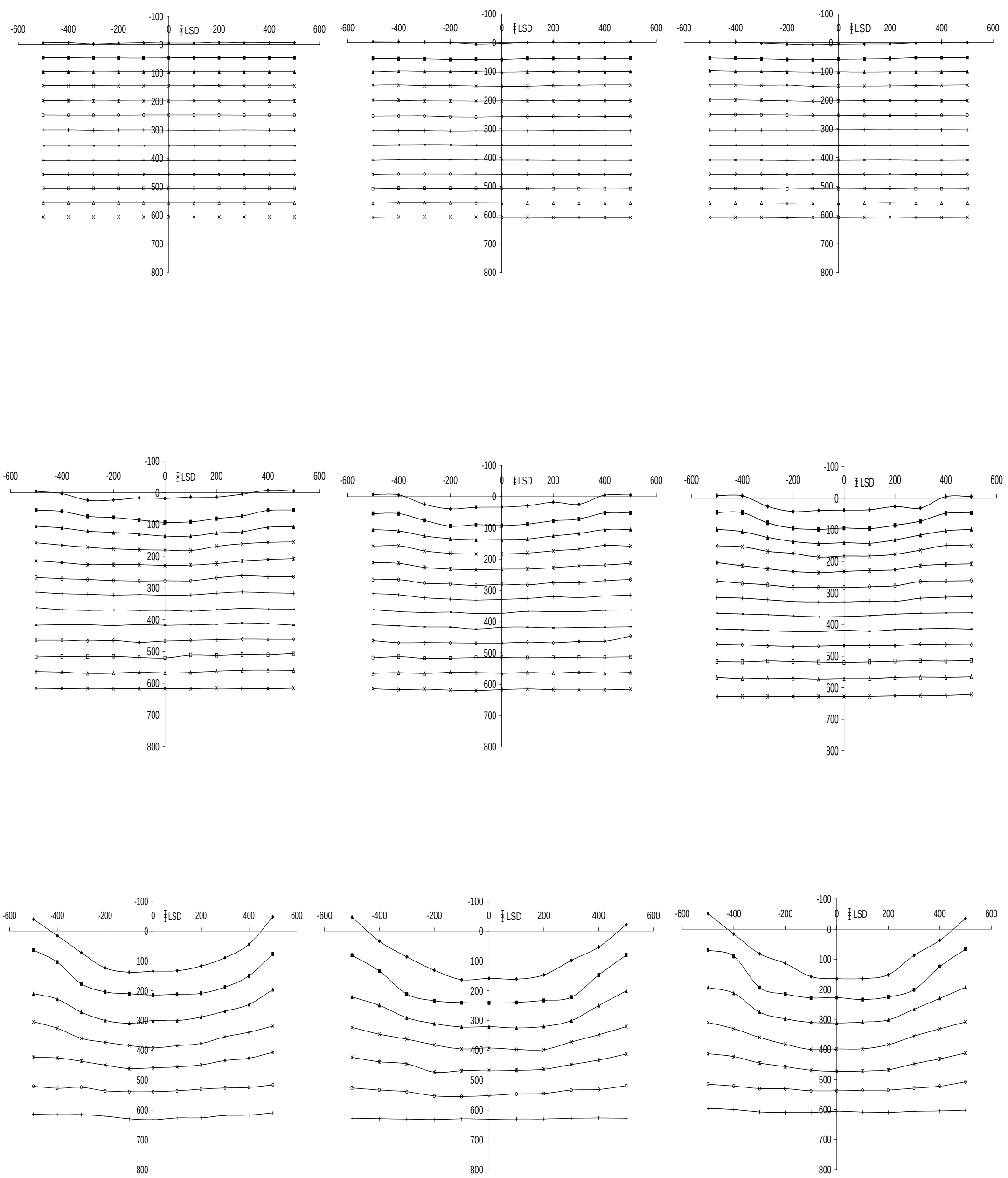


Figure 20 Soil deformation profiles for an 800mm section width tyre at three inflation pressures 0.9 bar left, 1.6 bar centre and 2.2 bar right and three dry bulk densities 1.57 t m^{-3} top, 1.35 t m^{-3} middle and 1.25 t m^{-3} bottom

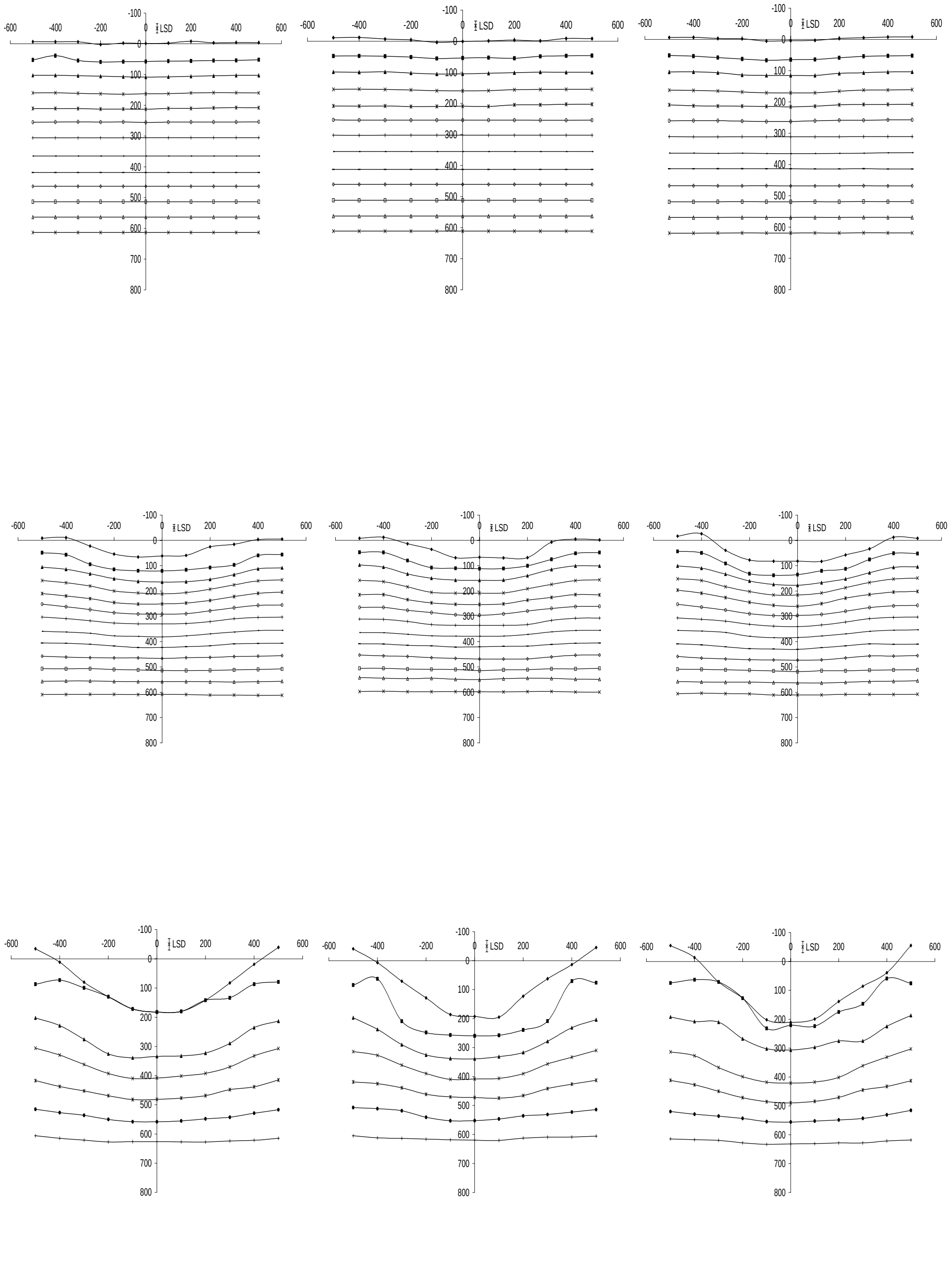


Figure 21 Soil deformation under a 700 mm section tyre at three inflation pressures 0.9 bar left, 1.6 bar centre and 2.2 bar right at three dry bulk densities 1.57 t m^{-3} top, 1.35 t m^{-3} middle and 1.25 t m^{-3} bottom

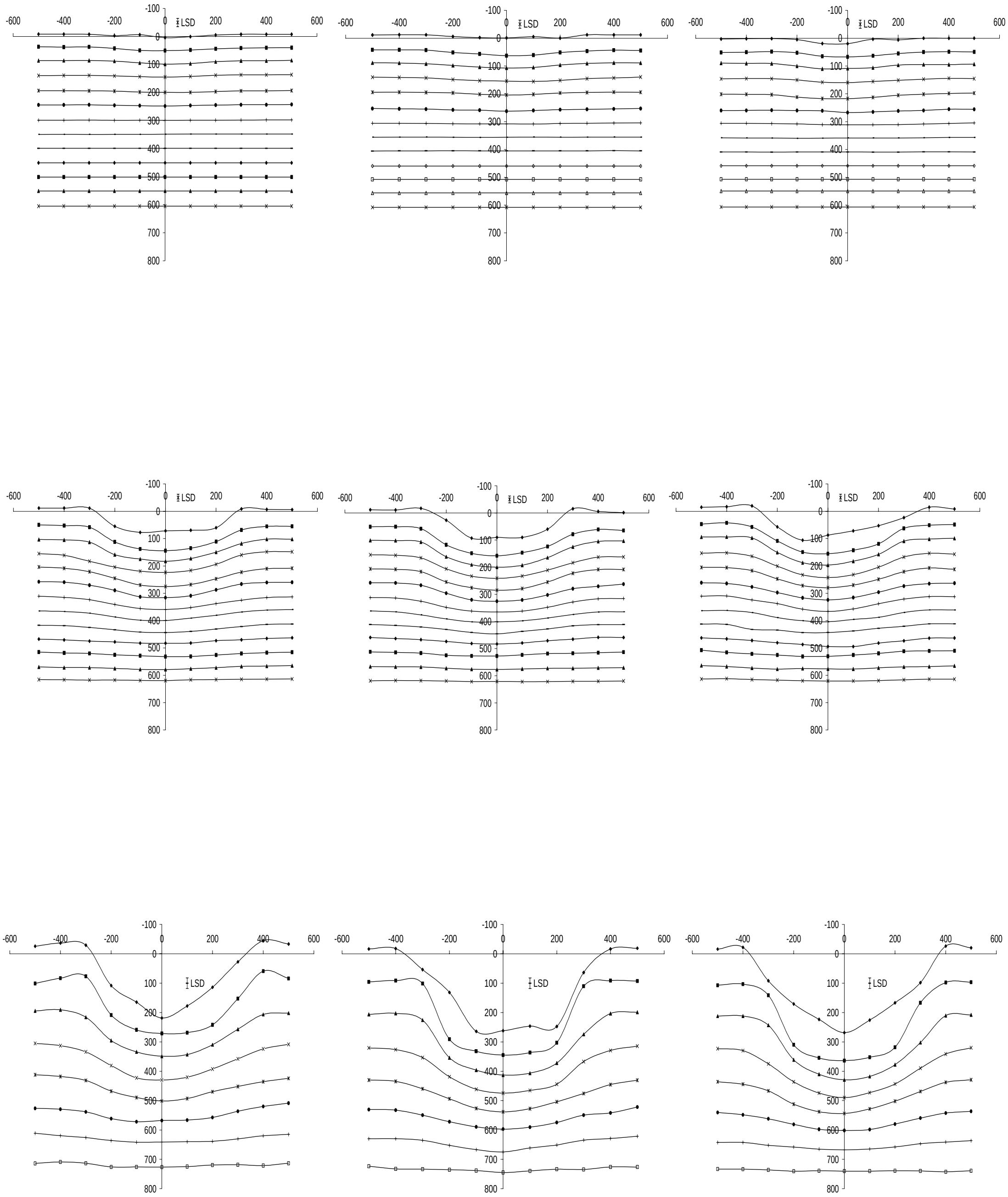


Figure 22 Soil deformation under 500 mm section tyre at three inflation pressures 1.6 bar left, 2.2 bar centre and 2.9 bar right at three soil dry bulk densities; 1.57 t m^{-3} top, 1.35 t m^{-3} middle and 1.25 t m^{-3} bottom

If the results for these tyres when operated on the medium density soil (1.35 t m^{-3}) are examined the depth to which deformation occurred has increased in all three cases. It can be seen that the depth of deformation for the 800 mm section tyre has increased to 400 mm at all three operating pressures. The first layer of soil was uniformly moved down with little or no compaction occurring in this layer, the next layer of soil was compacted under each inflation pressure, compaction of soil also occurred at a depth of 300 mm to 350 mm depending on inflation pressure. As the inflation pressure increased so the depth of deformation increased.

When the results for the 700 mm section tyre (Figure 21 middle) are considered soil deformation can be seen down to a depth of between 400 mm and 450 mm. There is soil deformation in the top two layers under all three inflation pressures but it is greatest when the tyre is inflated to 2.2 bar. It was observed that there would seem to be a more compacted layer at a depth of 250 mm to 300 mm below the surface under all three inflation pressures; on closer examination and when accounting for the standard error statistically this is not the case. The amount of soil “heave” caused by the passage of the tyres also increased as the inflation pressure increased.

Examining the graphs for both the 800 mm and 700 mm section tyres on the soft soil (1.25 t m^{-3}) it can be seen that there is significant rut formation at all pressures, there is also a large amount of “heave”. It was observed during the experimental procedure that the wheel caused a large ‘bow wave’ (Figure 23) as it moved over the soil.

Figure 23 Photograph of the 'bow wave' (top) caused by the tyre pushing the soil in front of it along

It can be seen from the graphs that the soil deformation decreased as the depth increased but it is not certain if the amount of deformation was restricted by the depth of the soil in the bin only being 800 mm. The effect was also observed for the lateral movement of the soil as the larger tyres have 350 mm and 400 mm respectively on each side of the tyre to the edge of the bin. This could have provided a confining stress on the soil and prevented it from moving freely away from the tyre.

The soil deformation caused by the 500 mm section tyre (Figure 22) on the hard soil (1.57 t m^{-3}) has very little surface deformation but the depth of soil deformation ranges from 250 mm with an inflation pressure of 1.6 bar to 300 mm under 2.9 bar inflation pressure. The graphs for the weaker soils show a similar form. In the 1.25 t m^{-3} density soil there is again a more compacted second layer but as the depth increases the deformation of the soil is restricted by the bottom of the Soil Bin. It should be noted that as the tyre inflation pressure increased the depth of the soil deformation increased. The depth of deformation was restricted again by the depth of soil and the concrete base of the Soil Bin.

4.5.2 Soil deformation rate of change

The graphs in Figures 20, 21 and 22 show the movement of each layer when looking at the whole profile and give a picture of the way that each soil deforms when a specific load and tyre are passed over them. To understand how the soil distributes the applied load through the profile the amount of movement in each layer was investigated. Ansorge (2005) developed a technique for investigating the vertical movement in the soil profile. The position of each layer in the compacted profile was compared to its position in the original profile and graphs were plotted. Each point on the graph was made up of the five centre readings from the profile to give an average maximum amount of deformation for all tyres on both the hard and medium density soils. For the soft soil the averages were taken from the centre three points, this was done as the amount of deformation in the soft soil was considerably greater than on the other two soils because of its low initial bulk density.

A statistical analysis was undertaken of the original data and the least significant difference obtained to the 95% confidence interval (CI) (Table 4). Graphs (after Ansorge 2005) were plotted and are shown in Figures 24, 25 and 26. These graphs show the amount of change in deformation of each layer plotted against the depth through the profile. Trend lines ($y=ax+b$) were added and from these values for the co-efficient of regression (R^2) were extracted.

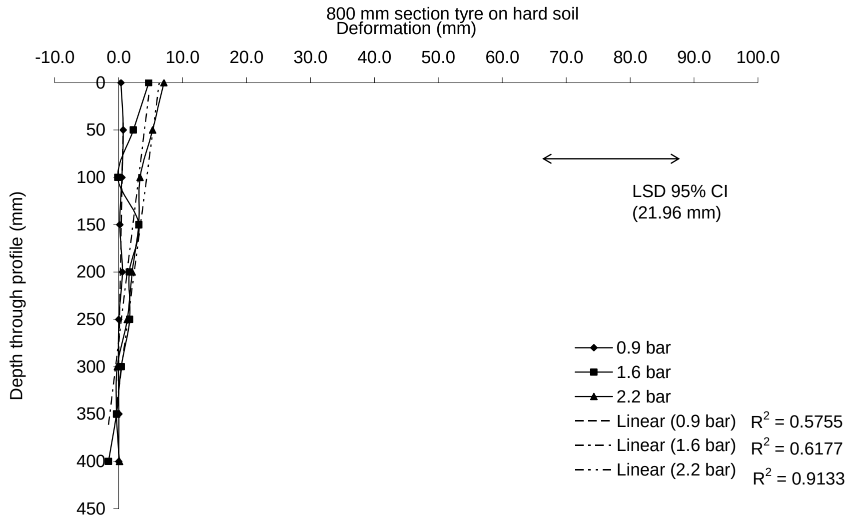
Figure 24 shows the plots for all three tyres on the hardest soil. It can be seen from these that the amount of deformation increases as the size of the tyre decrease, also the depth to which deformation occurs increases as the tyre size decreases. Although there is some variation in the curves for each of the pressures, possibly caused by errors when taking the measurements, all three lines fall within the least significant difference. It can therefore be stated that on soils with a dry bulk density of 1.57 t m^{-3} the change in inflation pressure for each tyre has no significant effect on deformation rate of change.

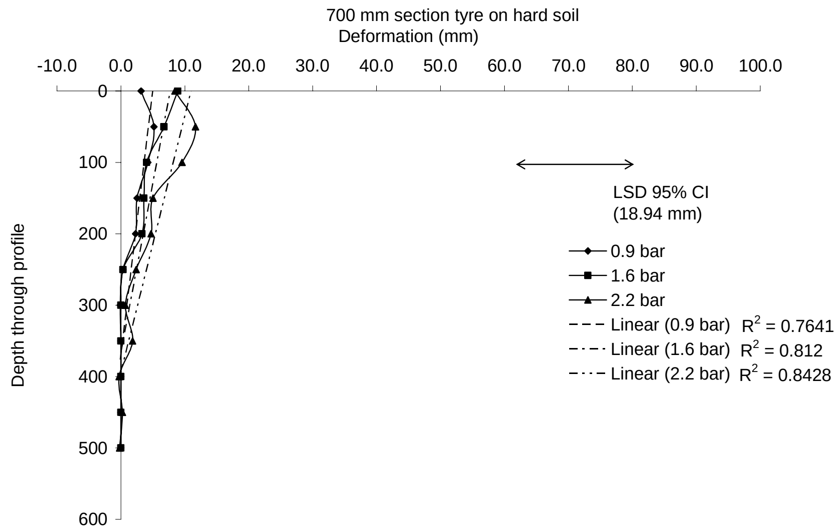
If each tyre is compared with the others and examining the statistical results it can be seen that there is no significant difference between the 700 mm section tyre and the 800 mm section tyre at all inflation pressures, the least significant difference being 16.5 mm at the 95% confidence interval. There are significant differences between the 700 mm section tyre and the 500 mm section tyre; also between the 500 mm section tyre and the 800 mm section tyre. This means that there is an advantage to increasing the size of the tyre fitted to a pea harvester from 500 mm section width to at least 700 mm.

Examining Figure 25 it can be seen that there is some variation in the amount of deformation in each layer; however, the trend is in a straight line down to a maximum measured depth of 550 mm. The values of deformation plotted on each curve are within the least significant difference quoted. When considering the statistics, and comparing each tyre and inflation pressure, a change in inflation pressure in the 800 mm section tyre is significant; the same is true for the 700 mm and 500 mm section tyres.

Table 4 Summary of statistical analysis for the effect of soil dry bulk density, tyre section width and inflation pressure

Soil Density (t m^{-3})	Tyre size and inflation pressure compared to tyre size and inflation pressure		Degrees of freedom	LSD	Pr (t)
1.25	500 mm 1.6 bar	500 mm 1.6 bar & 2.2 bar	1458	23.85886	0.0066
1.25	500 mm 1.6 bar & 2.2 bar	700 mm at all inflation pressures	1458	24.9557	<0.0001
1.25	500 mm 1.6 bar & 2.2 bar	800 mm 0.9 bar & 1.6 bar	1458	25.12786	<0.0001
1.25	500 mm 1.6 bar	800 mm 2.2 bar	1458	24.85343	<0.0001
1.25	500 mm 2.9 bar	700 mm all inflation pressures	1458	25.19825	0.0015
1.25	500 mm 2.9 bar	800 mm all inflation pressures	1458	25.36876	0.0325
1.25	700 mm all inflation pressures	700 mm all inflation pressures	1458	25.28309	0.3705
1.25	700 mm all inflation pressures	800 mm all inflation pressures	1458	25.45303	0.9152
1.25	800 mm all inflation pressures	800 mm all inflation pressures	1458	25.62184	0.8793
1.35	500 mm all inflation pressures	500 mm all inflation pressures	1458	17.13903	<0.0001
1.35	500 mm 1.6 bar & 2.2 bar	700 mm and 800 mm at all inflation pressures	1458	17.36746	0.7025
1.35	500 mm 2.9 bar	700 mm and 800 mm at all inflation pressures	1458	16.77005	0.9793
1.35	700 mm and 800 mm at all inflation pressures	700 mm and 800 mm at all inflation pressures	1458	16.50504	0.8736
1.57	500 mm 1.6 bar & 2.2 bar	500 mm at all inflation pressures	1458	19.46537	0.7562
1.57	500 mm 1.6 bar & 2.2 bar	700 mm at all inflation pressures	1458	19.68148	<0.0001
1.57	500 mm 1.6 bar & 2.2 bar	800 mm at all inflation pressures	1458	21.1932	<0.0001
1.57	500 mm 2.9 bar	700 mm at all inflation pressures	1458	19.4161	<0.0001
1.57	500 mm 2.9 bar	800 mm at all inflation pressures	1458	20.94701	<0.0001
1.57	700 mm at all inflation pressures	700 mm at all inflation pressures	1458	18.94008	0.2805
1.57	700 mm at all inflation pressures	800 mm at all inflation pressures	1458	20.50655	0.5425
1.57	800 mm at all inflation pressures	800 mm at all inflation pressures	1458	21.96158	0.8393





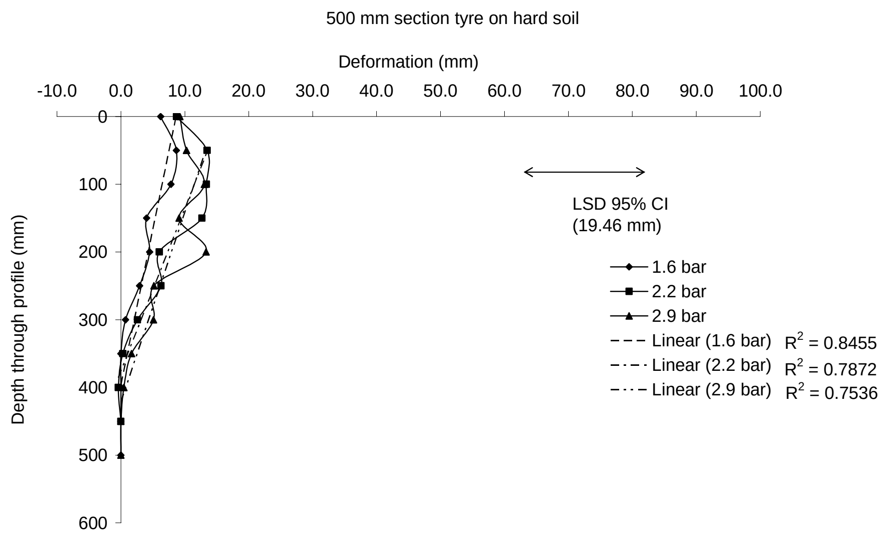
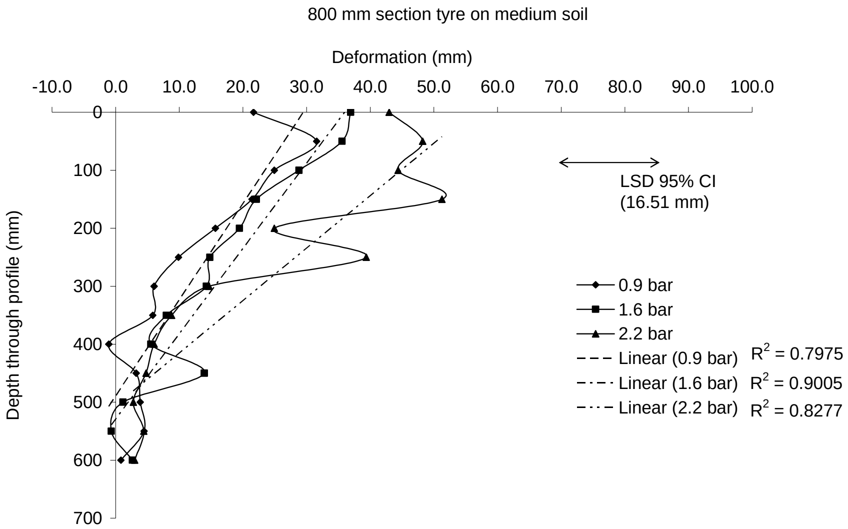
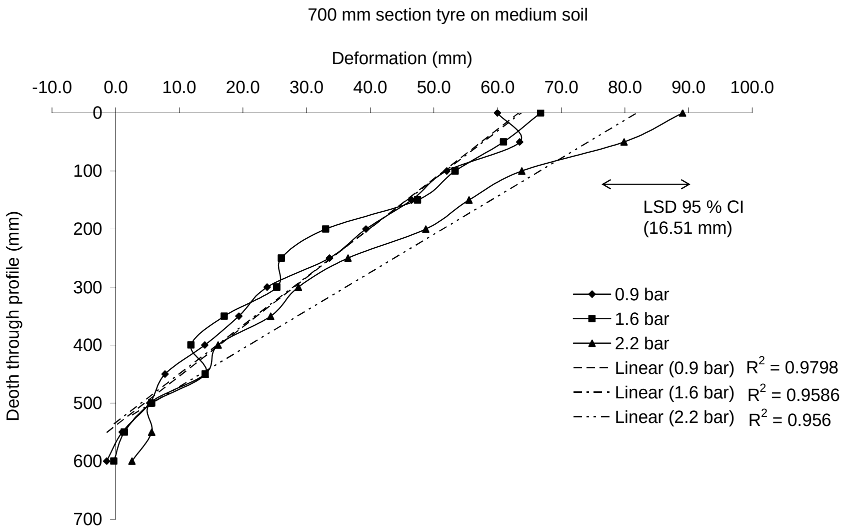


Figure 24 Change in soil deformation over depth for all tyres on 1.57 t m^{-3} density soil at all inflation pressures during this study





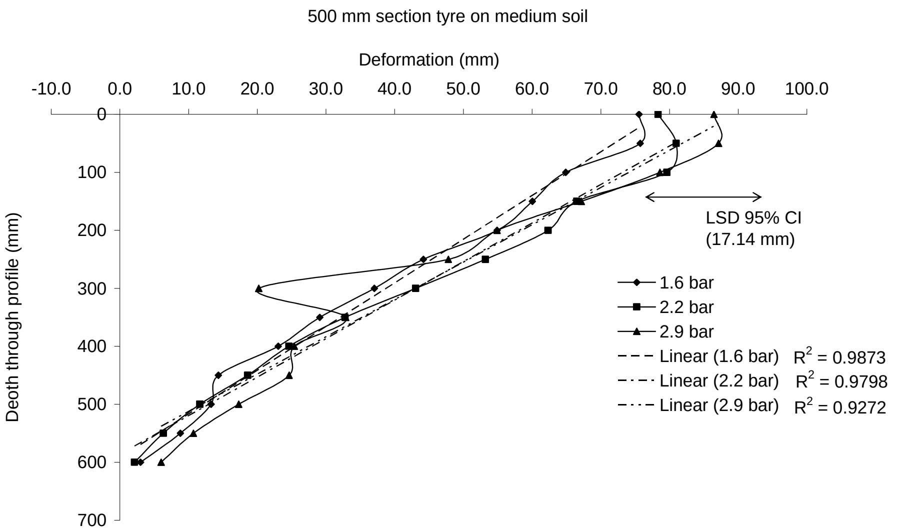


Figure 25 Change in deformation over depth for all tyres on 1.35 t m^{-3} density soil at all inflation pressures during this study

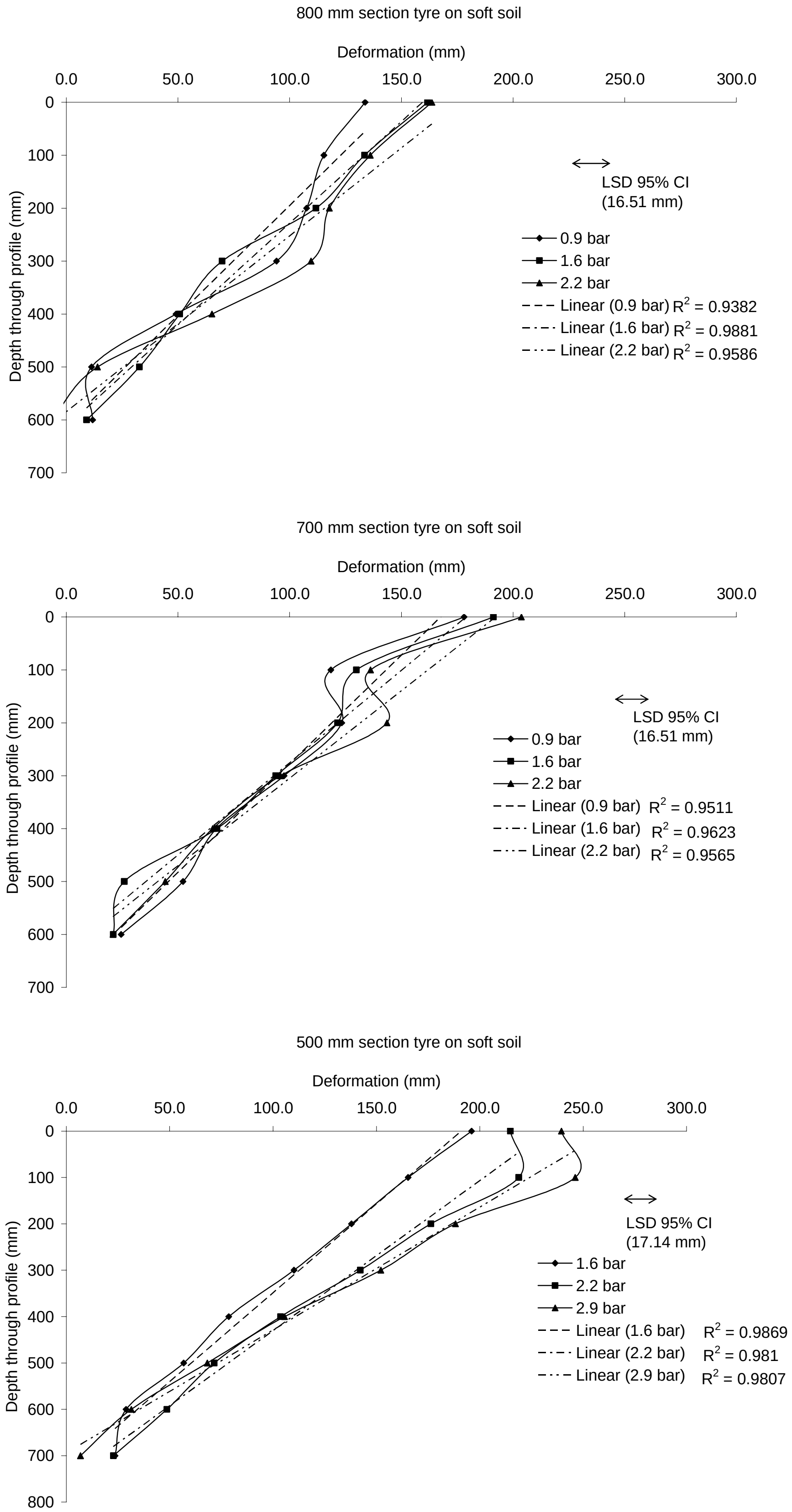


Figure 26 Change in deformation over depth for all tyres on 1.25 t m^{-3} density soil at all inflation pressures during this study

When comparing the tyres against each other at all inflation pressures by examining the statistical analysis there is significant difference between the 500 mm section tyre when inflated to 1.6 bar and both the other tyres at each of the three inflation pressures. When the pressure was increased to 2.2 bar there is no significant difference between it and the 700 mm tyre but there is a difference between it and the 800 mm section tyre. This indicates that operating a machine in the field on either a 500 mm section or 700 mm section tyre on a soil with this bulk density would make no difference to the amount of soil deformation.

Examining the statistical results for the 700 mm tyre and comparing it with the 800 mm section tyre there is no significant difference between them when both are inflated to 0.9 bar or when the 800 mm section tyre is increased to 1.6 bar inflation pressure. When the inflation pressure of the 700 mm tyre is increased to 1.6 bar it is only significantly different to the 800 mm section tyre when that is operated at 0.9 bar. Increasing the inflation pressure in the 700 mm section tyre to 2.2 bar leads to a significant difference at all inflation pressures in the 800 mm section tyre. This would lead to the conclusion that increasing the size again from 700 mm to 800 mm, at the pea harvester manufacturers recommended inflation pressure (2.2 bar) for the load carried and road speed, there would be a significant decrease in soil deformation on a soil with a dry bulk density of 1.35 t m^{-3}.

Figure 26 shows plots for each tyre on the softest (1.25 t m^{-3}) bulk density soil. The depth of deformation has increased to 600 mm with the amount of deformation at the surface increasing to between 150 mm and 250 mm depending on the size of tyre and its inflation pressure. The trend of the deformation is again linear with some small deviations; these are however within the limits of least significant differences shown on each graph. The statistical analysis shows that there is no significant difference between the 500 mm section tyre inflated to 2.2 bar and the same tyre at 2.9 bar inflation pressure. There is also no difference between the 700 mm section tyre and the 800 mm section tyre at all combinations of inflation pressure. All other combinations of tyre size and inflation pressure are significantly different from each other.

The complete profiles were examined and plots shown for the rate of change in deformation through the profile, these profiles give information for each tyre at each inflation pressure in each soil condition. To understand the relationship between all these effects a method had to be devised to link the amount of soil deformation for each of the treatments. Ansorge (2005) states that the change in deformation over depth (mm / mm) can be expressed as a percentage derived from the reciprocal of the slope of the line this also represents a percentage change in the soil bulk density. These were then plotted against actual average initial dry bulk density (Figure 27) and initial penetration resistance values (Figure 28). This method of determining changes in bulk density is more sensitive than the density ring sampling method to determine bulk density changes used to obtain the results discussed in Section 4.4.

Considering the average actual density of the soil (Figure 27) as influenced by the size of each tyre and its inflation pressure it can be seen that there is very little difference in the rate of change between the 800 mm tyre at 0.9 bar and the same tyre at 1.6 bar inflation pressure; although on the hard (1.57 t m^{-3}) soil the rate of change when the tyre is inflated to 0.9 bar has reduced to near zero. The same tyre when inflated to 2.2 bar has a similar effect on the soil as the 700 mm tyre inflated to 1.6 bar. The 700 mm section tyre traces for the two lower inflation pressures are almost identical with the percentage rate of change being negligible. The forms for the 500 mm section tyre show the largest amount of change at the lowest bulk densities, however the rate of change between the 1.35 t m^{-3} and the 1.57 t m^{-3} soils is similar to that of the 700 mm section tyre. The graph for the penetration resistance shows a similar trend albeit with lower measured initial bulk densities which have biased the curves.

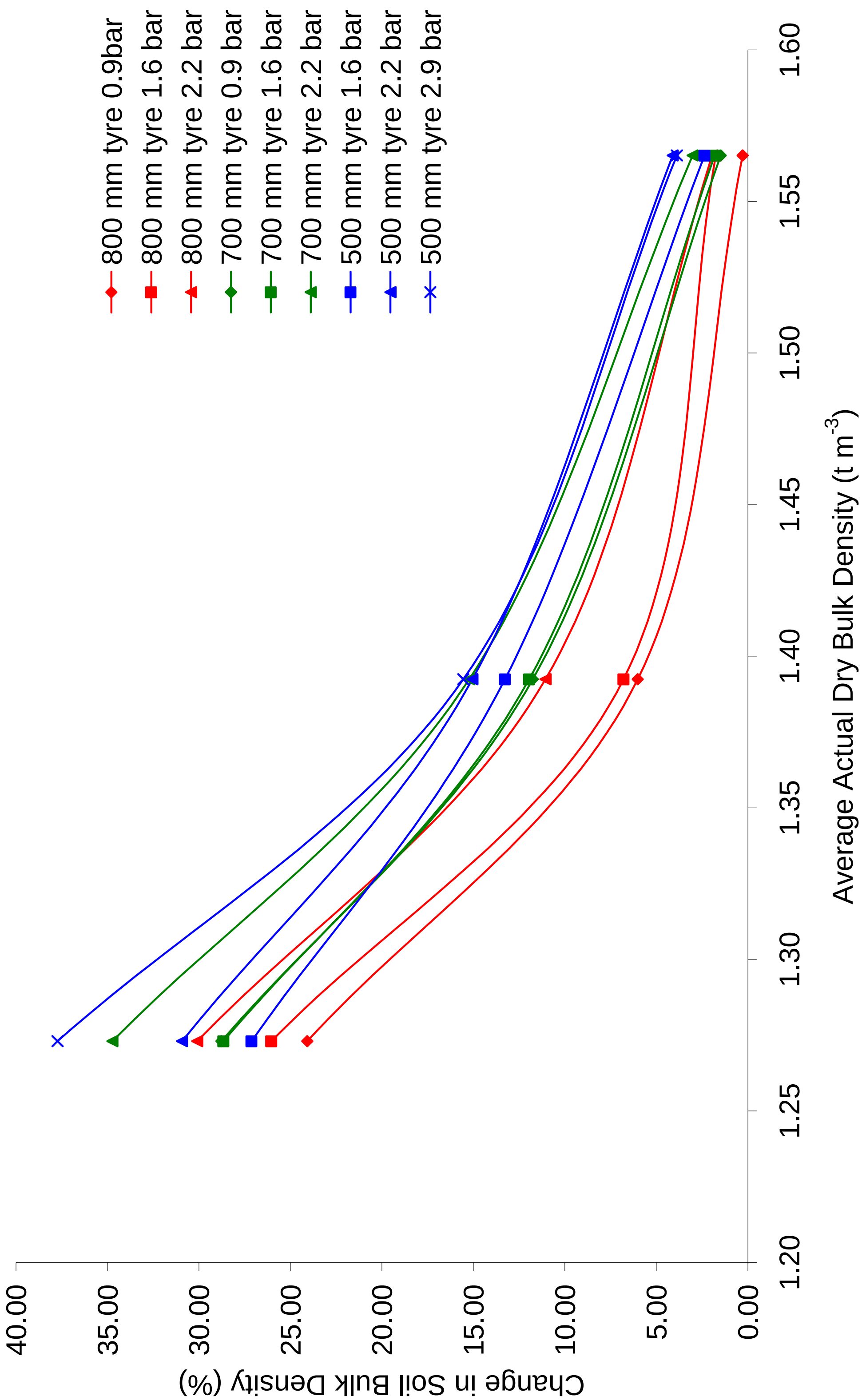


Figure 27 The effect of average actual initial dry bulk density on percentage rate of change in soil bulk density

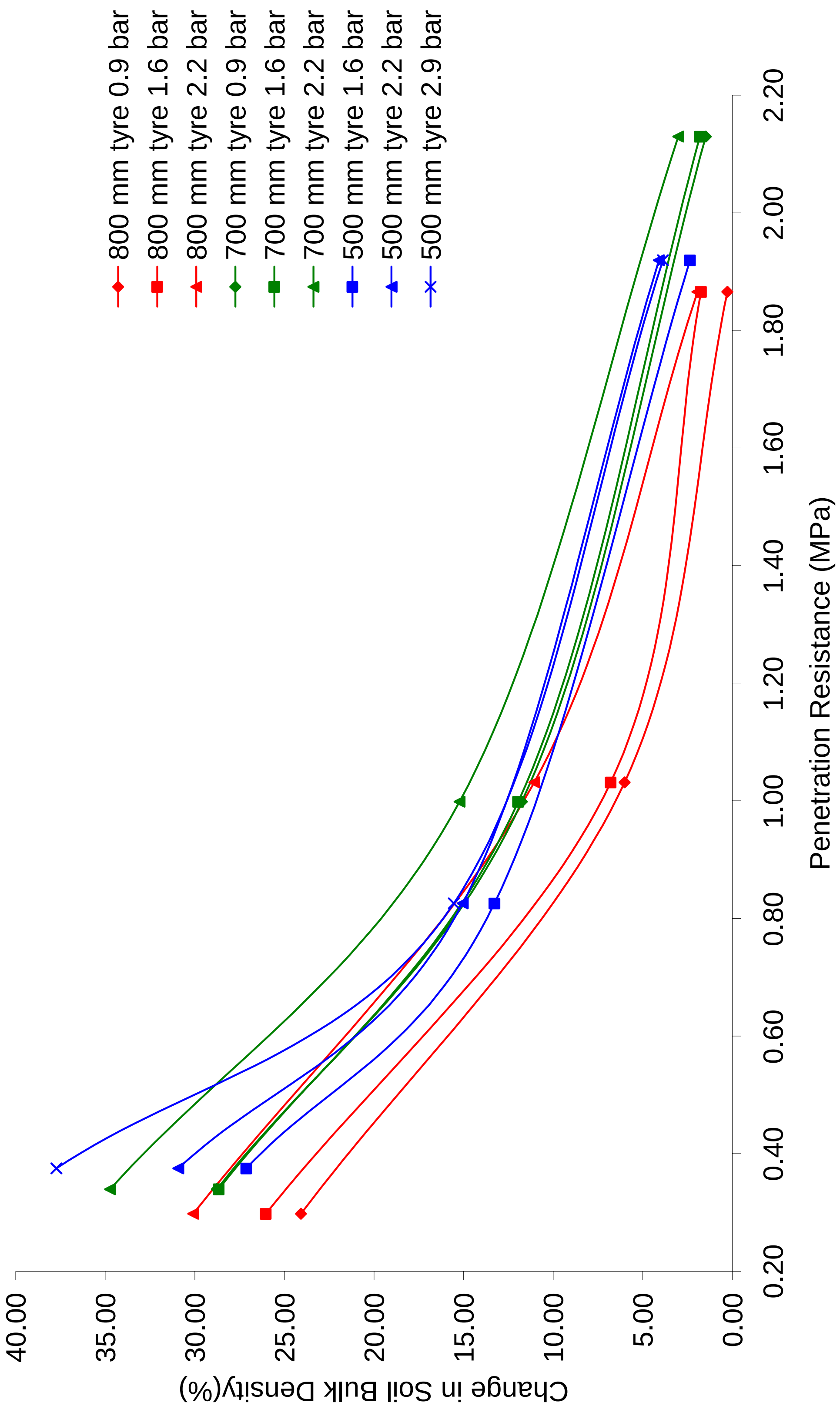


Figure 28 The effect of measured initial penetration resistance on percentage rate of change in soil bulk density

It can be seen from the graphs that the tyres are ranked according to tyre size and within each tyre according to inflation pressure with a difference between the 800 mm section tyre at 0.9 bar and the 500 mm section tyre at 2.9 bar of 14% on the low bulk density soil, 10% on the medium density soil and 4% on the soft soil. This enables tyres to be selected for relative effect on soil bulk density by section width and inflation pressure.

Table 5 Percentage density change on an initial soil bulk density of 1.4 t m^{-3} at two manufacturers recommended operating speeds and inflation pressures for a load of 4.5 t

Speed	10 km / h		25 km / h	
Tyre section width	Recommended inflation pressure (bar)	Change in soil density (%)	Recommended inflation pressure (bar)	Change in soil density (%)
500 mm	2.4	15	2.4	15
700 mm	1.5	11.5	1.7	11.5
800 mm	1.5	6	1.5	6

Table 5 shows the potential reduction in density change for the three tyres tested at the nearest inflation pressure to those recommended by the tyre manufacturer (Trelleborg) on a given soil condition. The values in the table were interpolated from the graph in Figure 27. This indicates that by reducing the inflation pressure and increasing the tyre size the density change can be reduced from 15% to 6%. Using the same principle and penetrometer data from in field measurements (Table 6) before harvesting it can be seen that the graphs predict a change in bulk density shown in Table 6 at two inflation pressures.

Table 6 Penetrometer resistance from in-field measurement

Depth	Penetration resistance (MPa)	Percentage change in bulk density	
		1.6 bar	2.2 bar
35	0.52	24	31
70	0.69	18	23
105	0.83	15.5	19
140	1.02	12	15.5
175	1.14	10.5	13

5 Comparison of tyre performance

The effect of soil conditions, that is initial bulk density, has a marked impact on the performance of all three tyres. Increasing the bulk density reduces the amount of rolling resistance and deformation through the profile. The bulk density results were a little more erratic, caused by the way the soil was prepared and was largely dependant on the preparation and treatment of the soil during the previous blocks.

The size of the tyre had a pronounced effect on the depth of the deformation of the soil. The 500 mm tyres at high inflation pressure previously used on a pea harvester was shown to have the largest amount of soil deformation and the largest amount of penetration resistance increase in all soil conditions. Reducing the inflation pressure in this tyre did have some effect on reducing soil deformation but this was not significant. This confirms the work carried out by van den Akker et al (1994). This study however, investigated the effect of increasing the section width and shows that by increasing the width of the tyre and reducing inflation pressure the amount of deformation, both at the surface and through the profile, can be significantly reduced.

The use of a tyre with a greater section width leads to a reduction in both soil deformation and penetration resistance. By using low inflation pressures the amount of deformation can be considerably reduced on low bulk density soils. If the inflation pressure in the 500 mm section tyre is lowered from 2.9 bar to 1.6 bar there is an 18% decrease in the deformation at the soil surface. By increasing the tyre size to 800 mm and reducing the inflation pressure to 0.9 bar the deformation at the surface is 44% less, while the rolling resistance shows a decrease of 33%.

The reduction of tyre inflation pressure in all cases reduces the amount of deformation in the soil, if deformation is directly linked to compaction, and this study would indicate that it is, then the results from this study confirm findings by Danfors (1994) that reducing the inflation pressure to below that recommended by the tyre manufacturer decreases compaction on firmer soils.

There is a direct correlation between the rolling resistance and the rut depth. If the graphical representation of the rolling resistance (Figure 9) is considered against that of the rut depth (Figure 13) it can be seen that as rut depth decreases rolling resistance also decreases.

A study by Smith and Dickson (1990) concluded that a high axle load would lead to increased amounts of compaction at depth with a lesser effect at the surface. This study would concur with their findings in that on a dense soil most of the compaction occurs in the upper layers of the soil profile, indicated in this study by the soil deformation rate of change graphs (Figure 24).

Penetrometer resistance results for all tyres show that as the tyre size increases and inflation pressure decreases the depth at which the maximum resistance occurs decreases. For any tyre an increase in the inflation pressure moves the point at which maximum penetration resistance occurs downwards through the profile. This is more likely to be caused because the depth of the rut formed, especially on the lower bulk density soils, increases with inflation pressure. It should be noted that the rate of change of all penetration resistance results is similar for each tyre and each soil condition.

The use of soil deformation as a means of determining changes in soil bulk density would appear to be a better indicator than the use of density ring samples. The method of sampling cores is vulnerable to operator error in that, especially on low bulk density soils, the corer can be pushed into the soil too far inducing a change in the bulk density. This would not be easily noticed and could lead to false measurements. The use of soil deformation gives a good approximation of changes in bulk density through the profile and, in the soil bin, is a relatively easy method of determining soil bulk density. It would be more difficult in the field to measure these changes in this way.

6 Conclusions

1) Measuring the deformation of the soil at the surface (rut depth) and at a range of depths throughout the profile indicates relative changes in soil bulk density. This is influenced by both the tyre section width and inflation pressure. Whilst soil strength (bulk density) has a very significant effect upon the changes in bulk density, the 800 mm section tyre causes less compaction at all inflation pressures over the other tyres especially at 1.6 bar and below.

2) The development of the exponential curves allows the manufacturer, farmer or operator of a pea harvester to determine the relative effects of tyre section width and inflation pressures for any soil condition.

3) In weaker soils the minimum rolling resistance occurs at the optimum inflation pressure. Increased rolling resistance results if the tyre inflation pressure is below that recommended by the tyre manufacturer as a result of tyre wall deflection and increased rut depth above this point. The deflection of the tyre wall can be attributed to the carcass stiffness of the tyre being too small and the tyre aspect ration being too great to withstand the applied load.

4) The economic advantage to the operator of increasing the tyre section width to 800 mm is £455 000 per annum in fuel at the current market price of 39.5 pence per litre.

5) The pea harvester manufacturer is investigating the engineering requirements to accommodate a tyre section width of 800 mm.

6) As a result of this study pea harvesters are now being fitted with a central tyre inflation system to allow the inflation pressure to be altered for field and road conditions leading to less soil deformation in the field.

Therefore, in answering the initial aim, the results will enable tyre systems to be selected that will reduce their effect on compaction and rut depth.

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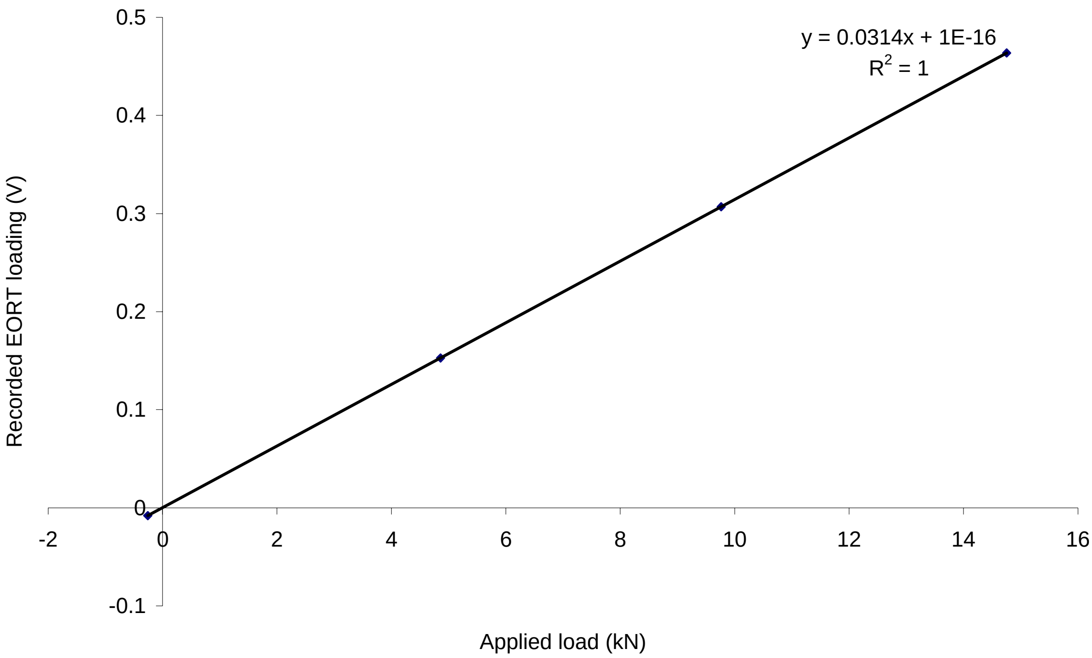
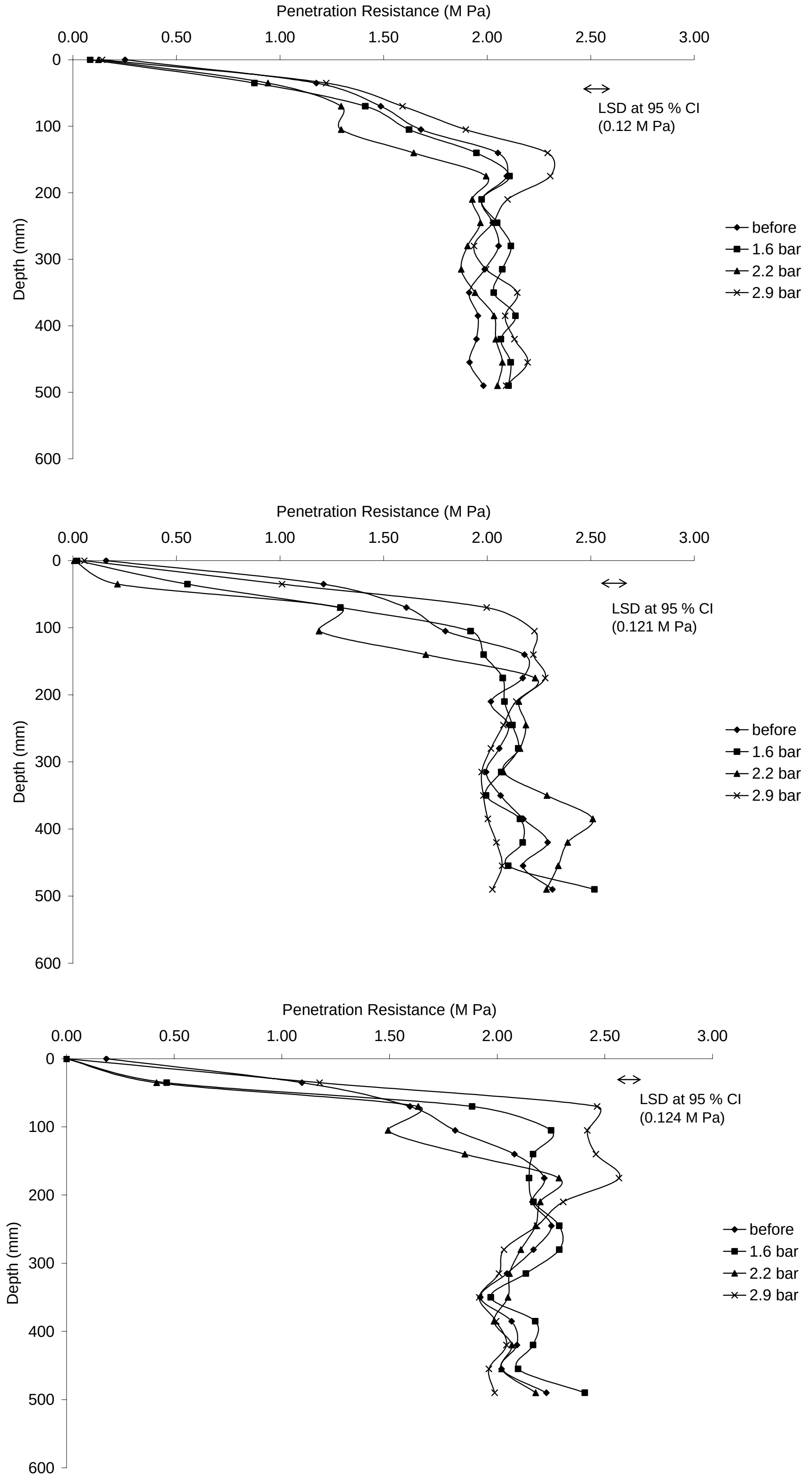
8 Appendix A



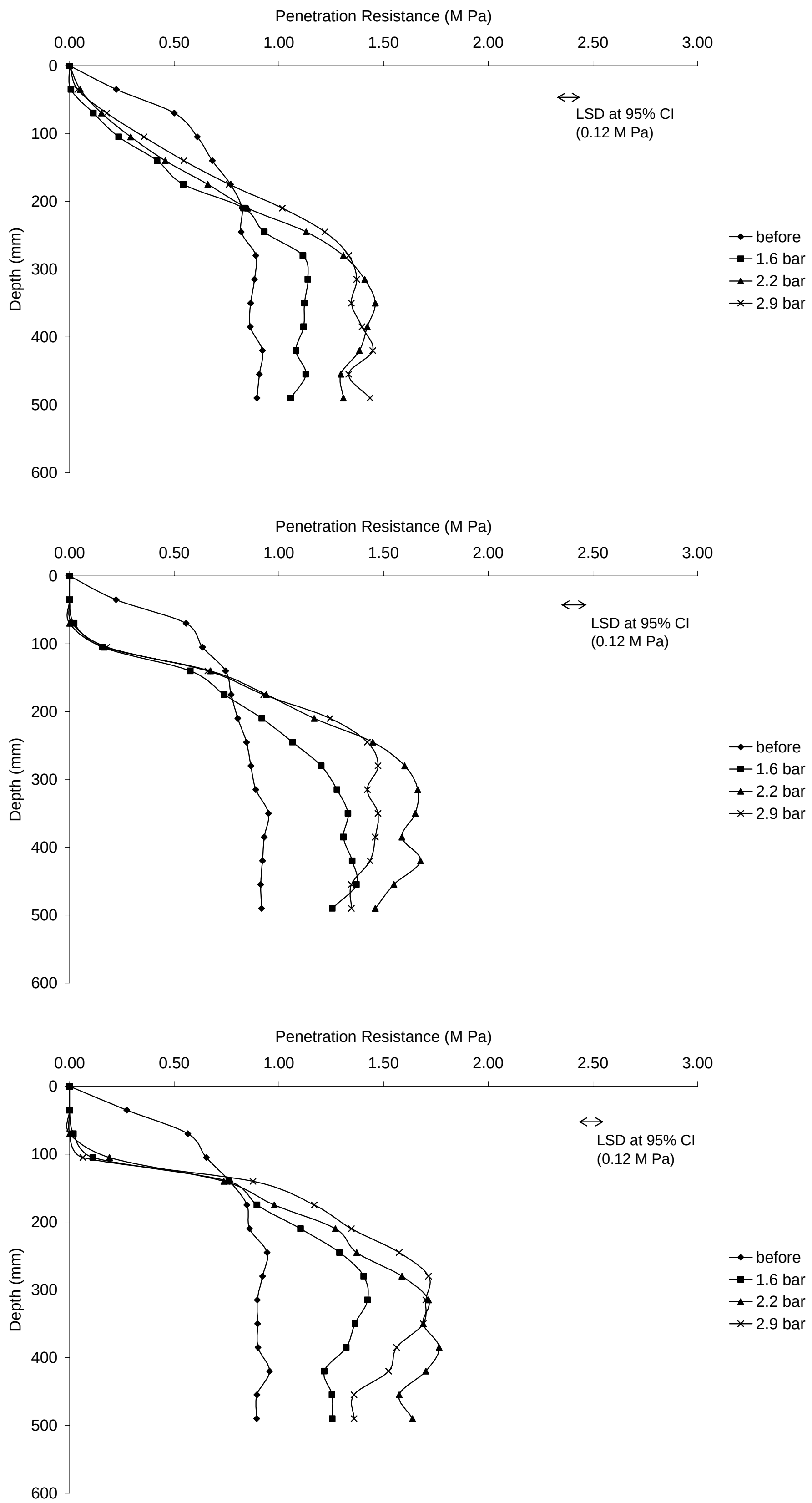
Calibration of the Extended Octagonal Ring Transducer

The slope of the graph 0.0314 V kN^{-1} represents the conversion factor for applied load to voltage. The results required were from voltage to load therefore the conversion factor used was the reciprocal of 0.0314 V kN^{-1} which is 31.82 kN V^{-1}.

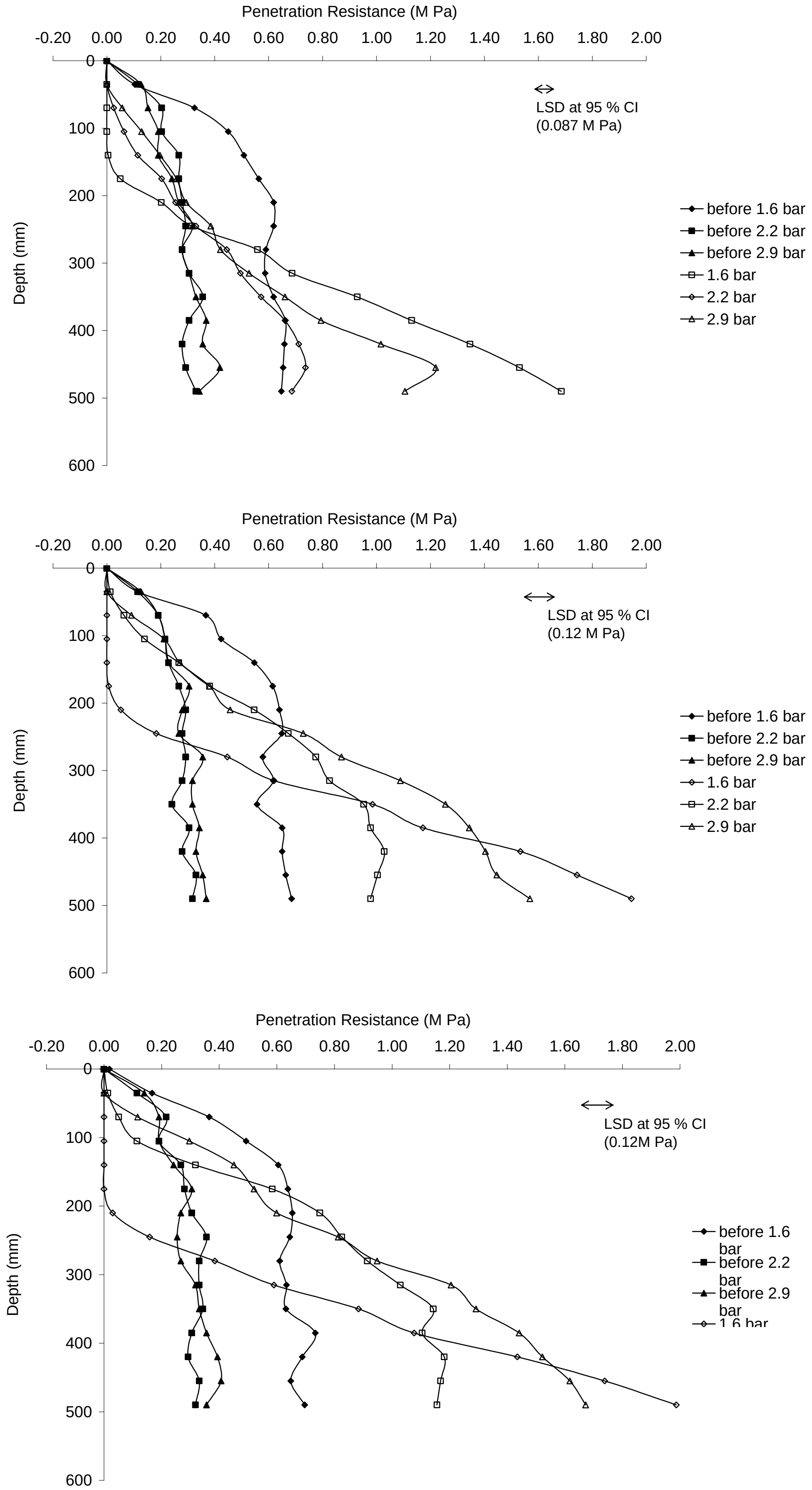
9 Appendix B



Penetration resistance for 500 mm section tyre on 1.57 t m^{-3} density soil 250 mm (upper), 150 mm (middle) and 50 mm (lower) form the centre line of the tyre



Penetration resistance for 500 mm section tyre on 1.35 t m^{-3} density soil 250 mm (upper), 150 mm (middle) and 50 mm (lower) form the centre line of the tyre.



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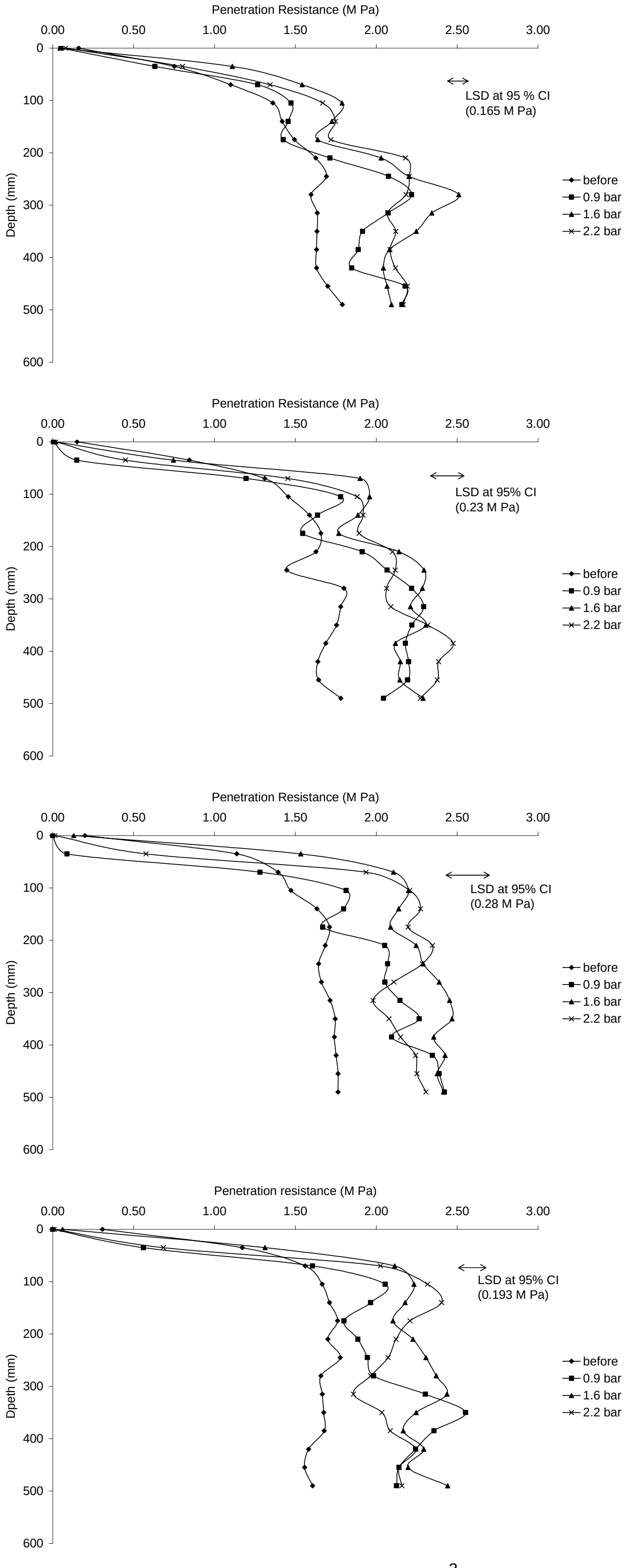
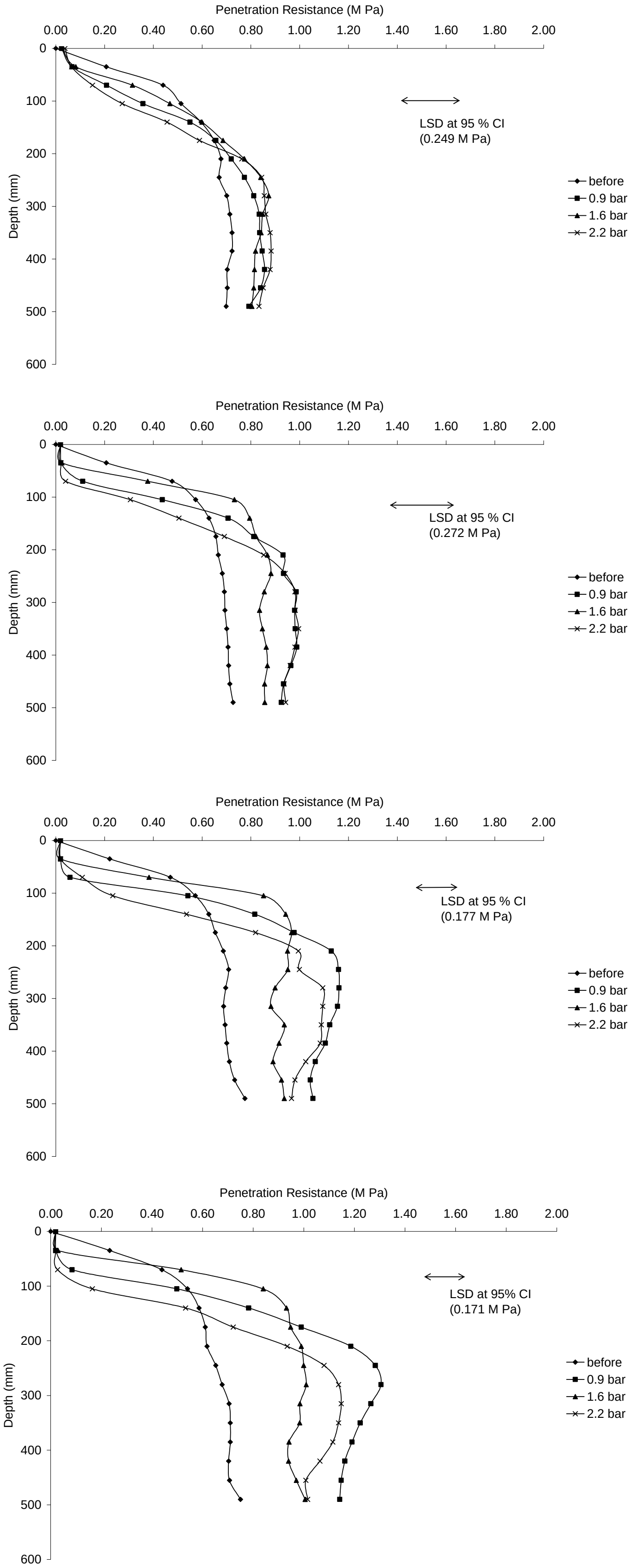
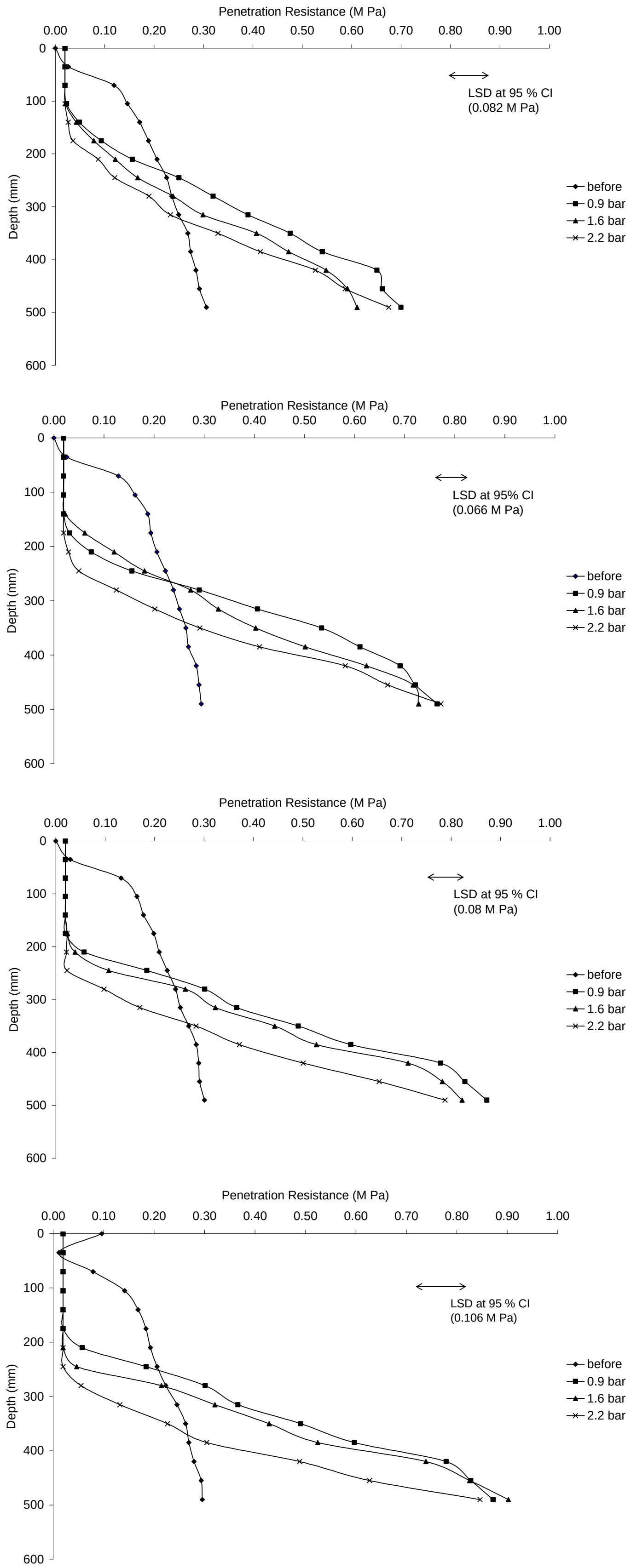


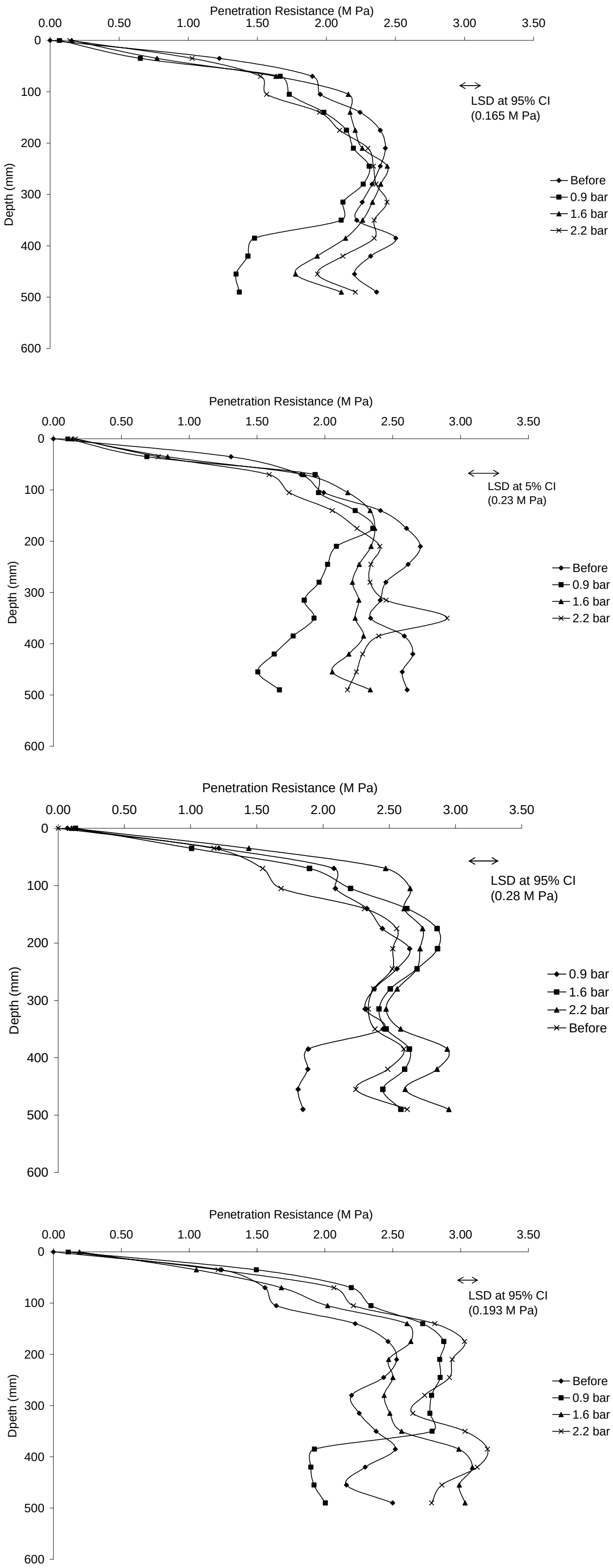
Penetration resistance for 500 mm section tyre on 1.57 t m^{-3} density soil 350 mm (upper), 250 mm (middle upper), 150 mm (middle lower) and 50 mm (lower) form the centre line of the tyre.



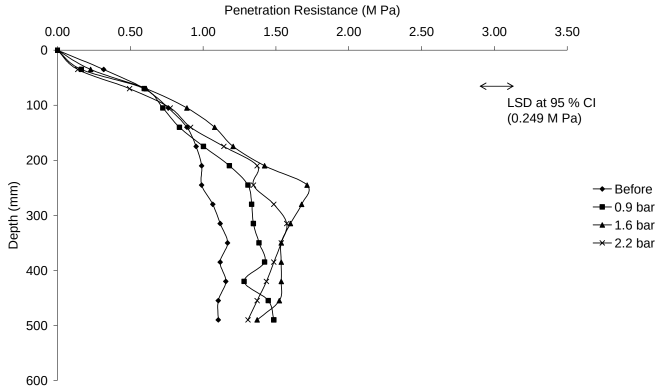
Penetration resistance for 700 mm section tyre on 1.35 t m^{-3} density soil 350 mm (upper), 250 mm (middle upper), 150 mm (middle lower) and 50 mm (lower) form the centre line of the tyre.

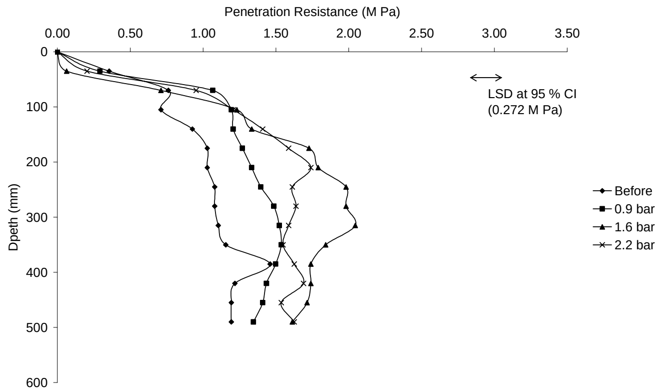


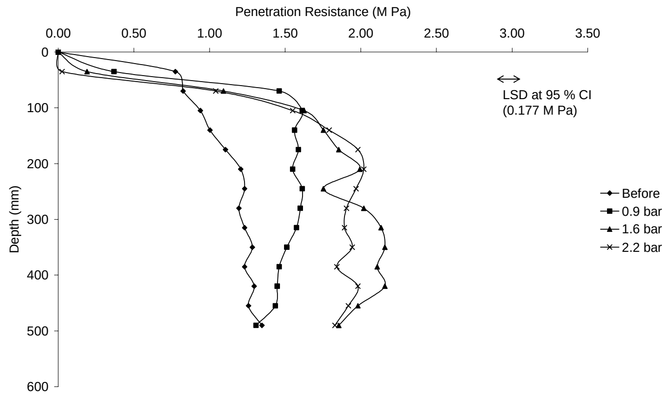
Penetration resistance for 700 mm section tyre on 1.25 t m^{-3} density soil 350 mm (upper), 250 mm (middle upper), 150 mm (middle lower) and 50 mm (lower) form the centre line of the tyre.

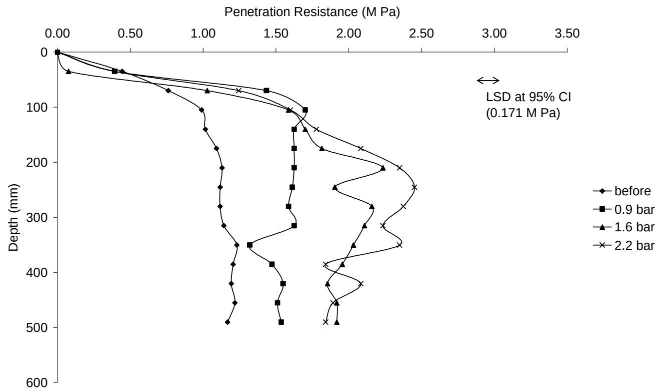


Penetration resistance for 800 mm section tyre on 1.57 t m^{-3} density soil 350 mm (upper), 250 mm (middle upper), 150 mm (middle lower) and 50 mm (lower) form the centre line of the tyre.

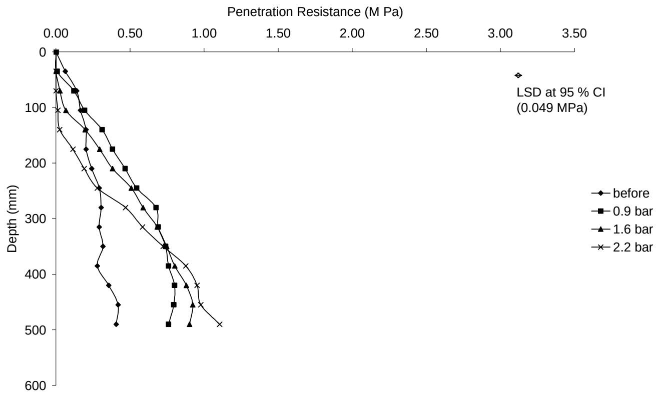


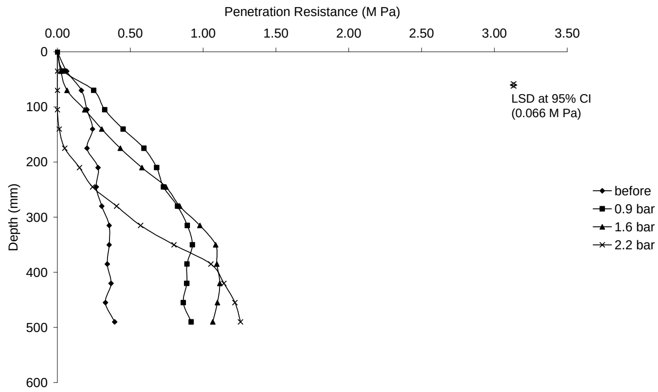


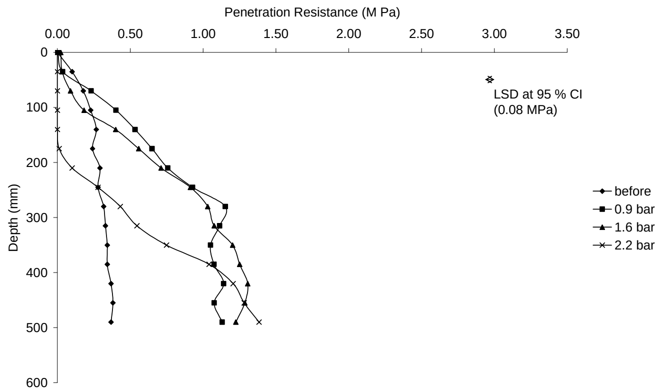


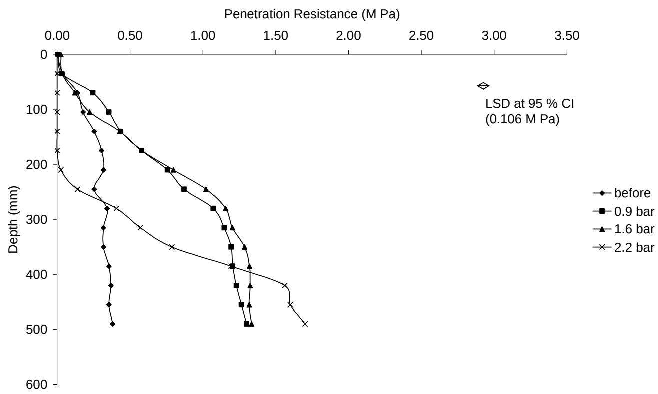


Penetration resistance for 800 mm section tyre on 1.35 t m^{-3} density soil 350 mm (upper), 250 mm (middle upper), 150 mm (middle lower) and 50 mm (lower) form the centre line of the tyre.









Penetration resistance for 800 mm section tyre on 1.25 t m^{-3} density soil 350 mm (upper), 250 mm (middle upper), 150 mm (middle lower) and 50 mm (lower) form the centre line of the tyre.