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THE UNIVERSITY OF ALBERTA

TRACTION EFFECTS ON SOIL COMPACTION

by

JOSEPH FREDERICK RICKMAN

A THESIS

SUBMITTED TO THE DEPARTMENT OF GRADUATE STUDIES AND RESEARCH
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Date 9th May 1988

ABSTRACT

The problem of soil compaction has paralleled the growth in farm machinery size and weight. Compaction problems have been reported from virtually every form of mechanised agriculture in the world.

This study examined the effect that the passage of a driven wheel had on soil compaction and the subsequent effect on crop growth. The parameters studied were vehicle mass, inflation pressure, the number of passes and wheelslip. Soil density readings were taken prior to compaction, immediately after compaction and prior to crop harvest. The individual plots were harvested with a combine harvester.

Increasing the load, the inflation pressure of the tire, and the number of passes increased the soil density to a depth of 200 mm. After reaching a threshold tire load, further increases in soil density depended more on an increase in inflation pressure than an increase in load. The greatest amount of soil compaction occurred as a result of the first pass. Wheelslip appeared to be a surface phenomenon and any effect on soil density was removed by cultivation.

Crop yield was dependent on soil density. The relationship was quadratic in nature with maximum yields attained when the soil density reached a level equivalent to approximately 10% air filled porosity at field capacity. The growth of the crop reduced soil compaction by approximately 50% of the initial change.

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1. INTRODUCTION

Compaction is defined as the reduction in volume for a given mass of soil without a change in moisture content. It is often expressed as a change in bulk density, void ratio, or porosity. Many of the soil's hydraulic properties such as hydraulic conductivity and liquid and vapour diffusion are affected by compaction so the net result is generally a reduction in crop yield. Compaction also reduces the volume of water which can be held in the soil profile.

Problems such as excessive soil hardness, poor crop establishment, irregular and reduced crop growth, wet and puddled soils, and ineffective tile drainage are now recognised as symptoms of soil compaction. However, in some instances it is desirable to increase the density of the soil. In drier climates, soils are often compacted after sowing to slow evaporation and aid both crop establishment and growth. However, soil conditions which are necessary for good crop growth are not generally conducive to high tractive efficiencies and flotation. Road constructors often till the soil intensely before compaction with pneumatic tires.

The problem of soil compaction has paralleled the growth in farm machinery size and mass. Compaction problems have been reported from virtually every form of mechanised agricultural and horticultural undertaking, the grazing of fodder crops, and forestry. The damage caused by compaction averages over a billion dollars per year in the United States of America alone (Gill 1971) and proportionate losses could be assumed wherever mechanised agriculture is practised.

In the context of rising costs and rural labour shortages, the mechanical and economic efficiency of using larger, heavier, and more complex farm machinery can be justified. Whilst it has been argued by some authors that tires and crop production are not compatible, (Taylor 1986) the fact remains that the majority of farmers will continue to use farm machinery in a manner similar to their current situation. Erbach (1986) calculated that over 80% of a field will be trafficked at least once per season for crops such as corn and soyabeans in the USA. Swedish studies showed that for small grain crops, the wheel track surface is 4 to 5 times as great as the soil surface on an annual basis (Eriksson et al. 1974). Corresponding results for northern Australia suggest that the wheel tracked surface at least twice the annual cropping surface area.

In some of the most vulnerable soils and crops, compaction is probably not seriously reducing yields as deep tillage has become an annual management practice. However deep tillage is very costly and treats only the symptom and not the cause.

1.1 Soil Response

Conventional soil mechanics show that the degree of soil compaction is highly dependent upon soil texture, soil moisture content, and energy input. When a load is applied to the soil it causes the soil particles to be rearranged increasing bulk density and reducing pore volume.

Resistance to compaction is determined by grain-size distribution and composition of the grains in a soil (Harris 1971). Compaction is achieved most easily in soils consisting of different sizes of grains where smaller grains can move into voids between larger grains. Loams, because of the wide distribution of grain sizes, compact to greater densities than clays or sands for the same loads. Russell (1971) reported that in England, the soils most severely affected by vehicle traffic are those high in fine sand and silt and low in clay. High bulk densities have been recorded in soils with more than 40% silt-size grains (Diebold as cited by Warkentin 1971). Clay soils are not easily compacted because swelling on wetting decreases bulk density (Warkentin 1971). The deleterious effects on clay soil usually result from the reorientation of soil fabric causing smearing and puddling.

Resistance to compaction also is dependent on the initial soil density. Davies et al. (1973) found that the passage of a wheel caused only slight changes in density when the initial density for a silty loam soil was 1.48 Mg m^{-3}. However when the initial density was 0.94 Mg m^{-3}, the same treatment increased the density by 0.34 Mg m^{-3}.

Soil compactability also is affected by the organic matter content. The greater the organic matter content, the lower the maximum bulk density and the higher the optimum moisture content for compaction. Bruce (1955) measured the maximum bulk density and moisture contents after continuous corn, in a mixed rotation with manure, and after pasture. The respective bulk densities were 1.75, 1.61 and 1.53 Mg m^{-3}. The maximum densities were attained at moisture contents of 15.5, 18.0 and 21.0% respectively. Swanson, as cited by Soane (1970), found the addition of farmyard manure over a number of years decreased the destruction of macropores under light tractors but not heavy tractors.

1.1.1 Moisture and Load Relationships

For a given energy input, there is an optimum moisture content at which the maximum density will be attained. These soil moisture-density relationships are both well known and widely used in civil engineering. The relationship, best described by a quadratic function, is shown in Figure 1.

Hovanesian, as cited by Harris (1971), showed that the relationship between bulk density and applied load at a constant water content is best described by a logarithmic function. The influence of type of loading on compressibility was established by Soehne (1958). Measurements showed that soil compaction under a rolling tire followed the same basic relation to the pressure over the wheel contact area as that observed during static or kneading compaction tests in the laboratory. Relationships between applied pressure and porosity for a given soil moisture content and between porosity and soil moisture for a given pressure have been established by a number of authors.

Soehne (1958) determined that for cultivated soil, compaction could be described by the following equation :

$$N = A \log PM + C \qquad 1.1$$

where N = porosity,

A = constant for a given soil,

PM = maximum compressive pressure, and

C = value dependet on soil moisture.

Amir et al. (1976) expressed porosity as a function of applied pressure, residual pressure and volumetric soil moisture contents between 0.4-0.9 of saturation. This relationship is expressed

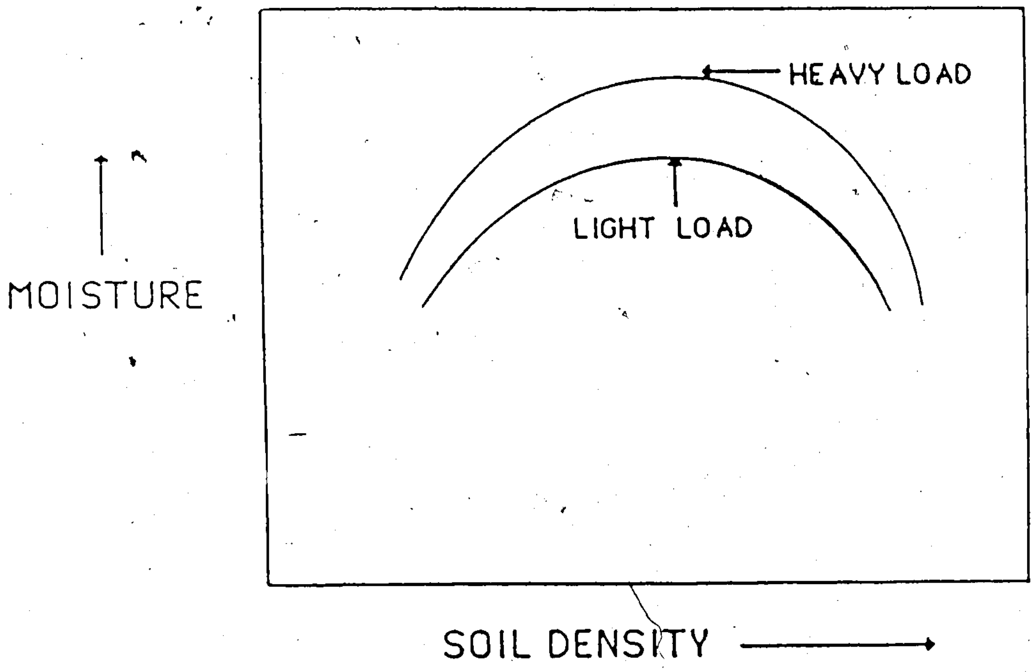

FIGURE 1. The soil moisture-density relationship (modified from Lambe as cited b Soane 1970).

by the following equation:

$$N = An - Bn \log(Pr + P) - Cn \log M \qquad 1.2$$

where N = porosity,

P = applied load,

Pr = residual pressure derived from virgin soil conditions,

M = volumetric soil water content in percent and

An, Bn and Cn are constants.

Raghavan et al. (1976) presented a similar equation to Amir et al. (1976) but used dry density (D) as the dependent variable in the relationship:

$$D = a + b(P + Po) + c \log Wv - Wv\ opt \qquad 1.3$$

where D=dry density (g cm^{-3}),

P= applied pressure (kg cm^{-2}),

Po = the preconsolidated pressure (kg cm^{-3}),

Wv= volumetric moisture content (g cm^{-3}),

Wvopt=the moisture content for the peak density obtained in the standard Proctor density test and

a, b, and c are constants.

Tests also showed for a number of passes or loadings, P= np where n=number of passes and p=contact pressure at each pass.

While these equations predict the changes in packing state qualities of a particular soil, they give little information about the soil as an environment for root development.

1.1.2 Air Filled Porosity

Irrespective of what soil parameters are measured, the net effect of soil compaction is usually a reduction in air filled porosity.

If air filled porosity decreases sufficiently, gaseous transfer may be severely restricted or curtailed. A review by O'Connell (1975) concluded that a minimum air porosity of 10% at field capacity probably defines the minimum conditions for British soils. Other authors including Vomocil and Flocker (1961) and Grable (1971) presented similar conclusions. On clay soils, Osborne (1984) concluded that the 10% air filled porosity figure was probably high especially in a reduced tillage situation. Grable and Seimer(1968) showed oxygen levels at shallow depths dropped abruptly when air filled porosity was reduced to some critical level. This critical level may be as high as 20% if temperatures and microbial activity are high. Also reduction in air filled porosities have been shown to reduce nitrification. (Miller and Johnson 1964)

If the particle density and soil moisture content are known, the relationship between air filled porosity and bulk density can be expressed by the following equation.

$$\mathbf{AFP = 100\ (1-(DB/PD)-((GM/100)x(DB/DW))} \qquad \mathbf{1.4}$$

where AFP=air filled porosity (%),

DB=bulk density (Mg m^{-3}),

DW=density of water(Mg m^{-3}),

PD=particle density (Mg m^{-3}), and

GM=gravimetric soil moisture content (%).

From this relationship, it becomes possible to link the changes in packing state qualities to a parameter which has biological meaning. O'Connell (1975) suggested that the bulk density equivalent to 10% air filled porosity, at field capacity, may be the upper density limit at which compaction may become a problem. Rickman (1987) came to similar conclusions through preliminary laboratory studies.

1.2 Compactive Forces

Forces which cause compaction originate from either mechanical sources such as vehicle tires or natural phenomema such as consolidation or slumping. A further associated effect is non-compactive deformation which may occur locally under a loaded surface, as smearing, or over a larger volume as plastic flow. All of these effects contribute to changes in soil physical properties and the passage of a wheel is accompanied by a complex association of these processes.

There are three primary types of forces exerted on the soil during the passage of a driven wheel (Soane et al. 1980). These are the downward acting forces due to the dynamic load on the wheel, the shear resulting from the torque acting around the axle and the vibration effects transmitted from the engine through the carcass of the tire. Whilst all of these forces are present for tractors and self propelled harvesters, the wheels of towed equipment will only exert a dynamic load.

During the passage of a driven wheel, changes occur to the physical state of the soil. These changes are represented schematically in Figure 2.

The soil immediately under the tire is subjected to very intense shearing forces, especially if wheelslip is high. These shearing forces cause soil particles to be re-aligned in an orientation parallel to the direction of the shear force (Davies et al. 1973). As a result there is considerable smearing, causing destruction of the natural surface structure (Soane 1970). Soil density and cohesiveness are increased, resulting in clods of higher strength and reduced water infiltration.

Davies et al. (1973) found that wheelslip caused a substantial increase in rut depth and shear strength in both silty loam and clay loam soils. Increasing the tractor weight without slip had a small effect. By deliberately increasing wheelslip there was a tendency for larger tractors to cause greater compaction. This may be associated with the higher thrusts produced by larger tractors. Raghavan et al. (1978) showed maximum compaction occurred when wheelslip was between 15-25% on a clay soil. In these studies, higher levels of wheelslip also increased rut depth as more soil was displaced from the ruts. Byers (1958) found wheelslip caused the most damage in the top 75 mm of soil. Wheelslip caused larger increases in bulk density in sandy loam soils than clay soil (Raghavan et al. 1978). Natural amelioration of smeared layers has been reported in clay soils by Kuipers (1980) and McGowan et al. (1983). After slight drying the smeared layer cracked, allowing plant roots to penetrate and therefore not affecting final yields (McGowan et al. 1983).

Not all soil displacement caused by a driven wheel is taken up in reduced volume. Some soil may be displaced by plastic flow around the tire causing heave (Davies et al. 1973).

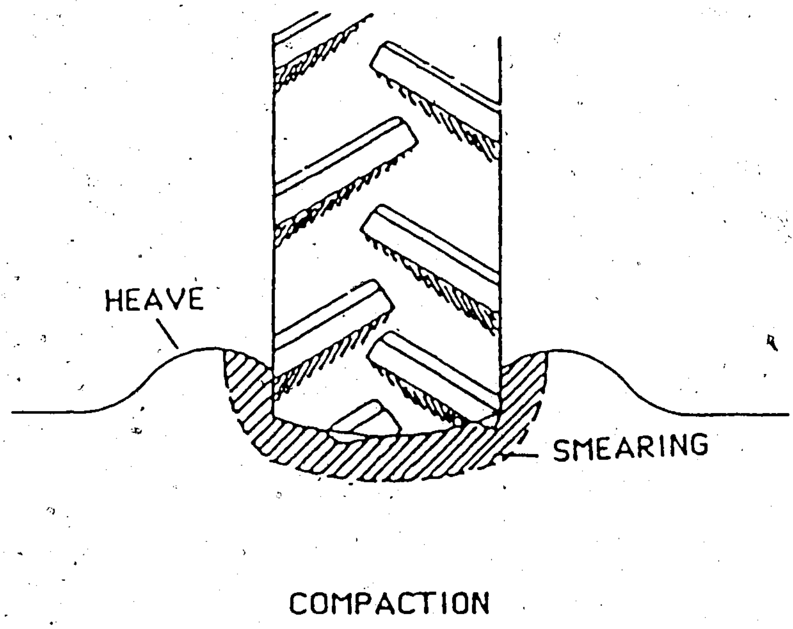

FIGURE 2. Soil reaction to the passage of a driven wheel (modified from Soane 1970).

The amount of soil movement will depend on the shear strength, the soil texture, and soil moisture content (Soane 1970). If the soil is very wet, its compactability will be low as the pore space is largely filled with water. In this situation, plastic deformation can be large. If no heave is detected, it can be assumed that all sinkage has been translated into compaction (Davies et al. 1973).

Whilst compaction in the surface layers causes management problems, it is the soil below the cultivation depth that has received the most attention from researchers. In this zone, there is a concentration of downward forces and shearing stresses from the wheel (Soane 1970). Compaction occurs with an intensity and distribution which is dependent on the applied pressure, the total load, the duration of loading, the dimensions of the contact area as well as the soil strength below the soil surface.

Reducing the inflation pressure reduces the actual pressure on the soil (Danfors 1974). Campbell et al. (1984) found that reducing tire pressures from 105 kPa to 42 kPa resulted in lower bulk densities and increased air filled porosities in a sandy clay loam soil. Bulk densities were 1.16 Mg m^{-3} and 1.12 Mg m^{-3} respectively. Koger et al. (1985) also found that lower bulk densities occurred when pressures were reduced from 172 kPa to 103 kPa. Soane et al. (1980) stated that tires act like rigid bodies when pressures are high and this accounts for more compaction at higher pressures. Taylor et al. (1980) reported greater soil pressure at depth for heavier loads at similar tire pressures. On clay soils, Eriksson et al. (1974) found that loads of 6 tonne per axle increased densities at depth in wet conditions but loads of 8 tonne per axle were required when the soil was dry. Loads of 2-4 tonnes had no measurable effect. On clay loam soils, Voorhees (1986) found that if the axle mass was less than 5 tonnes, compaction did not exceed a depth of 300 mm. Loads in excess of 10 tonnes caused compaction to 600 mm depth and reduced porosity from 51% to 41%. Results presented by Duval et al. (1987) showed no measurable differences in the number of pores, 3 μm in size, after the applying loads from 5 to 18 tonnes on a clay soil.

Increasing tire width to reduce compaction will not necessarily have the same benefits as increasing tire diameter. Fekete as cited by Soane et al. (1980) found that an effective reduction in compaction can only be achieved if the increase in tire width is such that the contact pressure can be reduced by at least 50%. Koger et al. (1985) showed that smaller tires, 18.4 x 34 inches, caused a significant increase in bulk density when compared to larger diameter tires, 24.5 x 32 inches. Taylor et al. (1975) found that a pneumatic track which had a footprint twice as long and half as wide as a pneumatic tire improved tractive efficiency and decreased compaction.

Tires of radial ply construction are now widely used on tractor drive wheels. Over a range of inflation pressures and loads, the radial tire has an increased contact area compared to the crossply tire. However, this increase in contact area has led to only small decreases in compaction (Abeel and Declercq 1977).

Soil density also will be affected by the number of passes of a wheel. The effect varies largely with soil texture and the initial soil strength. Koger et al. (1985) reported significant increases in compaction on loamy sand soil between the second and third pass. However no differences were recorded on clay or sandy loam between the second and fourth pass. Davies et al. (1973) found that 84% of the increase in density occurred with the first pass on clay soils but the magnitude of the change depended on the initial density. Taylor (1986) found 75% of the total change in bulk density and 90% of the rut depth occurred in the first pass. Raghavan et al. (1976) suggested that for predicting bulk density changes in homogeneous sands and sandy loam soils, contact pressure should be multiplied by the number of passes. In Sweden, Eriksson et al. (1974) found yields were not affected by compaction even after four passes on soils that contained less than 20% clay.

The duration of loading also will influence the degree of compaction. Stafford et al. (1981) found the level of tire sinkage decreased and water infiltration in the ruts increased with an increase in operating speed. Increasing the speed from 3 to 16 km h^{-1} resulted in a 12% decrease in bulk density. The change in speed had a larger effect on clay soils than sandy clay loam. However, Danfors (1974) suggested that increasing the forward speed does not result in lower bulk densities. Any benefit from increasing the speed was be negated by the effect that added bouncing and swaying may have, especially on uneven surfaces.

Effects of vibration forces transferred to the soil through the tire should be superimposed on those arising from wheelslip and load (Soane et al. 1980). Vibration, when transmitted through a rigid track, adds further to the loading effect. Cooper and Reaves, as cited by Soane (1970), found vertical loads under a track reached peak values of 0.7 kg cm^{-2} although surface pressure was about 0.35 kg cm^{-2}. The higher peaks were attributed to vibration and impact loads. Boels (1980) stated that it is unlikely that vibrations from tracklayers will cause problems if the track is not rigid. Little work has been done on the contribution that vibration may have to soil compaction under a pneumatic tire, although some studies suggest it may have an effect on sandy soils (Soane et al. 1980).

1.3 Crop Response

Crop responses to different degrees of soil compaction indicate that for each crop, soil and growing season there is an optimum level of soil compaction where crop production will be maximised. The position of this optimum moves toward higher levels of compaction for monocotyledenous crops, coarser textured soil and drier seasons (Figure 3) (Eriksson et al. 1974).

Chancellor (1976) has shown that heavy traffic prior to or during seedbed operations for wheat, sorghum and maize did not reduce yields. In some instances yield was increased due to a better continuity of water filled pores which led to higher plant establishment. The problem of insufficient compaction is particulary important on coarser textured soils subject to drought before or after sowing. Soane (1985) suggested that this may be associated with poor seed-soil contact, insufficient upward capillary conductivity of water or a deficiency in manganese, particulary in young seedlings. Raghavan et al. (1978) showed that in a dry year, the highest corn yields were recorded with an applied pressure of 500 kPa and densities of 1.05 Mg m^{-3}. In a wet year, the peak yields occurred at densities of 0.8 Mg m^{-3}. Swedish studies have shown a 40% increase in barley yields due to compaction in a dry growing season (Eriksson et al. 1974). Voorhees (1986) reported that compaction increased barley yields on coarse sandy soil irrespective of the season. On sandy loam soil, light compaction initially

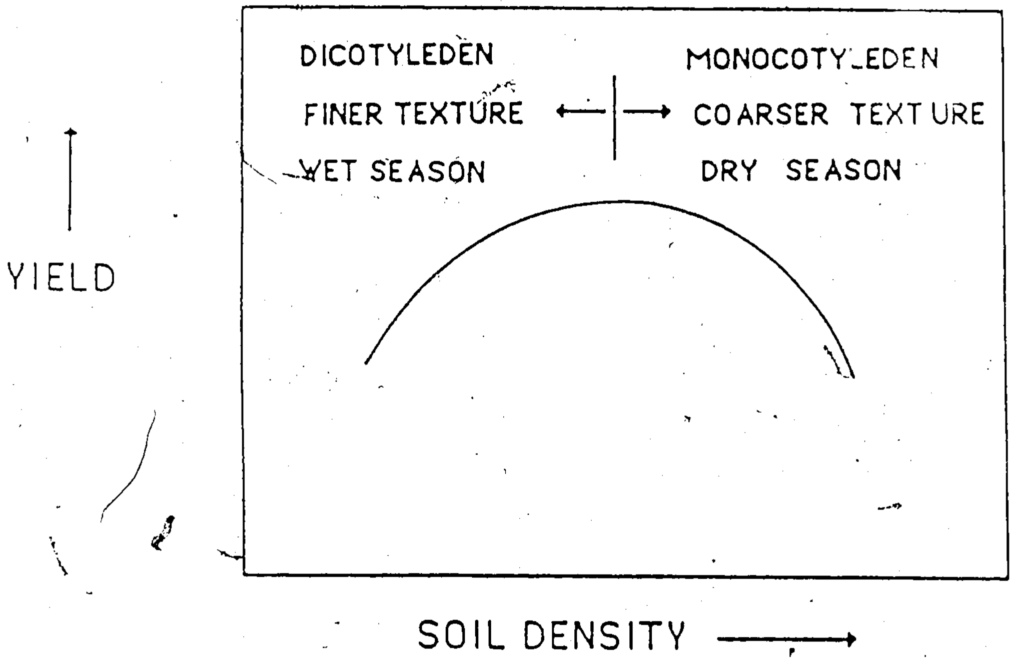

FIGURE 3. Yield response to different soil densities for various crops, soil textures, and seasonal conditions (modified from Eriksson et al. 1974).

increased yields but excessive traffic reduced yields. On silty loam soil, increased yield due to compaction was noted during a dry season but compaction was detrimental during wet years. McGowan et al. (1983) found that barley and bean yields were not affected by smeared layers in clay soils. Natural amelioration of these layers occurred after slight drying.

The negative effect of compaction on crop yield has been reported by many authors. Gill (1971) estimated that compaction was costing the USA over 1.18 billion dollars per year. Eriksson et al. (1974) estimated that cereal production on clay soils in Sweden would increase by at least 6% in the absence of compaction. Reports from the USSR have shown up to a 15% decrease in oat yields when the bulk density was increased by as little as 0.1 Mg m^{-3} above the optimum (Dvortzov and Polyak as cited by Soane et al. 1980). McKyes et al. (1980) recorded yield losses of 40% in hay and oats in areas compacted by construction traffic on clay soils. Densities had risen by 0.15 Mg m^{-3} in the top 300 mm of soil. In this study the relationship between density and yield appeared to be negatively linear. Over a three year period, Campbell et al. (1984) reported a 12% increase in yield by reducing tire pressures from 100 kPa to 42 kPa. However reduced soil densities were recorded in only two out of the three years.

1.4 Project Objectives

Accepting the fact that heavy farm machinery may be operated on soils vulnerable to compaction, it is important to understand the mechanics of soil compaction as it relates to the passage of a wheel and the biological response of the crop.

The objectives of this study were:

1. To examine the effect that wheel load, tire pressure, the number of passes and wheelslip have on soil bulk density.
2. To examine the effect that any resultant changes in soil density may have on crop yields.
3. To examine the effect that crop growth has on reducing soil compaction through the growing season.

2. MATERIALS AND METHOD

2.1 Experimental Location and Duration

The study was conducted at the Ellerslie Research Station near Edmonton, Alberta. Soils at the research station have been described as Eluviated Black Chernozems (Sanborn 1981).The study commenced in May 1987 and was completed in September 1987.

2.2 Machinery

A two wheel drive Massey Ferguson tractor, Model 2805, and a White combine harvester, Model 5542, were used to compact the different treatments.

To vary the load on each tire, the tractor was operated in both a dual and single tire configuration. The total mass and distribution between the steer and drive tires for the tractor and combine harvester are given in Table 1. The tractor was operated on 20.8 x 38 inch tires whilst the combine harvester was operated on 28L x 26 inch tires. Equal tire pressures were used in both the drive and steering tires of both vehicles when compacting the plots. Complete coverage of each plot was achieved by driving back and forth at a constant speed of 7.2 km h^{-1}.

The mass per tire was measured by weighing each axle on a weighbridge and then dividing by the number of tires (Table 1). Tire pressures were measured with a tire pressure gauge when the valve was as close to the ground as possible. Ground speed was measured by timing the tractor over a known distance at the desired throttle setting and gear.

The different levels of wheelslip were attained by varying the drawbar load on the Massey Ferguson 2805. This was achieved by varying the depth of cultivation for an 8 m wide cultivator. For this experiment the tractor was operated on dual tires inflated to 100 kPa.

To measure plot yields, the crop was swathed with a 4.5 m swather and then picked up and threshed by the White combine harvester.

TABLE 1. The total mass and distribution per axle for the tractor and the combine harvester.

VEHICLE		STEER AXLE (kg)	DRIVE AXLE (kg)	TOTAL MASS (kg)
TRACTOR	(DUALS)	2297	6776	9073
	(SINGLES)	2310	5890	8200
HARVESTER		670	4420	5090

2.3 Treatment and Design

The study was undertaken in three parts.

To examine the effect that variation in tire mass and pressure had on bulk density and crop yield, a 3x3 randomised factorial design was used and replicated three times. Each plot was 50 m long by 10 m wide. The three mass treatments were 1694 kg/tire, 2211 kg/tire, and 2945 kg/tire whilst the three tire pressures were 50 kPa, 100 kPa, and 200 kPa.

To examine the effect that the number of passes had on soil density, four different treatments were used in a randomised design and replicated three times. The treatments were 0, 1, 2, and 3 passes. Each pass was applied by the Massey Ferguson 2805 tractor travelling at 7.2 km h^{-1}, on single tires inflated to 100 kPa. Each plot was 50 m long by 10 m wide.

A diagram of the plot layout for the load, pressure and number of pass treatments is shown in Figure 4. Due to restrictions in area, some treatments from Replicate 1 were placed beside the block containing treatments from Replicate 2.

A paired plot design was used for the study of wheelslip. Comparisons were made between the wheel ruts and the untrafficked areas immediately adjacent to the wheel ruts. Also, comparisons were made between the wheel tracks in the uncultivated soil immediately behind the tractor tire and those disturbed by the cultivator. The six levels of wheelslip examined were 0%, 4%, 8%, 12%, 13.2%, and 16%. Each treatment was replicated twice. The tractor was operated on dual tires inflated to 100 kPa. Speed of operation was 7.2 km h^{-1}.

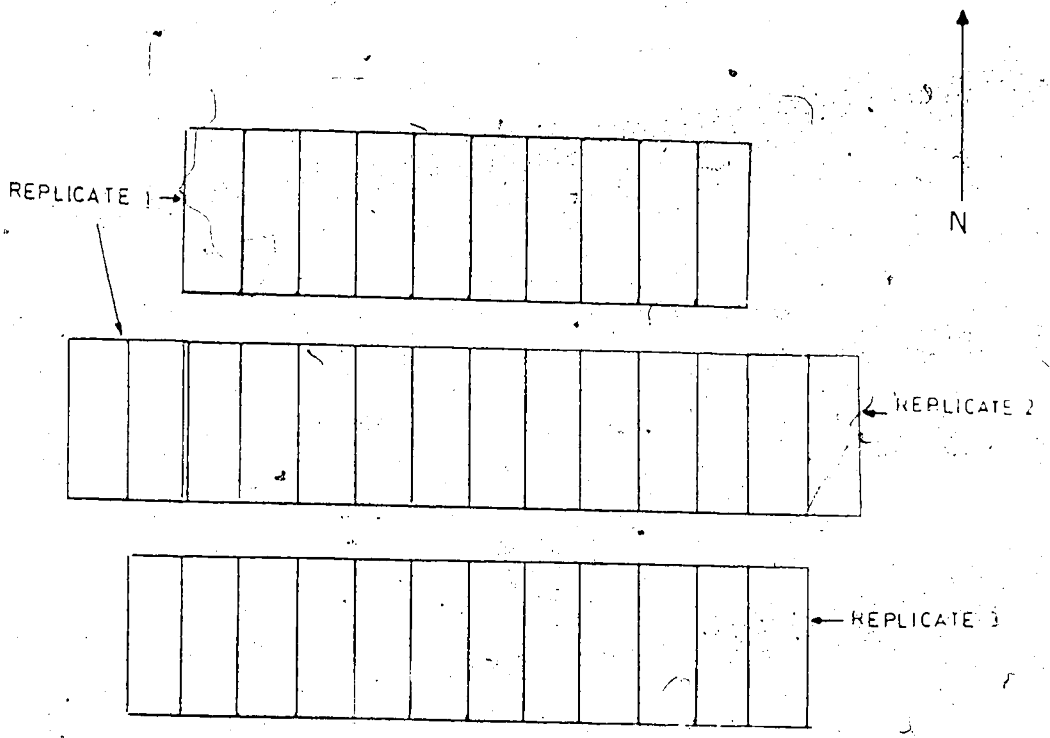

FIGURE 4. Field plot layout for the mass, pressure, and number of pass treatments.

To study the effect that the growth of a crop had on decompacting the soil, density recordings were taken immediately after compaction and prior to the crop harvest. Recordings were taken as close to the original sampling sites as possible.

2.4 Soil and Crop Management

Barley had been grown in the trial site in 1986. After the crop harvest in the autumn of 1986, the site had been cultivated, to a depth of 100 mm, and then left through the winter. Two cultivations, one an anhydrous ammonia application, were completed prior to applying the compaction treatments in May 1987. After applying the treatments the site was then sown to barley. One in-crop herbicide application was applied approximately 30 days after planting. All cultivations, sowing and spray applications were done perpendicular to the long direction of the treatments.

The wheelslip trial was conducted on a site approximately 1 km from the other two trials on soil that had been bare-fallowed through the summer.

2.5 Soil and Crop Measurements

2.5.1 Soil

Bulk density and soil moisture content were measured three times during the study period. Measurements were taken prior to compaction on May 25, after sowing on June 11, and prior to harvest on September 1.

Bulk density and moisture contents were measured with a twin probe gamma ray density meter (Campbell Pacific Nuclear Model MC-24S Stratigauge). The density meter had been calibrated in the laboratory using soil from the trial site. Recordings were taken over a range of soil moistures from wilting point to field capacity.

Five sites were sampled per treatment. Sampling sites were 10 m apart, along the centreline of each plot, with readings taken at 50 mm increments to a depth of 450 mm.

2.5.2 Crop

Visual observations of crop development and root growth were taken throughout the growing season. Plant populations, dry matter yields, and grain yields were measured for the load, pressure, and number-of-passes trials.

Grain yields were measured by both quadrat sampling and combine harvester. One metre square quadrats were hand-harvested from the same location that the bulk density and moisture readings were taken. These samples were then oven dried prior to hand threshing and cleaning. The combine harvester was used to thresh a 50 m by 4.5 m swath taken from the centre of each treatment. The grain was weighed after discharge from the main auger of the combine. The crop had been swathed at 35% moisture and threshed at 14% on dry basis.

2.6 Statistical Analysis

The analysis f variance test was used to determine the level of significant difference among treatments. If a significant F value was obtained in the analysis of variance test, the Least Significance Difference (LSD) range test was then used to compare the treatment means.

3. RESULTS

3.1 Visual Observations

3.1.1 Soil Heave

Differences in the amount of soil disturbance and heave were quite noticeable both between treatments within the replicates and also between the replicates. All of the treatments appeared to cause more soil disturbance in Replicate 3 than in Replicates 1 or 2. This may have been due to the higher soil moisture content of Replicate 3 at the time of compaction. Eleven millimeters of rain fell between the compaction of Replicates 1 and 2 and Replicate 3. The single tire treatments at 200 kPa left the deepest ruts and caused the most heave around the tire wall. The higher tire pressure treatments applied with the combine appeared to cause more soil disturbance and deeper ruts than treatments applied with the tractor on single tires.

3.1.2 Crop Maturity

No visual differences were noted in time to anthesis and crop maturity for the different treatments. However, differences in crop density and maturity were obvious wherever the wheels of the anhydrous ammonia applicator trailer had passed. The crop in these wheel marks was slower maturing and lodged badly in high winds during the grain-filling stage. Less plant tillering was also observed in these areas.

3.1.3 Lodging

Lodging occurred in most treatments following high winds generated by a tornado on July 31. The areas of higher soil density appeared to have a greater percentage of crop lodged. This was especially obvious on the headlands at the end of the treatments and the areas which received the most traffic.

However, crop yields did not appear to suffer from the lodging. There were very few barley seeds left on the ground after harvest. Differences between where the crop was badly lodged and the standing crop could not be detected by lodged or unharvested plants after swathing.

3.1.4 Root Growth

Visual observations suggest that the number of roots in the 300 to 400 mm zone were less in the more compacted treatments. However, this also was affected by the depth of the A-B horizon interface. Irrespective of treatment, few roots were visible in the B horizon. The restriction in root numbers could be associated with the higher density of the B horizon.

3.2 Physical Parameters

Using the Canadian System of Soil Classification, the soil in the A horizon at both locations was classified as a loam. The A horizon, which was approximately 450 mm deep, overlay a denser clay loam B horizon. The mean density for the A horizon was 1.1 to 1.4 Mg m^{-3} and the B horizon 1.4 to 1.6 Mg m^{-3}. The A horizon contained 35% sand, 41% silt and 24 % clay. The particle density was 2.56 Mg m^{-3} and the soil contained approximately 8% organic matter (Chanasyk 1988). Moisture content at -33 kPa and -1500 kPa pressure were 29 % and 19 % (gravimetric) respectively.

The mean gravimetric soil moisture content, at the time of compaction, varied between the replicates. Moisture contents in the top 100 mm for Replicates 1, 2, and 3 were 24%, 25 %, and 32% respectively. At depths between 100 mm and 450 mm, the average moisture levels were 32%, 33% and 37% respectively.

The monthly precipitation at Ellerslie in 1987 was 56.3, 45.2, 118.8, and 84.0 mm for the May, June, July, and August respectively compared to 1951-80 averages of 44.8, 77.7, 84.5, and 66.7 mm respectively.

3.2.1 Bulk Density

3.2.1.1 Pre-Treatment

An analysis of variance was completed on the soil density readings taken prior to compaction for the mass and pressure treatments (Table 2). The mean density for the main treatments are shown in Table 3 and the mean density of the soil profile is shown in Figure 5.

The natural variability within the trial site was such that the difference in bulk density between pre-treatment and post compaction was a more meaningful parameter to use for analytical purposes than absolute bulk density. The initial mean densities for each mass and pressure treatment by depth are presented in Appendix 1.

3.2.1.2 Density Changes

Moisture

The mean gravimetric moisture content and the change in soil density for the soil profile in each Replicate are presented in Table 4.

Whilst a valid statistical analysis is not possible on the replicate means, the moisture contents of Replicates 1 and 2 are lower than that of Replicate 3 and the changes in density greater.

Mass and Pressure

The field results show that changing both mass and inflation pressure had a significant effect on soil density (Table 5). Significant differences were established at the 0.99 level for both the mass and the pressure treatments. No significant differences were established for the interaction between mass and pressure, mass and depth, pressure and depth or the interaction between mass, pressure and depth. The combined means for the density change due to mass and pressure (Table 6) were established by subtracting the mean pre-compacted density for each plot from the post-compacted density, for the full soil profile.

TABLE 2. Analysis of variance for the pre-treatment density for the mass and pressure treatments.

SOURCE of VARIATION	DEGREES of FREEDOM	MEAN SQUARE	F VALUE	PROBABILITY
REPLICATE	2	0.1226		
MASS	2	0.0133	8.31	0.99
PRESSURE	2	0.0063	3.95	0.99
DEPTH	8	0.1115		
ERROR	228	0.0016		
TOTAL	242			

TABLE 3. Mean density (Mg m^{-3}) for the mass and inflation pressure treatments for all depths prior to compaction.

MASS (kg)		PRESSURE (kPa)		
	50	100	200	MEAN
1694	1.28	1.27	1.28	1.28
2211	1.26	1.24	1.27	1.25
2945	1.29	1.26	1.27	1.27
MEAN	1.28	1.26	1.27	1.27

TABLE 4. Mean moisture content and density change for each replicate.

REPLICATE	GRAVIMETRIC SOIL MOISTURE (%)	SOIL DENSITY CHANGE (Mg m^{-3})
1	32	0.04
2	33	0.05
3	37	0.02

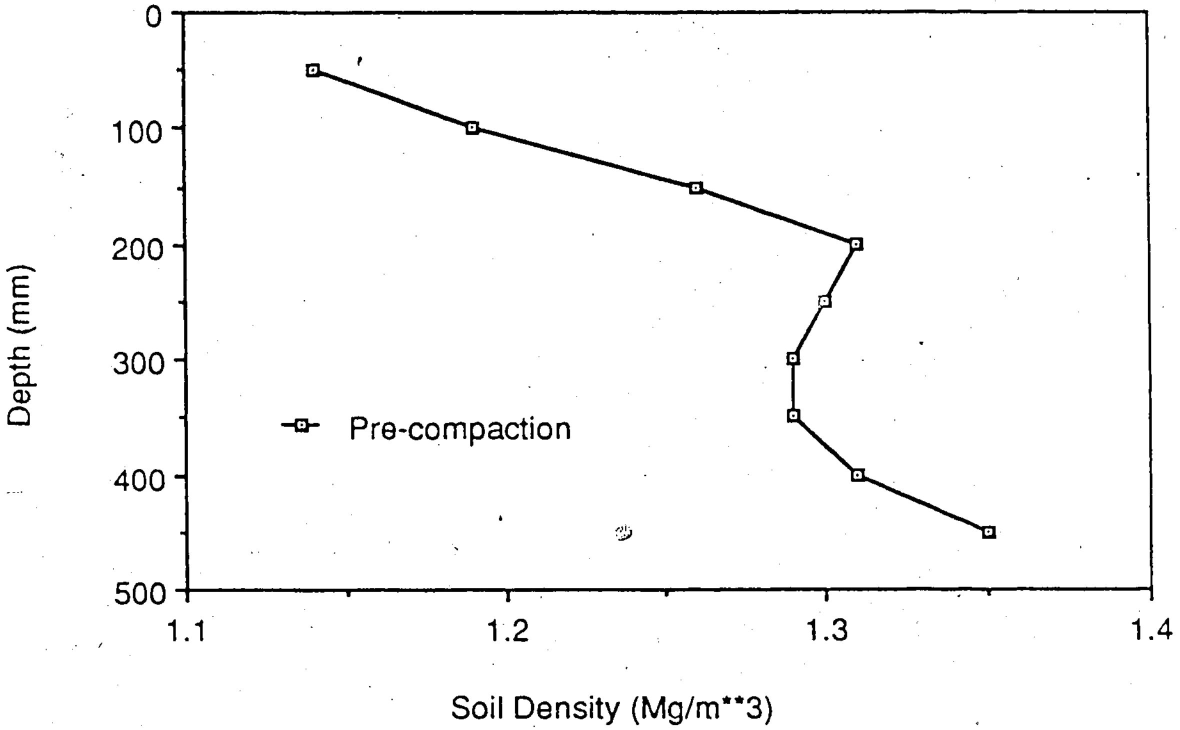

FIGURE 5. The soil density profile prior to compaction.

TABLE 5. Analysis of variance for mass and pressure treatments.

SOURCE of VARIATION	DEGREES of FREEDOM	MEAN SQUARE	F VALUE	PROBABILITY
REPLICATE	2	0.0163		
MASS	2	0.0118	6.3913	0.99
PRESSURE	2	0.0218	11.8586	0.99
DEPTH	8	0.0490	26.6304	0.99
MxP	4	0.0009		
MxD	16	0.0006		
PxD	16	0.0004		
MxPxD	32	0.0013		
ERROR	160	0.0018		
TOTAL	242			

M=Mass, P=Pressure, D=Depth

TABLE 6. Mean density change (Mg m^{-3}) for mass and pressure.

MASS per TIRE (kg)	PRESSURE (kPa)			MEANS	
	50	100	200		
1694	0.00	0.02	0.04	0.02	a
2211	0.02	0.05	0.05	0.04	b
2945	0.03	0.05	0.06	0.04	b
MEANS	0.02	0.04	0.05	0.03	
	a	b	c		

Significant differences shown by different letters.

The mean change in density, for all treatments, with depth is shown in Figure 6. The individual changes for load and pressure treatments are shown in Figure 7 and Figure 8 respectively.

The relationship between mass per tire, tire pressure, and change in soil density was established using multiple regression techniques. As mass per tire and tire pressure are mutually inclusive, the sum of both functions was necessary to establish an equation which would express the resultant change in density.

The algorithm which describes the change in bulk density for a change in either mass or pressure or both is expressed by:

$$D = a + bM + cP \tag{3.1}$$

where D=bulk density change ($Mg\ m^{-3}$),

M=mass per tire (kg), and

P= pressure (kPa).

The regression coefficients were a= -0.06401, b=0.00005, and c=0.00067. The R^2 for this relationship was 0.92. These results have also been expressed as a surface response curve in Figure 9. The change in density with depth for the top 200 mm of soil for the mass, pressure, and number-of-pass treatments are presented in Table 7.

Number of passes

Increasing the number of passes had a significant effect on increasing soil density. The analysis of variance results for the number of passes are given in Table 8.

The effect of increasing the number of passes was significant at the 0.99 level. However the interaction between the number of passes and the depth of soil was not significant. The mean density change for the different numbers of passes, for the full soil profile, are presented in Table 9 and the soil densities both prior to and after traffic are shown in Figure 10.

Wheelslip

The analysis of the wheelslip results was undertaken in two parts. The first part compared the passage of the tractor without slip to a non-traffic control. Results are given in

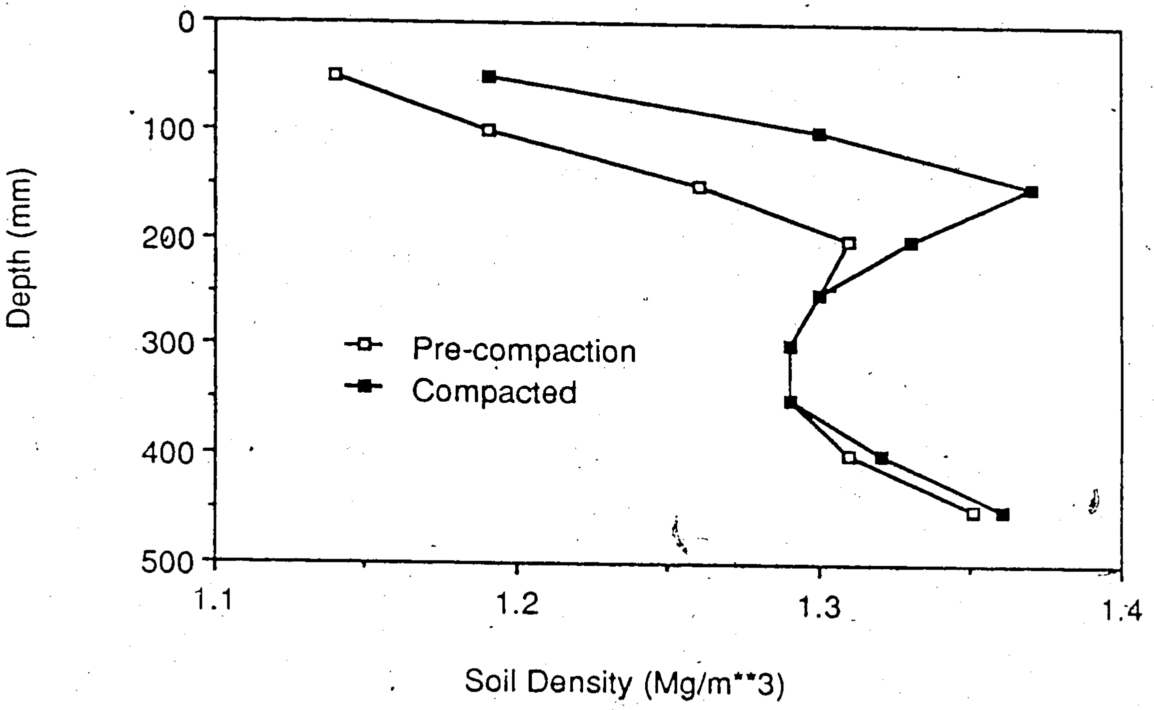

FIGURE 6. Mean change in soil density prior to compaction and immediately after compaction.

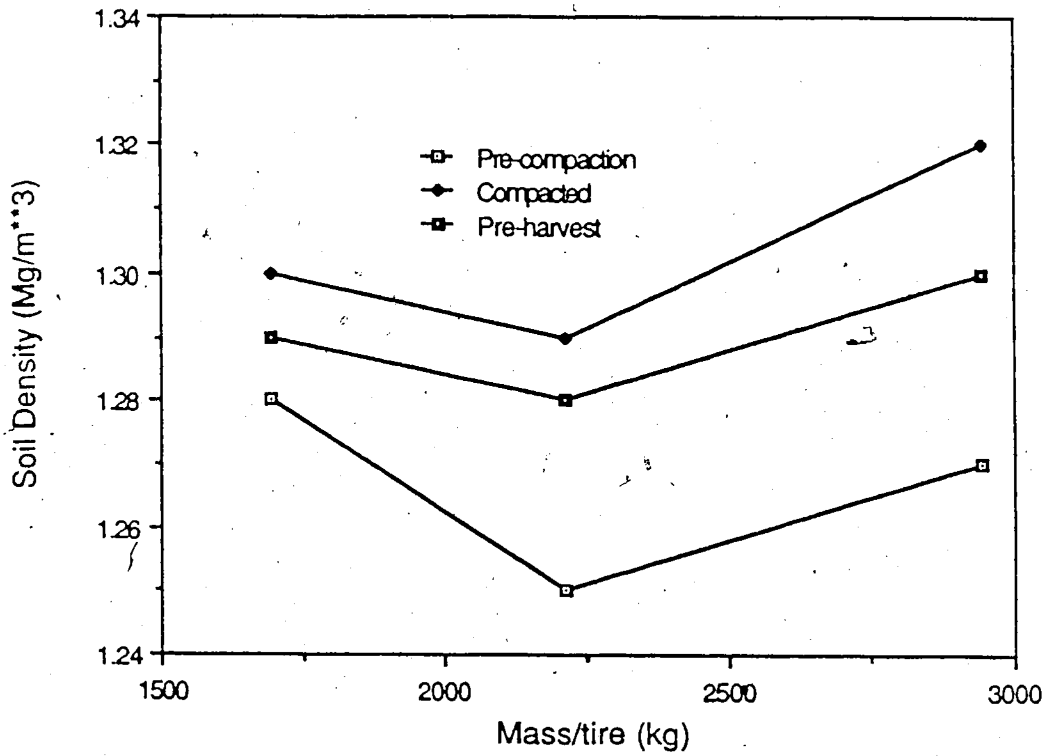

FIGURE 7. Mean change in soil density fo[illegible] change in mass per tire.

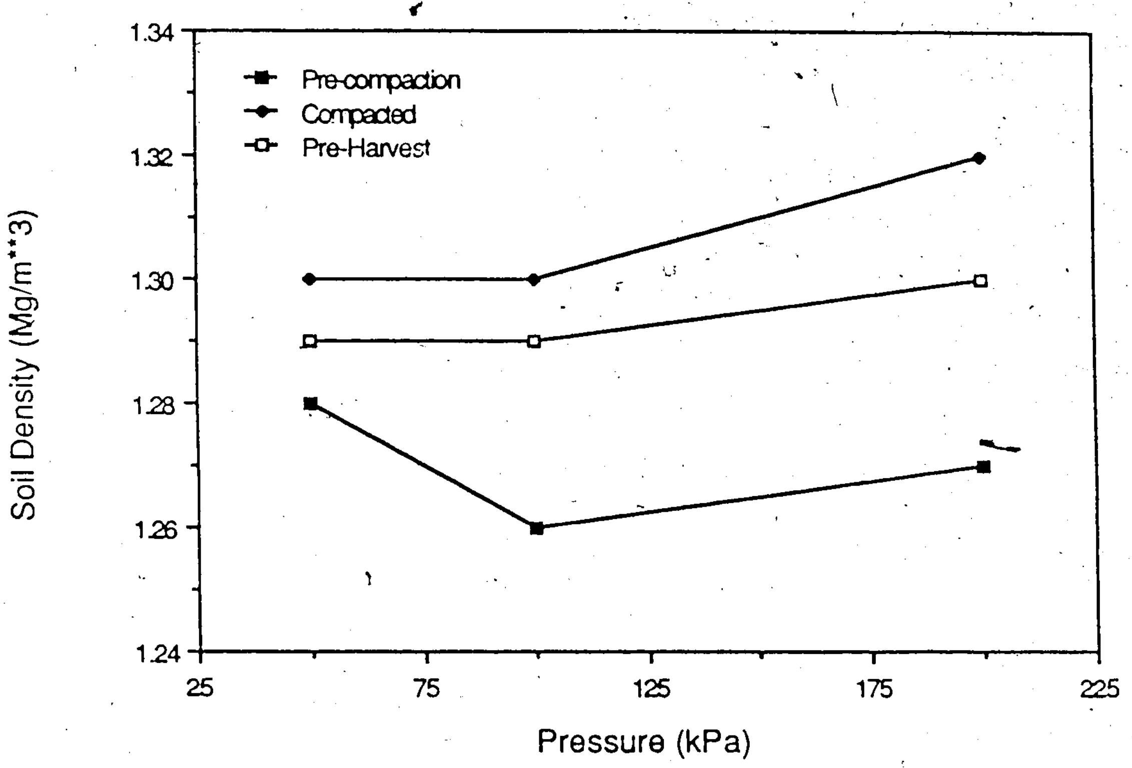

FIGURE 8. Mean change in soil density for a change in tire pressure.

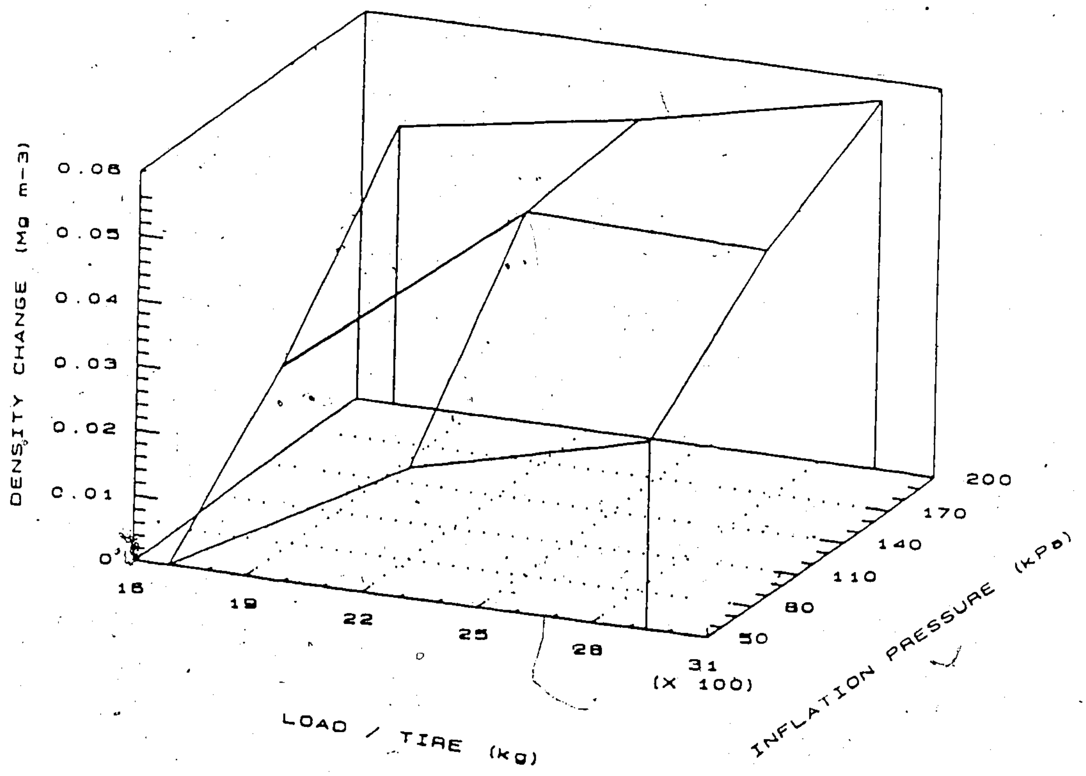

FIGURE 9. A surface response curve for mass per tire, tire pressure, and soil density.

TABLE 7. The density change (Mg m^{-3}) with depth due to changes in mass and pressure.

TREATMENT	SOIL DEPTH (mm) 0-50	50-100	100-150	150-200
MASS / TIRE (kg)				
1694	0.04	0.08	0.09	0.02
2211	0.05	0.11	0.11	0.04
2945	0.06	0.13	0.10	0.04
PRESSURE (kPa)				
50	0.03	0.08	0.07	0.01
100	0.06	0.11	0.10	0.04
200	0.07	0.20	0.12	0.04

TABLE 8. Analysis of variance for number of passes.

SOURCE of VARIATION	DEGREE FREEDOM	MEAN SQUARE	F VALUE	PROBABILITY
REPLICATE	2	0.0079		
PASSES	3	0.0167	5.357	0.99
DEPTH	8	0.0290	9.265	0.99
PxD	24	0.0027		
ERROR	70	0.0030		
TOTAL	107			

PxD=PASSES x DEPTH

TABLE 9. Density changes for each pass (Mg m^{-3}).

NUMBER OF PASSES	DENSITY CHANGE (Mg m^{-3})	LSD	
		(5 %)	(10 %)
0	0.00	a	a
1	0.04	b	b
2	0.04	b	b
3	0.06	b	c

Significant differences are shown by different letters.

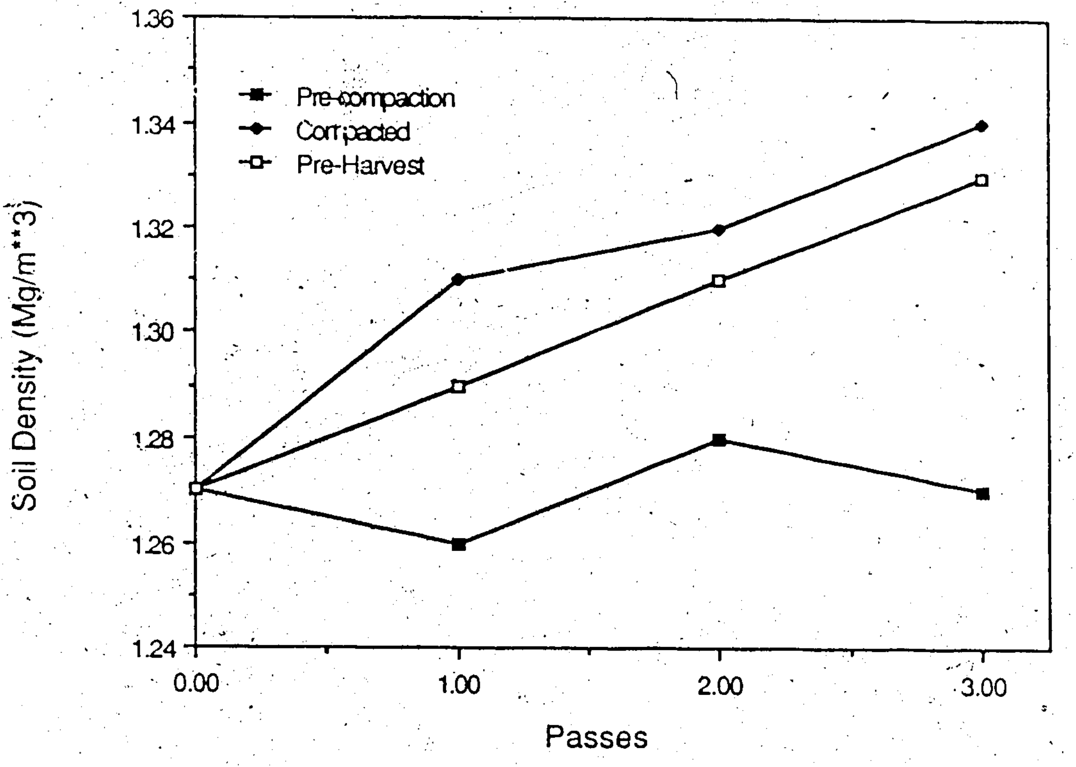

FIGURE 10. The change in soil density as a function of the number of passes.

Table 10.

The second part compared the passage of a tire with slip to the control, the effect cultivation had on decompacting the soil and the effect that various levels of wheelslip have on soil density (Table 11). Whilst these results suggest that there are differences between the various levels of wheelslip, the result was overshadowed by the fact that compaction, with wheelslip, was not significantly different from the control treatment without wheelslip. The effect of cultivation was significant in reducing compaction (Table 12).

Decompaction

Crop growth had a significant effect on decompacting the soil (Table 13). The results for decompaction both as a treatment and with soil depth were highly significant. The mean reduction in soil compaction for the soil profile is presented in Figure 11.

3.2.2 CROP YIELD

3.2.2.1 Plot Yields

An analysis of the grain yields for the full plot are presented in Table 14. Significant differences were established between different tire pressure and yield, at the 0.95 level. Whilst no significant differences were established between the different mass/tire treatments (Table 14), the effect of increasing the tire pressure was greater at the higher levels of mass/tire. At the lowest mass /tire (1694 kg/tire), increasing the tire pressure from 50 to 200 kPa reduced yields by 1.2%. When the mass/tire was increased to 2945 kg/tire, the same increase in tire pressure reduced yields by 7.2% The mean yield reduction for increasing the tire pressure from 50 to 200 kPa was 4.5% (Table 15).

A relationship was established between grain yield and bulk density using regression analysis. The relationship is best described by a quadratic function in the algorithm:

$$Y=a + bX + cX^2 \qquad 3.2$$

where Y = yield (kg ha^{-1}),

X = bulk density (Mg m^{-3}),

TABLE 10. Analysis of variance results for the passage of a wheel without slip.

SOURCE of VARIATION	DEGREES FREEDOM	MEAN SQUARE	F VALUE	PROBABILITY
REPLICATE	2	0.0068		
TRACTOR	1	0.0241	19.1	0.99
DEPTH	8	0.0281	22.3	0.99
ERROR	42	0.0013		
TOTAL	53			

TABLE 11. Analysis of variance results for wheelslip and cultivation.

SOURCE of VARIATION	DEGREES FREEDOM	MEAN SQUARE	F VALUE	PROBABILITY
REPLICATE	1	0.0151		
TRAFFIC	1	0.0027	1.22	
WHEELSLIP	4	0.0365	16.18	0.99
CULTIVATION	1	0.0737	34.11	0.99
DEPTH	8	0.2546	117.59	0.99
ERROR	344	0.0022		
TOTAL	359			

TRAFFIC compares the passage of a tire with slip to the passage of a tire without slip.

TABLE 12. Means for the effect of wheelslip and cultivation on soil density (Mg m^{-3}).

TREATMENT	BULK DENSITY (Mg m^{-3})
CONTROL	1.44
4.0%	1.42
8.0%	1.43
12.0%	1.42
13.2%	1.42
16.0%	1.46
NON-CULTIVATED	1.45
CULTIVATED	1.42

TABLE 13. Analysis of variance for decompaction by plant growth.

SOURCE VARIATION	DEGREES FREEDOM	MEAN SQUARE	F VALUE	PROBABILITY
BLOCKS	26	0.0240		
TREATS	1	0.0266	21.288	0.99
DEPTH	8	0.0881	70.440	0.99
ERROR	450	0.0013		
TOTAL	485			

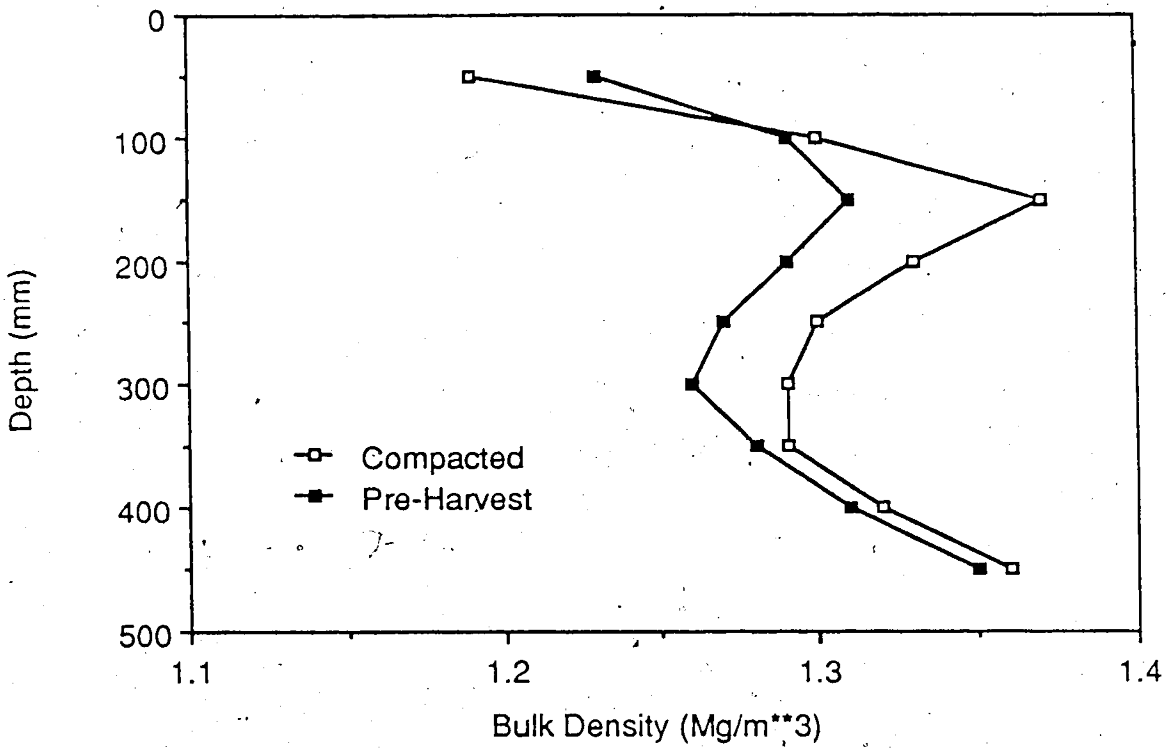

FIGURE 11. Changes in soil density during the growing season.

TABLE 14. Analysis of variance of the grain yields harvested by the combine for the mass and pressure treatments.

SOURCE VARIATION	DEGREES FREEDOM	MEAN SQUARE	F VALUE	PROBABILITY
REPLICATE	2	90.28		
MASS	2	22.87	2.32	
PRESSURE	2	34.64	3.51	0.95
ERROR	20	9.86		
TOTAL	26			

TABLE 15. Mean crop yield (kg ha^{-1}) for the tire pressure and mass per tire treatments.

MASS		TIRE	PRESSURE (kPa)	
(kg)	50	100	200	MEAN
1694	3535	3658	3486	3559
2211	3535	3545	3363	3481
2945	3648	3648	3385	3560
MEAN	3572	3617	3411	3533
LSD (5%)	a	a	b	

Significant differences are shown by different letters.

a, b and c the regression coefficients.

The regression coefficients were a= -451379, b=701626 and c= -270479. The R^2 was 0.73. The relationship between the measured and estimated density (using Equation 3.2) and grain yield are also expressed in Figure 12. Equation 3.2 predicts a maximum yield of 3625 kg at a density of 1.3 Mg m^{-3}.

3.2.2.2 Quadrat Yields

Significant differences between treatments could not be established using quadrat yields. Regression analyses were used to compare yield and density, material-other-than-grain and density, and total yield and density. Although analyses of the data were undertaken for the total trial area, the individual replicates, and treatments no significant difference was found between treatments.

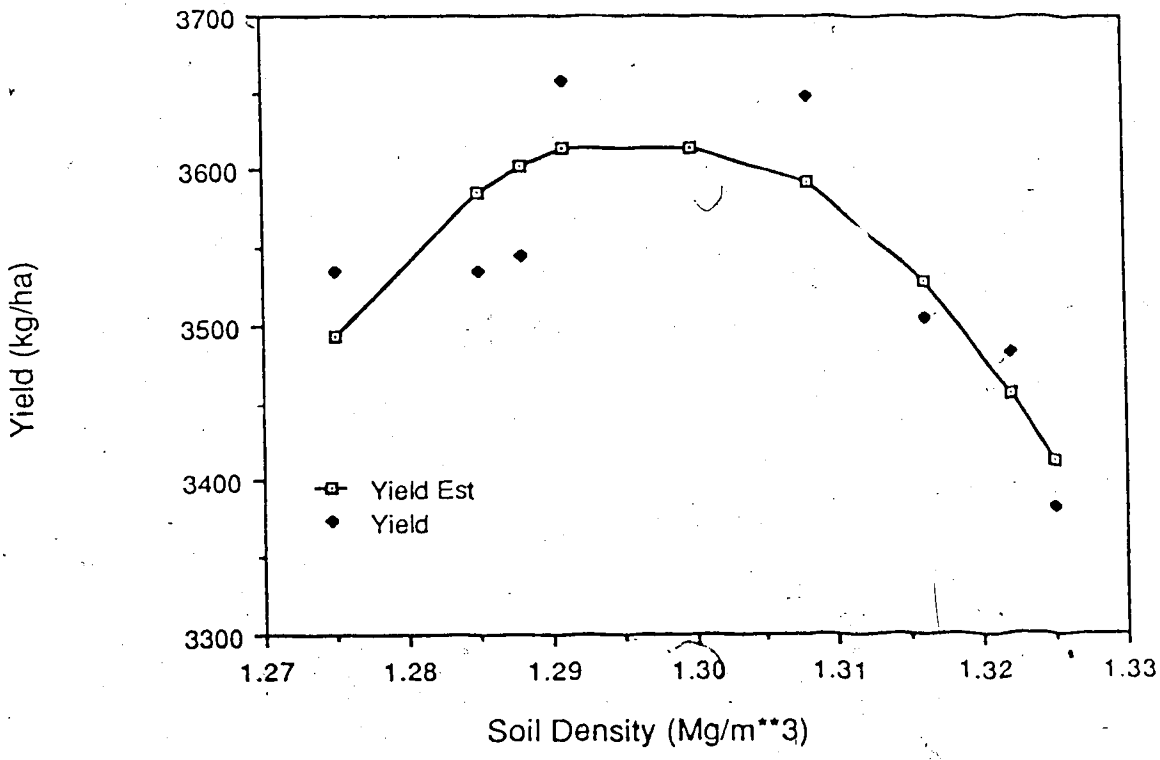

FIGURE 12. Grain yield as affected by soil density. (Estimated yield is from Equation 3.2; yield is field-measured yield).

4. DISCUSSION

4.1 Changes in soil density

4.1.1 Magnitude of Change

Increasing the load on the soil surface caused an increase in soil density. The change in soil density was dependent on the mass per tire, the tire pressure, the number of passes for each vehicle tire, and the soil moisture content at the time of compaction.

Significant changes in density were recorded when the mass per tire was increased from 1694 kg to 2211 kg. However no significant differences were recorded when the mass was increased from 2211 kg to 2945 kg per tire (Figure 7). This result is best considered in two related parts. Firstly, until a certain load is applied to the tire, little deformation will occur in the tire wall. The tire will act more as a rigid body and any increase in load will be transferred directly to the soil. This may account for the difference in effect of the 1694 kg mass and the 2211 kg mass. Secondly, after reaching a threshold load, increasing the load per tire without increasing the tire pressure will cause more tire deformation and should create a larger footprint area. If this increase in footprint area is proportional to the change in load, then little change would be expected in soil densities. This could then yield a result similar to the effects of the 2211 kg and 2945 kg treatments.

Increasing the tire pressure effectively reduces the footprint area and increases the normal stress on the soil. Changes in inflation pressure caused significant changes in soil density. Inflation pressures of 50 kPa caused significantly less compaction than inflation pressures of 100 or 200 kPa. Likewise 100 kPa caused significantly less compaction than 200 kPa. The changes in density were 0.02, 0.04 and 0.05 Mg m^{-3} respectively.

As mass and pressure are always present, their effects must be combined to give the total change to soil density. The combined effects (Figure 9) suggest that after reaching a certain mass, the significance of increasing that load further is reduced unless tire pressure is also increased. In practise this is what tends to occur. If a heavier load is to be carried on the same tire, tire pressures are normally increased. However the literature is replete with studies (Eriksson et al. 1974; Taylor et al. 1975; Voorhees 1986) that suggest that mass is the most important factor causing compaction below the plough layer. In these studies either little mention is made of tire pressure or it is not considered to cause increases in density below the top 300 mm of soil. However, results from this study suggest greater emphasis needs to be placed on tire pressure.

Increasing the number of passes significantly increased soil density. Mean density changes for 0, 1, 2, and 3 passes was 0.0, 0.04, 0.04, and 0.06 Mg m^{-3} respectively. These results support the findings of Taylor (1986) and Davies et al. (1973) that the majority of change to soil density occurs in the first pass. In this study 67% of the total change in soil density occurred as a result of the first pass.

Whilst differences in soil densities were observed between different levels of wheelslip, the net result of wheelslip on soil density was not significant. The analysis of results suggested that 8% and 16% wheelslip had significantly different effects on soil density than the other levels of slip. However, these results are overshadowed by a non-significant difference between wheelslip and the control treatments. This second result probably can be accounted for in two ways. Firstly, the natural variability within the trial site was too large for the number of samples taken to establish significant differences, if they did exist. Secondly, as wheelslip is a surface phenomenon (Byers 1958) its effect was removed by cultivation.

The second assumption is supported by a significant difference between cultivation and non-cultivation effects following the passage of a tire with slip. In all of the reports cited where wheelslip increased density, studies occurred prior to cultivation. In field situations, wheelslip is generally associated with tillage and thus any negative effect on soil structure may not necessarily be reflected in changes to soil density. Other parameters such as clod size, clod strength or implement draft measurements may be more meaningful parameters to guage the affect that wheelslip has on soil structure.

4.1.2 Depth

Whilst the magnitude of the change varied between different treaments, the increase in density was restricted to the top 200 mm of soil for all treatments.

Increasing the mass per tire did not increase the depth of effect as suggested by Eriksson et al. (1974), Taylor et al. (1975), and Voorhees (1986). Change in den [illegible] or the three mass treatments was evident to 200 mm. The magnitude of the change was significantly less for the lower mass and pressure treatments.

Increasing the inflation pressure increased both the magnitude and the depth to which density changes occurred. Inflation pressures of 50 kPa caused density changes to 150 mm depth. Inflation pressures of 100 kPa and 200 kPa increased the depth of effect to 200 mm and the magnitude of change at each recording depth.

The depth to which density changes occurred was not affected by the number of passes of the tractor tire. The magnitude of the change was greater for 3 passes than for either 1 or 2 passes but the depth of change was similar for all passes (200 mm).

4.1.3 Soil moisture

Whilst there is no valid statistical test for the replicate effects, it is interesting to note that the magnitude of the density change was lower for Replicate 3. The moisture content of Replicate 3 was higher than the other two Replicates at the time of compaction. Visual observation showed more heave and soil disturbance on the surface. These two factors suggest that the soil may have been close to its plastic limit at time of compaction; hence, the smaller change in density.

4.1.4 Decompaction

The growth of the crop reduced the soil density. The mean density increase for the whole area, as a result of compaction, was 0.034 Mg m^{-3}. The crop reduced this by 0.017 Mg m^{-3}. Sixty percent of this reduction occurred in the 50 to 200 mm zone. Natural consolidation increased soil densities in the top 50 mm of soil during the growing period by 0.04 Mg m^{-3}.

The amount that soil density was reduced depended on the initial level of compaction. In the least compacted treatments, where soil densities were increased by 0.02 Mg m^{-3}, the growth of the crop reduced this by 0.01 Mg m^{-3}. However in the more compacted treatments where densities were increased by 0.04 Mg m^{-3} and 0.05 Mg m^{-3}, crop growth reduced these densities by 0.02 Mg m^{-3}.

4.2 Grain Yield

4.2.1 Plot yields

The average grain yield for this trial (3533 kg ha^{-1}) was below the long term district average of approximately 4000 kg ha^{-1}. Increasing the soil density initially increased and then significantly reduced grain yield. Similar findings have been reported by Eriksson et al. (1974) and Voorhees (1986). While the effect of increasing the mass/tire on crop yield, was not significant, the combination of high tire pressure (200 kPa) and the heavier mass (2945 kg/tire) did cause the greatest reduction in yields (Figure 15). The same combination also caused the greatest increase in soil density.

The regression analysis (Figure 12) shows that maximum yield was attained with soil densities at approximately 1.3 Mg m^{-3}. A soil density of 1.3 Mg m^{-3} is equivalent to an air filled porosity of approximately 10% at 30% moisture (Equation 1.4). A number of authors (Vomocil and Flocker 1961; Grable and Seimer 1968; O'Connell 1975) reported that if air filled porosities fall much below this value, at moisture levels near field capacity, plant growth will be affected. These results tend to support that assertion.

4.2.2 Quadrat yields

A relationship between yield and soil density could not be established by quadrat sampling. This reflects the amount of in-crop variability within the treatments, as a correlation was established between the total plot yields and soil density for each treatment.

5. CONCLUSIONS

1. Increasing the load on the soil surface increased the soil density.
2. The magnitude of the density change depended on the mass per tire, the tire pressure and the number of passes.
3. Changes in tire pressure appeared to have a greater effect on soil density than did changes in mass.
4. After a tire loading of approximately 2200 kg, an increase in soil density depended more on an increase in tire pressure than an increase in mass.
5. The greatest amount of soil compaction occurred as a result of the first pass.
6. Irrespective of the treatment, the depth to which density changes occurred remained constant at 200 mm. The magnitude of change at each recording depth varied according to the load.
7. Wheelslip appeared to be a surface phenomenon and any effect on soil density was removed by cultivation.
8. Crop yield was quadratically related to soil density with yields maximised at a density corresponding to 10% air filled porosity at a moisture level near field capacity (30%).
9. The growth of the crop reduced soil compaction. The magnitude of the change depended on the amount of compaction. The mean reduction in density was approximately 50% of the difference between the pre-compacted density and the post-compacted density.
10. Quadrat sampling proved to be an inappropriate method for evaluating the effect that compaction had on crop.

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APPENDIX

1. Mean density for mass and pressure treatments (Mg m^{-3}).

(RECORDED MAY 25, 1987)

DEPTH (mm)

	50	100	150	200	250	300	350	400	450
M1S1	1.20	1.29	1.38	1.40	1.36	1.36	1.35	1.41	1.41
M1S2	1.13	1.18	1.26	1.29	1.34	1.34	1.36	1.38	1.47
M1S3	1.15	1.27	1.36	1.35	1.33	1.34	1.36	1.44	1.48
M2S1	1.14	1.2	1.29	1.33	1.26	1.24	1.25	1.27	1.34
M2S2	1.13	1.2	1.29	1.31	1.30	1.26	1.25	1.26	1.25
M2S3	1.08	1.19	1.29	1.32	1.35	1.39	1.42	1.47	1.46
M3S1	1.15	1.22	1.30	1.28	1.35	1.38	1.42	1.43	1.45
M3S2	1.15	1.27	1.28	1.33	1.32	1.31	1.32	1.35	1.38
M3S3	1.16	1.21	1.31	1.35	1.34	1.35	1.37	1.43	1.47

RECORDED (JUNE 11,1987)

M1S1	1.16	1.21	1.22	1.29	1.28	1.24	1.24	1.28	1.30
M1S2	1.13	1.22	1.31	1.31	1.26	1.25	1.26	1.30	1.36
M1S3	1.14	1.21	1.21	1.24	1.27	1.25	1.25	1.24	1.25
M2S1	1.08	1.18	1.25	1.27	1.28	1.26	1.25	1.25	1.28
M2S2	1.06	1.16	1.17	1.23	1.29	1.25	1.23	1.23	1.26
M2S3	1.15	1.16	1.24	1.30	1.26	1.22	1.21	1.22	1.22
M3S1	1.16	1.25	1.32	1.31	1.26	1.22	1.21	1.24	1.26
M3S2	1.10	1.19	1.30	1.29	1.24	1.21	1.24	1.26	1.32
M3S3	1.11	1.14	1.21	1.27	1.24	1.23	1.24	1.24	1.26

RECORDED (SEPTEMBER 1,1987)

DEPTH (mm)

	50	100	150	200	250	300	350	400	450
M1S1	1.17	1.19	1.19	1.31	1.31	1.27	1.27	1.27	1.32
M1S2	1.13	1.16	1.20	1.31	1.32	1.29	1.26	1.29	1.31
M1S3	1.21	1.16	1.20	1.29	1.32	1.33	1.30	1.30	1.34
M2S1	1.18	1.17	1.23	1.32	1.32	1.29	1.29	1.32	1.38
M2S1	1.17	1.16	1.21	1.28	1.34	1.32	1.30	1.31	1.33
M2S1	1.16	1.15	1.20	1.28	1.31	1.25	1.28	1.29	1.33
M3S1	1.19	1.18	1.26	1.32	1.33	1.30	1.30	1.31	1.37
M3S2	1.08	1.11	1.23	1.27	1.27	1.26	1.27	1.31	1.39
M3S3	1.13	1.17	1.20	1.31	1.33	1.31	1.30	1.29	1.30

M1=MASS 1694 kg	S1= 50 k
M2=MASS 2211 kg	S2=100 kPa
M3=MASS 2945 kg	S3=200 kPA

2. Average soil density for the number of passes (Mg m^{-3}).

RECORDED (MAY 25,1987)

DEPTH (mm)

	50	100	150	200	250	300	350	400	450
P0	1.15	1.27	1.37	1.36	1.36	1.34	1.33	1.34	1.36
P1	1.15	1.27	1.28	1.33	1.32	1.31	[illegible]	1.35	1.38
P2	1.15	1.27	1.36	1.35	1.33	1.34	1.36	1.44	1.48
P3	1.08	1.19	1.29	1.32	1.35	1.39	1.42	1.47	1.46
P0	1.10	1.20	1.28	1.28	1.27	1.25	1.26	1.27	1.31
P1	1.10	1.19	1.30	1.29	1.24	1.21	1.24	1.26	1.32
P2	1.10	1.19	1.30	1.29	1.24	1.21	1.24	1.26	1.32
P3	1.13	1.20	1.29	1.31	1.30	1.26	1.25	1.26	1.25
P0	1.10	1.08	1.05	1.17	1.25	1.28	1.28	1.31	1.35
P1	1.08	1.11	1.23	1.27	1.27	1.26	1.27	1.31	1.39
P2	1.16	1.15	1.20	1.28	1.31	1.25	1.28	1.29	1.33
P3	1.08	1.11	1.23	1.27	1.27	1.26	1.27	1.31	1.39

RECORDED (JUNE 11,1987)

P0	1.16	1.23	1.33	1.35	1.29	1.28	1.27	1.25	1.29
P1	1.21	1.37	1.38	1.36	1.30	1.31	1.32	1.33	1.38
P2	1.25	1.41	1.42	1.36	1.34	1.37	1.39	1.38	1.46
P3	1.27	1.43	1.46	1.40	1.38	1.39	1.40	1.43	1.46

P0	1.25	1.30	1.34	1.30	1.26	1.20	1.23	1.29	1.36
P1	1.24	1.28	1.30	1.29	1.26	1.26	1.23	1.28	1.27
P2	1.16	1.31	1.37	1.31	1.26	1.26	1.26	1.26	1.32
P3	1.25	1.37	1.38	1.34	1.27	1.25	1.24	1.26	1.29

P0	1.12	1.19	1.22	1.29	1.28	1.26	1.29	1.32	1.36
P1	1.14	1.29	1.38	1.32	1.28	1.27	1.32	1.36	1.46
P2	1.15	1.31	1.36	1.32	1.30	1.28	1.28	1.31	1.34
P3	1.18	1.32	1.39	1.32	1.28	1.25	1.30	1.36	1.43

P0= NO PASSES
P1= 1 PASS
P2= 2 PASSES
P3= 3 PASSES

3. Grain yields for the mass and pressure treatments (kg / plot).

	PRESSURE (kPa)		
	50	100	200
R1M1	85.6	87.4	81.5
R1M2	79.7	78.3	77.2
R1M3	87.4	87.4	81.0
R2M1	77.4	79.9	82.6
R2M2	79.2	80.1	76.3
R2M3	82.0	75.6	76.0
R3M1	76.7	74.5	72.4
R3M2	77.6	75.8	74.7
R3M3	80.5	84.5	72.6

R1= REPLICATE 1	M1=1694 kg
R2= REPLICATE 2	M2=2211 kg
R3= REPLICATE 3	M3=2945 kg