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NATIONAL CENTRE FOR ENGINEERING IN AGRICULTURE

Cotton Research & Development Corporation
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MANAGING SOILS TO AVOID COMPACTION PROBLEMS IN COTTON GROWING

by

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Executive Summary

Introduction

This report summarises the findings from the CRDC funded project "Managing soils to avoid compaction problems in cotton growing". The project ran from 1989/90 to 1991/92. It had the principal aims of:

- developing a management system for cotton growers that would minimize tillage requirements, and
- avoiding current problems with soil compaction associated with heavy machinery.

The project was based on a controlled traffic approach so that compacted machinery lanes and compaction free plant zones were separately maintained.

The operation of the project was split between three interacting teams of experts. The teams worked on what became known as the Model, the Laneway and the Guidance subprojects. Separate detailed reports from each of these teams are included in this report.

The Modelling team assessed and quantified the dynamic changes in seedbed conditions by monitoring various soil physical and thermal properties. The information obtained could guide the industry as to the minimum tillage requirements of a cotton crop in a controlled bed environment.

The Laneway team developed guide-lines for the installation, operation and maintenance of suitable compacted laneways for cotton growing.

The Guidance team developed prototypes of automatic equipment that could allow farm equipment to be operated accurately and repeatedly on the compacted laneways over several years.

Staffing

The project drew on the professional skills of the following people and the resources of their respective institutions.

U.S.Q	C.S.I.R.O. / Q.D.P.I.
Dr. M. Porter,	Dr. B. Bridge, (CSIRO Div of Soils)
Dr. H. Harris,	Dr. D. McGarry, (QDPI. Land Res Mang Bnch.)
Dr. D. Hilton,	
Mr. D. Bakker,	
Mr M. Schoenfisch (CRDC Postgrad Fellow)	

Achievements

The potential benefits of controlled traffic farming, including reduced soil degradation, more reliable yields and less fuel usage, have been known for some time. Although widely employed throughout the cotton industry, controlled traffic growing has not always been able to deliver these benefits to the grower. The results of this project establish a sound, practical basis for instigating such a system in cotton growing. The quantitative understanding of key soil parameters developed in the project will also assist in identifying an optimum soil environment for cotton crops. Potential savings to the farmer thus include greater control of his soil resource, avoidance of yield depression and a reduction in tillage costs.

Specifically, we have achieved the following results:

Establishment of a detailed soil properties data base for a tilled Ug5.1 black soil under controlled traffic management on the Darling Downs,

Development of suitable air to surface temperature relationships for modelling soil temperatures

Establishment of soil strength parameters and consolidation behaviour,

Quantification of the dynamic behaviour of the soil in the tilled surface zone of a permanent bed,

Quantification of soil density changes in hills and furrows,

Assessment of the soil's hydraulic properties: its soil water potential, hydraulic conductivity and sorptivity,

Quantification of changes in the tilled soil surface profile, and the associated runoff behaviour over the duration of the project,

Quantification of structural improvement within the tilled zone of a controlled traffic crop

Establishment of a working image-analysis system for soil structural measurements

Quantification of dynamic stresses in the field soil under representative wheel loadings,

Established that tillage should occur below a water content of 30%,

Established that the soil is most compressible at about 30% water content,

Related soil strength to trafficability

Established that raised wheel tracks can provide a method for controlling compaction with no observed yield penalty,

Found that the dynamic component of machinery induced stresses on the soil represents a 30% increase on the static loadings,

Established that the vertical stress load is the dominant contributor to the stress state in the soil under the centre line of a tyre,

Established that a level of soil strength is necessary to limit the deformation occurring from the shear stresses developing 45 cm from the tyre centre line,

Completed a field evaluation of the potential life of compacted laneways,

Developed guidelines for establishing compacted laneways within a controlled traffic system.

Evaluated both leader cable and ultrasonic guidance technology, and constructed working prototypes of both systems,

Identified the limitations in existing guidance technologies when applied to cotton growing in controlled traffic beds,

Established a vision based guidance system as the preferred option for future development.

Produced 2 refereed journal, 9 conference and 6 general media publications, with a further 4 refereed publications now under preparation.

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Acknowledgements

This project was one of the first of the new generation of research activity. Conducted by a multidisciplinary team of engineers and scientists it drew on areas of expertise from three organisations: C.S.I.R.O., the Queensland Department of Primary Industries, and the University of Southern Queensland. The potential problems associated with such a large matrix of people and bureaucratic methodologies are far greater than that usually encountered during in-house projects. The degree of success finally achieved is due in no small part to the willingness of many people in all three organisations. Many of these remain unidentified within their organisations. The authors wish to thank all of these people who have contributed in small but important ways to maintaining our work effort.

We would particularly like to thank the technical support staff at the U.S.Q., the Q.D.P.I. and the C.S.I.R.O. for their dedicated efforts in this project. Mr Trevor Glasby (U.S.Q.) assisted in field work and maintaining the equipment used. Mr Peter Penfold and his staff in the university workshop manufactured much of the specialist equipment required, in particular for the stress sensor work. Mr Dennis Orange (C.S.I.R.O.) assisted in taking in-field disc permeameter readings and analysing the results. The workshop staff at the Q.D.P.I. Indooroopilly offices are thanked for their assistance in assembling the SOLICON test equipment for the project. All of these efforts were necessary for the smooth running of the project.

Special thanks are due to Mrs Melissa McKain and Mrs Mary Reilly for their efforts in administering the project and maintaining the necessary financial records.

Mr Harley Bligh, cotton grower and owner of the property Condamine Plains provided our trial sites. The resultant access to commercial crop data was extremely useful as was Harley's interest in the project. His practical advice has been greatly appreciated, as has the extra help provided by his staff as required during our field work and testing program.

Financial support for the project was provided by the Cotton Research and Development Corporation. The authors are grateful for this support, and for the interest maintained by the Corporation in the progress of the project. The overview provided by members of the Corporation assisted the research team in directing their efforts so that the results are of more direct application to cotton producers in this country.

Finally we thank Professor Peter Swannell, Dean of Engineering at U.S.Q. for his support and interest in this project. Hopefully we have convinced one leading civil engineer that this sort of research is at least as important to the country as is the task of making buildings that do not fall over.

Model sub-project

1. Aims

The modelling sub-project had two sets of goals. The first was to assess the seedbed conditions under a controlled traffic cropping system by regular measurements of various soil physical and thermal properties. The information obtained would quantify the dynamic changes that occur in the soil's properties and would form the basis of a computer management model for the tilled soil zone. This model represented the second major goal of the project. It would be written with a view to providing guidance on the tillage requirements of a cotton crop when grown in a controlled bed environment.

The project work was to be based on the grey vertisols of the Darling Downs with the trial results made available for cross-referencing with other cotton growing soils. This approach would allow the model to be exported to other regions. Soil from the field site would also be available for other studies of fundamental properties so that future research could increase the model's reliability and sophistication. Seedbed conditions were quantified in the project by the soil's macrostructure (arrangement of voids and aggregates) as well as its water content, water potential, bulk density, strength, sorptivity, hydraulic conductivity and temperature - all under the action of tillage, irrigation and weathering processes. Fundamental properties such as the soil's mechanical composition, shear characteristics and moisture characteristic were also established in the laboratory to supplement the field data base. The field and laboratory data were both to be used in the development of the computer model of the soil environment

The general intention of the project has been achieved. A data base of measured soil properties has been completed to describe the dynamic nature of the seedbed within the cropping zone of the controlled traffic system. This report concentrates on the findings from this data collection and analysis work. The algorithms required to develop the required computer model are largely in place. Analyses of the data base has proved to be more demanding then was originally anticipated and is still in progress. This work is continuing internally within the C.S.I.R.O., the Queenland D.P.I. and the U.S.Q. No further external funding is required for this work. The required model will be completed as the final results from the analyses become available. Several new uses for the model in follow-up projects are planned.

2. Methods

All field trials were conducted on the property "Condamine Plains" near Brookstead on the Darling Downs in south-eastern Queensland. The object of the field work was to quantify the dynamic nature of those soil properties that influence a seedbed environment. The field work program was based on the 1990/91 and 1991/92 cotton seasons. Some extra measurements were taken during the period leading up to the following crop in 1992/93. All field work was done in a commercial cotton field rather than in trial plots, so as to establish "industry best" performance in controlled traffic cropping.

Some agronomic and crop management data were also collected on the status of the cotton crops grown for future validation of the developed models. This data summarises the key dates in the crop phenology from sowing to picking as well as the times of irrigation and machinery working.

The methodologies used to collect the required data are described below.

2.1. Weather Data

An automatic weather station was located beside the study field for the duration of the experiment. The logger in this station was configured to record the daily maximum and minimum dry and wet bulb air temperatures, rainfall, solar radiation, and windrun plus the hourly soil temperatures at the surface and at 10 mm, 50 mm, 100 mm and 200 mm in the field.

2.2. Soil Composition

Topsoil samples were taken at random locations on the trial field and bulked into two samples for analysis. They represented overall soil conditions on the northern and southern halves of the field. The chemical and mechanical composition of these samples were determined by laboratory analysis in the Queensland Government Agricultural Research laboratory at Indooroopilly, Brisbane. Further tests at the University of Southern Queensland established the Casagrande limits and the Optimum water content for the soil.

The test procedures used by the Agricultural Research laboratory are listed below:

Test Performed	Method Employed
pH (H_2O)	20:100 Soil to H_2O mix.
Nitrate/Nitrogen ext	20:100 Soil to H_2O mix.
Organic Carbon	Walkley & Black
Air Dry water content	Air Dry content
% coarse Sand	sieving - gravimetric
% fine Sand	sieving - gravimetric
% Silt	hydrometer
% Clay	hydrometer

2.3. Soil Bulk Density

The soil bulk density was obtained from cores taken of the soil profile. A 100 mm diameter corer, 50 mm long, was pushed into the topsoil and then excavated. The corer and soil were sealed into a plastic bag and returned to the laboratory for oven drying and weighing. The soil bulk density was then calculated using the following formula:

$$\rho_d = \frac{M_d - M_c}{V_c}$$

where ρ_d = dry bulk density of soil (kg/m^3)
M_d = mass of sample corer and soil (kg)
M_c = mass of sample corer (kg)
V_c = volume of sample corer (m^3)

The soil bulk density was taken at depth increments of 50 mm in the profile at irregular intervals throughout the project.

2.4. Soil Water Content

The soil water content was obtained gravimetrically in the tilled soil zone and by using a neutron moisture meter for the root zone. The topsoil was sampled at random locations in the field whenever the site was visited. Sampling thus occurred on an irregular basis that largely coincided with farm operations, irrigations or when other soil parameters were being measured.

The topsoil samples were sealed in an air tight container and returned to the laboratory for oven drying and weighing. The gravimetric water content was then calculated using the formula:

$$\theta_g = \frac{M_s - M_d}{M_d - M_c}$$

where θ_g =gravimetric water content of soil (w/w)
M_s = mass of field soil sample (kg)
M_d = mass of dried soil sample (kg)
M_c = mass of sample container (kg)

Neutron readings were taken to a maximum depth of 1.1 m in the profile at 13 locations in the field prior to sowing and on a regular basis after squaring each year. These readings were taken at depth increments of 100 mm. The access tubes were spaced to cover the full length of the experimental field used.

The calibration curve for the neutron meter is shown below:

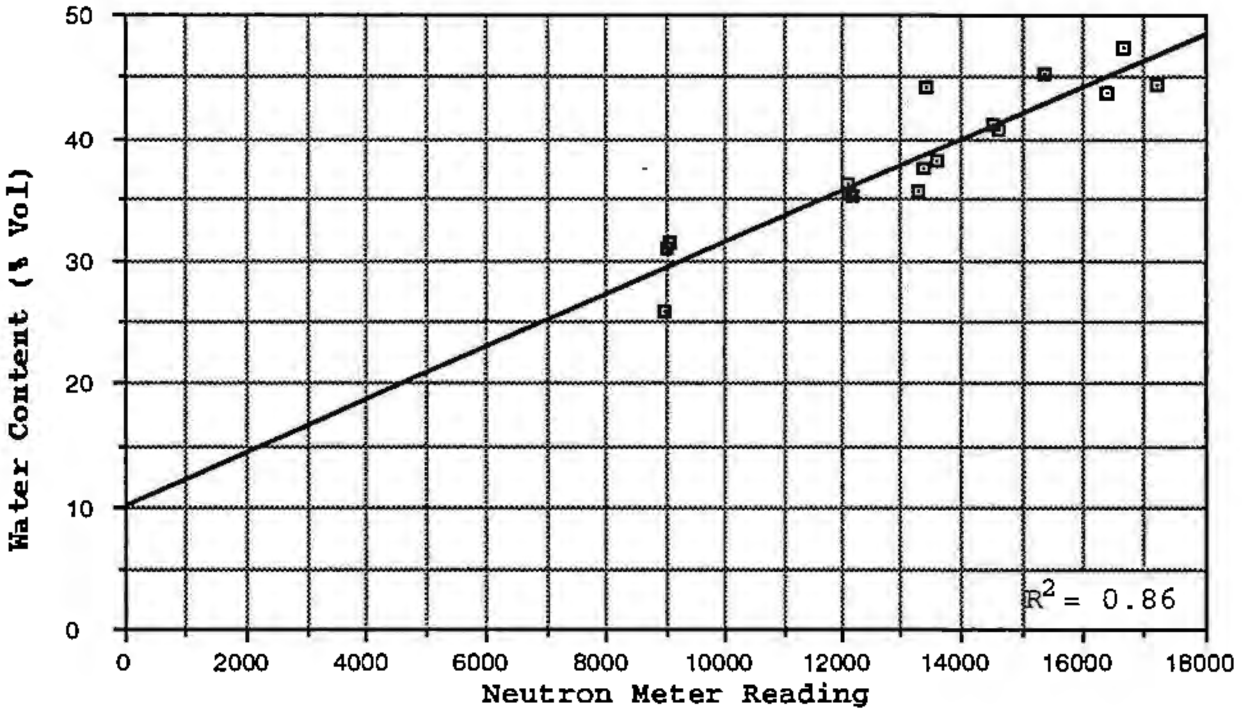

Figure 1. Calibration curve for Neutron meter based on field samples at Condamine Plains.

2.5. Soil Water Potential

The soil water potential was determined using the filter paper method first developed by Fawcett & Collis-George (1967)[1]. The potential was estimated by placing three sheets of Whatman #42 filter paper in contact with the soil taken for soil water determinations. The paper was sealed in the sample container and allowed to reach equilibrium with the soil's potential. The middle sheet of filter paper was then dried and weighed in the laboratory to determine its water content according to the following equation:

$$\theta_p = \frac{M_{ps} - M_{pd}}{M_{pd}}$$

where θ_p =gravimetric water content of filter paper (g/g)
M_{ps} = mass of filter paper in soil sample (kg)
M_{pd} = mass of dried filter paper (kg)

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[1] Fawcett, R.G., & Collis-George, N. (1967) A filter paper method for determining the moisture characteristics of soil. Aust. J. Exp. Agric & Animal Husb. 7:162-167

The filter paper water content was then used to establish the equivalent water potential from the standard calibration curve shown below:

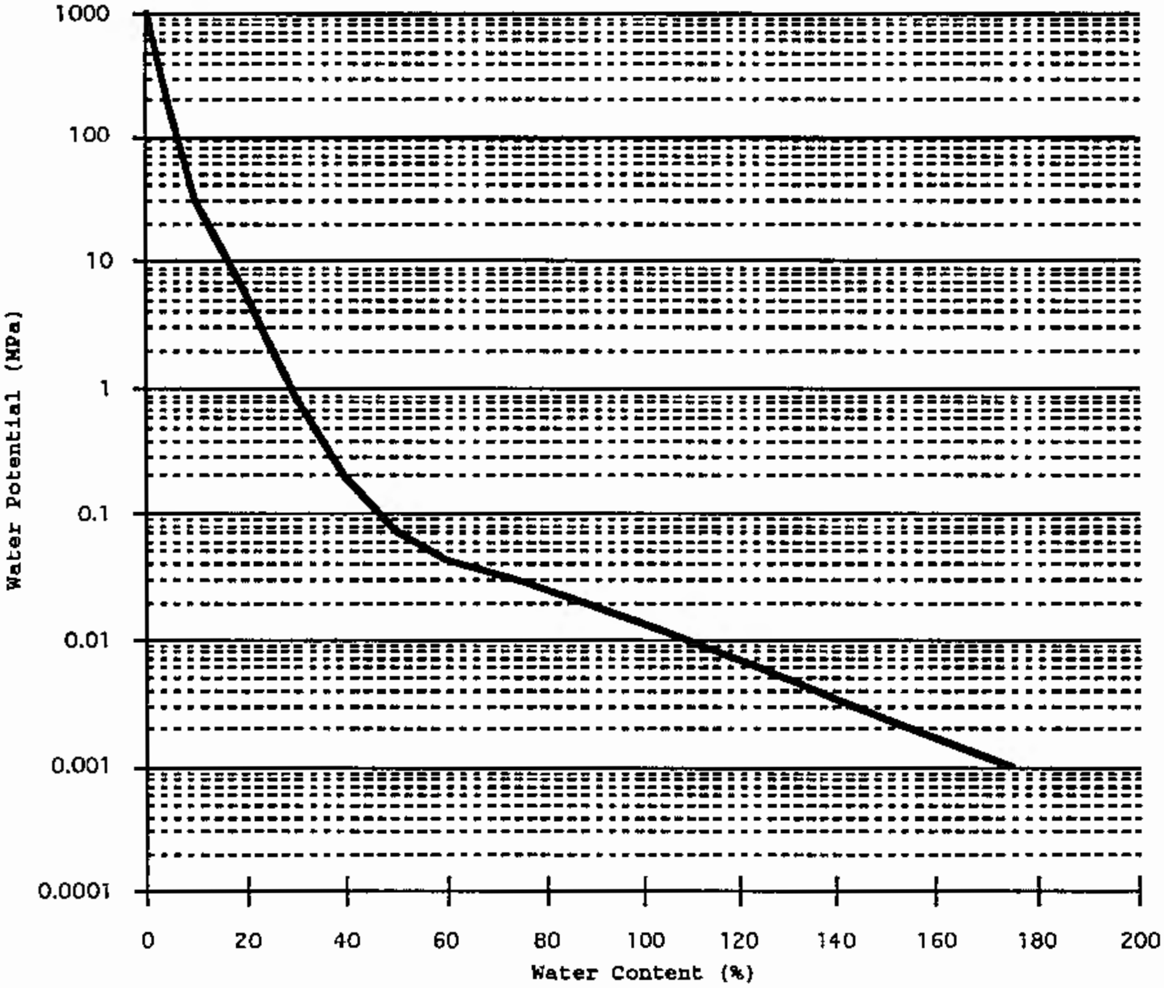

Figure 2. Calibration curve for Whatman #42 filter paper.

2.6. Sorptivity and Hydraulic Conductivity

The topsoil layer's hydraulic status was evaluated by disc permeameter on three occassions during the experiment. Experiments were conducted on the 22/10/90; the 30/4/91 and the 6/5/92.

Disc permeameters were used in sets of four which applied water to the saturated surface of the soil under imposed suctions ranging from 1 to 4 cm. The higher suctions restrain water from entering the smaller pore sizes in the soil, and so the combined results indicate the range of soil void spaces in the surface.

The rate of water entering the soil is recorded from each permeameter during a test. The results can be plotted to indicate both the saturated hydraulic conductivity of the soil and the surface sorptivity.

Sufficient permeameter readings (8 replicates at each section) were taken to compare the soil structure in the permanent hills and wheelways and to quantify any change in structure throughout the duration of the trial.

2.7. Soil Temperature

Hourly temperatures were recorded throughout the experiment at the soil surface (beside and within the field) and at depths of 10 mm, 50 mm, 100 mm and 200 mm. Recording commenced on 4th May 1990 and ceased on 20 July 1992.

Six channels from the weather station data logger were used to record this information.

2.8. Soil Strength

Soil strength is the most difficult of the tilled zone soil properties to measure. Most methodologies available to measure strength are destructive of soil structure and so return questionable values. All measure a surrogate or component of the total strength properties. The strength of the soil was therefore quantified in a number of ways for this project.

Penetrometer readings were taken during the experiment to provide representative values for the site. It is emphasised that these readings are only of limited use for inclusion in the proposed model of the seedbed. The penetrometer does not measure actual soil strength but an unknown combination of the soil's shear, compressive, and adhesive properties. It is known that penetrometer readings vary with soil water content and bulk density as well as composition, so while they can provide a useful broad indication of macro changes in the soil, such values are not readily amenible to numerical simulation. Penetrometer profile readings were taken on three occassions during the field trials.

In addition, the soil's consolidation and its shear characteristics were determined by laboratory testing in association with the laneway subproject work. Standard laboratory procedures were followed in all of these tests. The consolidation behaviour was determined using an odeometer. The shear characteristics were found using both the standard shear box and triaxial tests. These parameters were central to the laneway sub-project and are detailed in that part of this report.

2.9. Soil Macrostructure

The soil macrostructure was measured using image - analyses of profile samples held together by a binding resin. Steel moulds were pushed into the topsoil by a hydraulic jack and then excavated with the soil structural sample intact inside. The sample was sealed and returned to the laboratory where it was placed in cold storage so that moisture induced changes to the structure would be minimised.

The structural samples were impregnated with an epoxy resin containing a fluourescent dye prior to analysis. The blocks were then sectioned on a diamond saw and placed under an ultraviolet light source. A video camera was used to capture an image of the block which was passed to a dedicated computer that analysed the arrangement of voids and hence the macrostructure using the C.S.I.R.O. developed SOLICON software.

2.10. Surface Condition

The soils surface condition was measured using a purpose built profile meter. The meter consists of a rack of pins at 30 mm spacing that are lowered onto the ground surface from a level holding rack. An attached data logger digitises and stores the position of the top of each pin. The rack of pins was then moved 50 mm laterally on the holding rack so that readings were taken over a grid of size 0.93 × 1.05 m.

Special purpose software was used to simulate the filling and overflow of surface depressions during rainfall and the resulting runoff behaviour. These calculations allowed the total amount of water that could be stored on the tilled surface, and the point of initial runoff to be established. Both of these parameters will impact on the soil's erodibility. The computer was also used to quantify the soils random roughness which also forms a measure of the structure resulting from different tillage implements.

3. RESULTS

3.1. Weather Data

A large data base of daily weather data has been established for the trial site from 4 May 1990 to 20 July 1992. The data collected includes wet and dry bulb temperatures, maximum and minimum air temperatures, relative humidity, evaporation, windrun and solar radiation all recorded at 9am each day. The wet and dry bulb temperatures were also recorded at 3 pm each day.

3.2. Soil Composition

Soil at the test site was classified in a land use survey by Beckman and Thompson[2] as part of the Anchorfield Clay association. They described it as a black self mulching clay soil with a fine to medium structure, alluvial in origin. It is known to be a vertisol, and is classified as a Ug5.15 soil by the Northcote (1979)[3] system.

The soil composition as determined in this project is summarised below:

Parameter	Average of all samples
pH (H_2O)	8.3
Nitrate/Nitrogen ext	9
% Organic Carbon	1.1
% coarse Sand	4
% fine Sand	9
% Silt	19
% Clay	68
% Air Dry water content	8.3
% Wilting Point (1.5 MPa)	31
% Field Capacity	62
% Plastic limit	28.7
% Liquid limit	83.4
% Optimum Water Content	32

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[2] Beckmann, G.G. & Thompson, C.H. (1960) Soils and land use in the Kurrawa area, Darling Downs, Queensland., C.S.I.R.O. (Div Soils)., Soils and Land Use Series 37.

[3] Northcote, K.H. (1979) A factual key to Australian soils. Rellim, Adelaide.

3.3. Soil Bulk Density

A total of 130 data points were collected for analysis. The bulk density of the tilled zone was measured and related to water content and tillage history. It was found that neither the time from tillage nor the type of tillage implement improved the regression results between the bulk density values and the the soil water content. The amount of rainfall following tillage had a statistically significant but very small (coefficient = 0.00037) effect on the bulk density. These findings were unexpected, but are probably due to the self mulching nature of the soil at the site. It was observed during the trials that any clods formed by primary workings at the start of the season weathered to a uniform structure within a couple of weeks after tillage.

Bulk density was found to be related to depth in the profile and the water content of the soil - again emphasising the self mulching nature of this soil type. The regression equation between these variables takes the following form :

$$\rho_h = 0.955 + 0.002 \times z - 0.004 \times \theta \qquad (r^2 = 0.64)$$

where ρ_h = bulk density in permanent bed (kg/m^3)
z = depth below surface (mm)
θ = gravimetric water content (%)

Further investigation established that in common with many other natural properties, the density profile within the top layer of the soil is logarithmic. The regression line shown below has an r^2 value of 0.64. The scatter in the measured data decreases with depth in the profile.

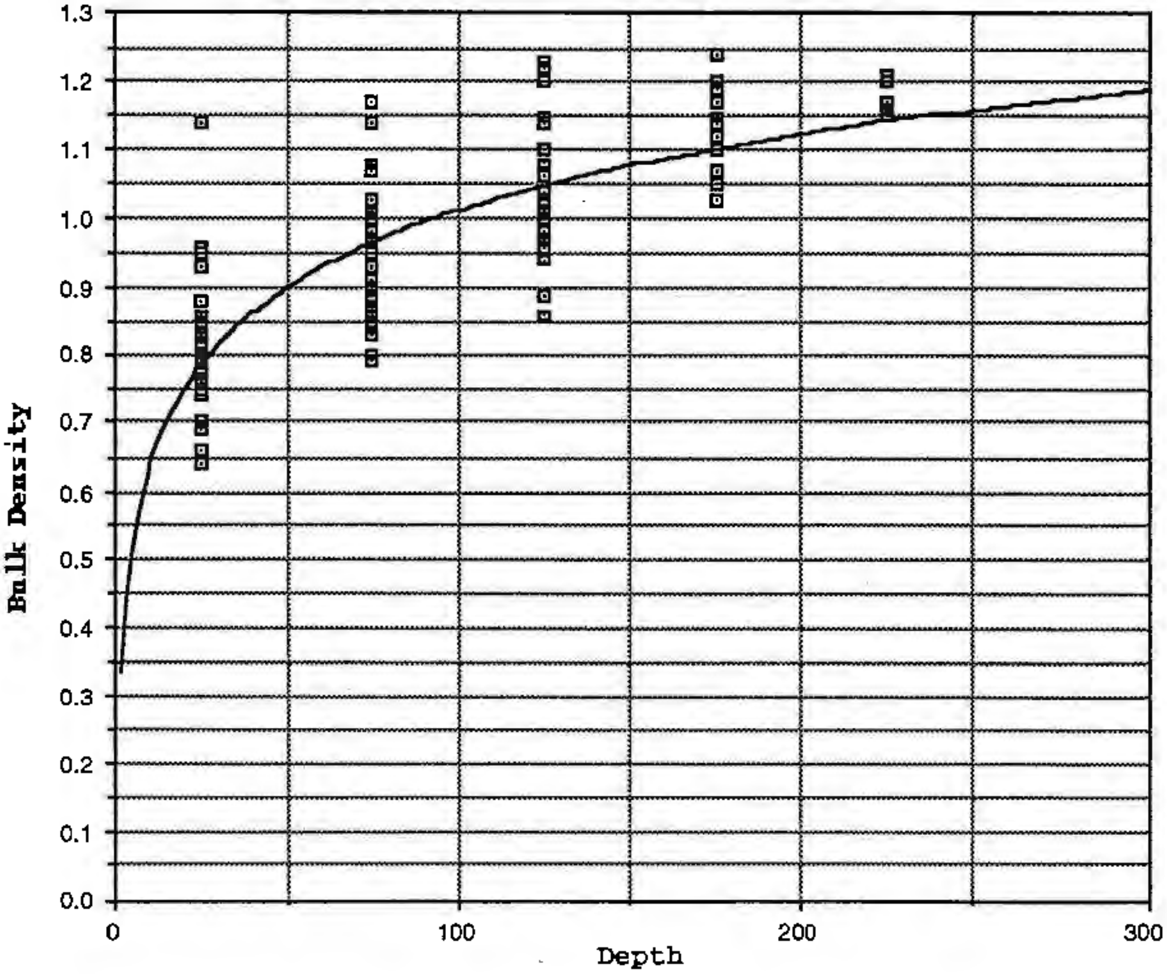

Figure 3. Experimental density profile within topsoil layer. All tilled data except following roller operations are represented.

The average density profile shown on the above diagram was used to transform all density values to an equivalent value at 75 mm depth below the surface. The transformed values were then related to soil water content using the theoretical framework proposed by Fox (1964)[4]. This method postulates two possible shrinkage modes in a field soil - either 1 or 3 dimensional. One dimensional swelling/shrinking occurs when the soil is free to move only in the vertical direction while three dimensional behaviour occurs when the soil can move laterally as well. The latter mode is characterised by the formation of cracks in a swelling soil.

Field observations indicated that the soil in this project commences to crack soon after saturation as the soil dries. Preliminary analysis also indicated that the slope of the density drying curve was greater than could be explained by 1 dimensional shrinkage alone. This finding indicated that some particle rearrangement occurs during drying and that three dimensional behaviour was probable. The coefficients for Fox's three dimensional curve were therefore obtained by fitting to the transformed data. The resulting equation relating the bulk density at 75 mm to the soil water content at that depth is:

$$\rho_{75} = \frac{0.875}{(0.360 + 0.00875\theta)^{\frac{1}{3}}}$$

where ρ_{75} = density of soil at 75 mm depth (kg/m^3)
θ = gravimetric water content (%)

This relationship is shown with the density data in the following diagram:

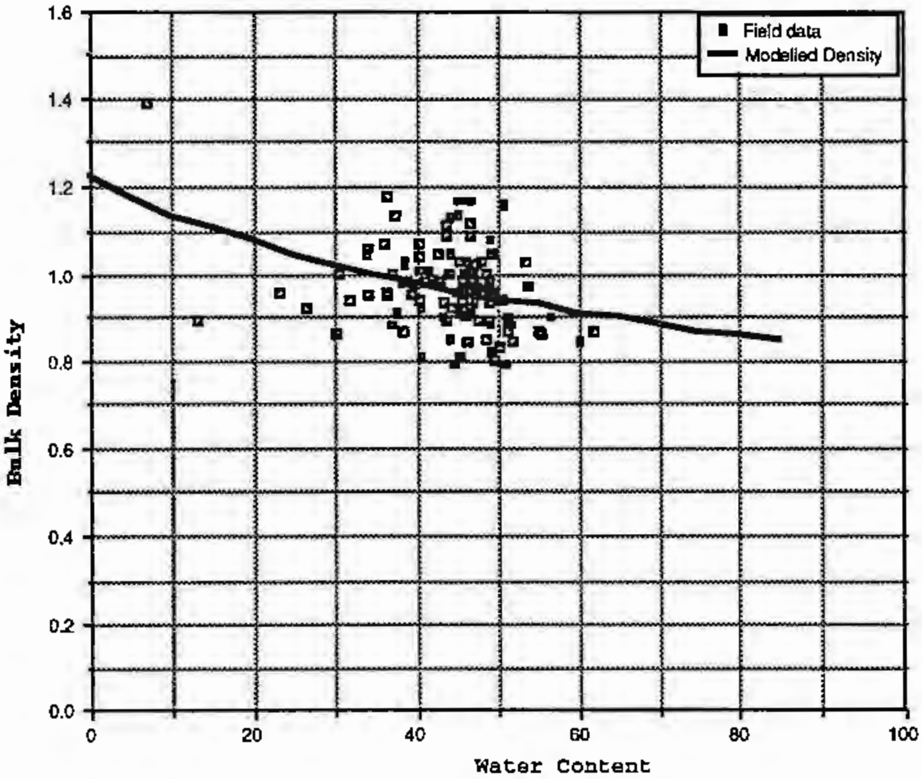

Figure 4. Graph of bulk density of tilled soil at 75 mm depth as a function of water content. (Measured density values have been transformed to an equivalent value at 75 mm).

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[4] Fox, W.E., (1964) A study of bulk density and water in a swelling soil. Soil Sci., 98:307-316

The three dimensional shrinkage curve, together with the logarithmic profile described above, can thus be used to estimate the tilled bulk density at any depth within the cropping zone of the controlled bed system.

Comparison of congruent hill and furrow density data at all depths allowed the following equations to be developed to determine the density of the wheeled and non-wheeled furrows (the traffic and irrigation zones) from the tilled density:

$$\rho_w = 0.674 + 0.512\rho_h$$

$$\rho_n = 0.118 + 1.148\rho_h$$

where ρ_w = density of soil in wheel tracks (kg/m^3)
ρ_n = density of soil in non-wheeled tracks (kg/m^3)
ρ_h = density of soil in cropped zone (kg/m^3)

These relationships indicate that the soil under the irrigation furrows has a slightly higher density then that which is tilled in the hills, but that it responds to changes in water content at a similar rate. The equations also support the observation that soil under the wheel tracks is more compacted and stable. The density in the wheeled tracks is much higher than that in the tilled soil, and it changes less with changes in the hills.

The relationships summarised in this section have been developed into a density sub-model for the proposed tilled soil simulation model.

3.4. Soil Water Content

The necessary data have also been collected, and the relationships developed, for the water balance submodels required for the controlled traffic soil model. The following diagram gives a sample profile of the measured record at depths of 100, 200 and 300 mm in the soil. This information combines the gravimetrically and volumetrically measured data. Similar data are available to 1 m depth in the trial plot and some gravimetric data are available at 50 mm. This information will be used to validate the water balance simulations of the field.

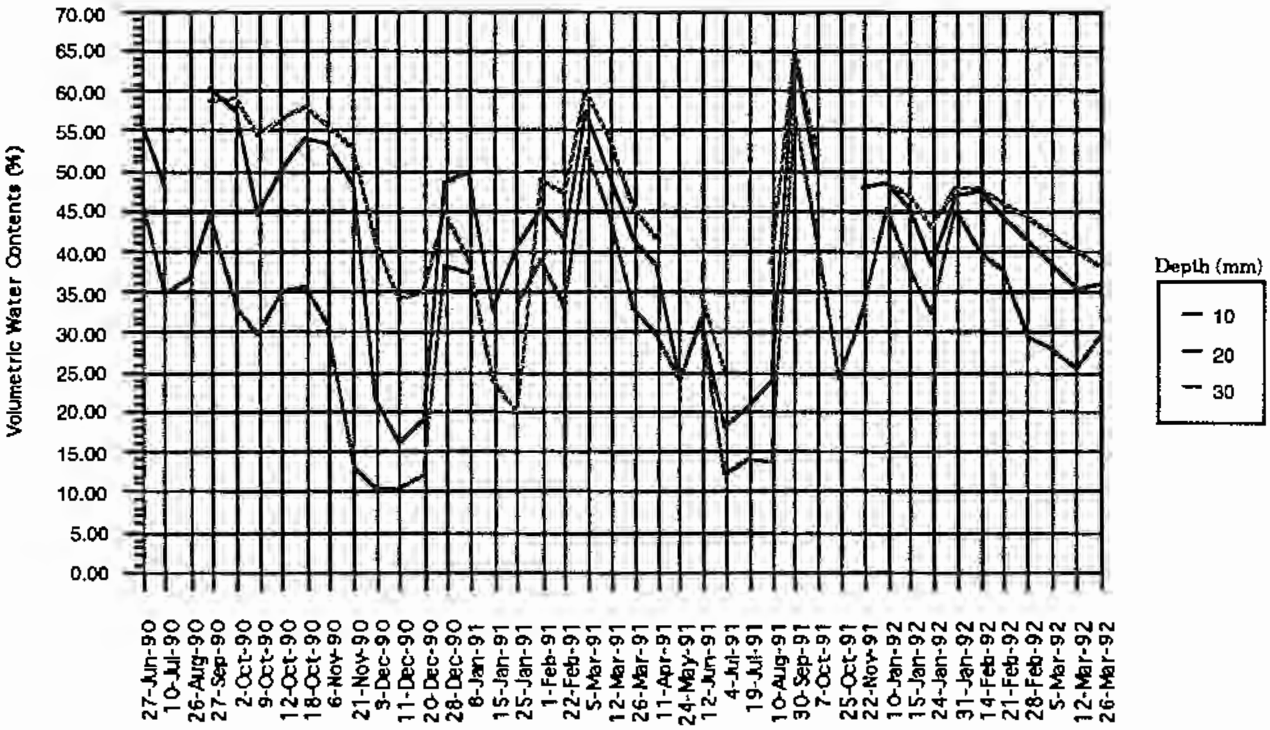

Figure 5. Sample water content profiles

3.5. Soil Water Potential

The following diagram shows the measured water potential data as a function of soil water content.

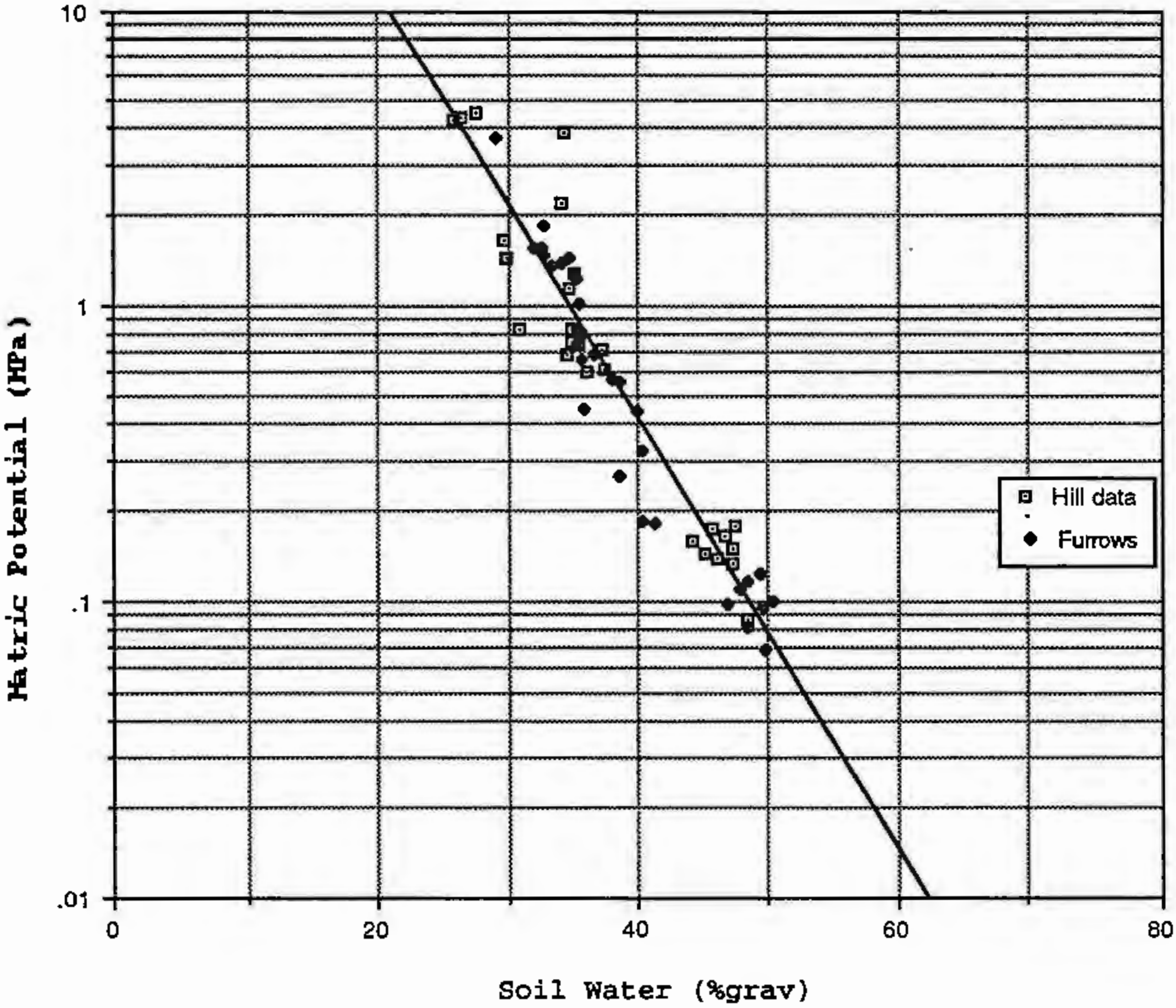

Figure 6. Plot of water potential against water content for hills and furrows from filter paper data.

The data show that both the tilled soil and the compacted soil in the laneways follow the same regression line. That is, the water potential of the soil is independent of bulk density. The regression line shown has the following form:

$$\psi = 320.64 \times 10^{\{-0.07234\theta_g\}} \qquad (r^2 = 0.91)$$

where ψ = water potential (MPa)
θ_g = gravimetric water content (%)

The measured data were also found to agree well with those predicted by the generic regression equations of Rawls et al (1982)[5]

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[5] Rawls, W.J., Brakensiek, D.L., & Saxton, K.E. (1982) Estimation of soil water properties. Trans. A.S.A.E. 25:1316-1320,1328.

A submodel has been written to simulate the soil water potential in the grey clay of the trial site. The simulated values will be used in the overall model to control water movement and redistribution in the profile.

3.6. Sorptivity and Hydraulic Conductivity

The disk permeameter readings over the three year project summarise the effects of any development in surface soil structure. They can be presented either on the basis of hydraulic conductivity or sorptivity values.

The data show a distinct development in structure in the hills. The hydraulic conductivity of the soil at 1 and 2 cm suction increased, while that at 3 and 4 cm suction decreased. There is a corresponding trend for an increasing number of macropores between 1.0 and 3.0 mm diameter over the same period with fluctuating numbers of macropores in the 0.74 to 1.0 mm range. The increase in the larger macropores can be interpreted as an improvement in soil structure.

The trends in the furrows between the hills was not as obvious as those in the permanent beds. There was some increase in macropores in the furrows over the three year period but not to the same extent as the hills. It was concluded that some surface structural improvement occurred in the laneways, despite the wheeled traffic over them. The structural comparisons beneath the surface rely on other measures, such as the results from the SOLICON analyses below.

The sorptivity results parallel the hydraulic conductivity results, but are not as definite. Sorptivity is greatly affected by the initial water content of the soil θ_i. A higher value of θ_i will result in a generally lower sorptivity value. The initial volumetric water contents were recorded as 25% in 1992, 12% in 1991 and 16% in 1990 implying that the sorptivities for 1992 would have been higher and the trends more distinct if θ_i had been around the same value for 1991 and 1990.

The following table summarises the statistically significant results from the disk permeameter on the surface of the permanent hills.

TABLE III. Disk permeameter results for the three year period from 1990 to 1992. Significant differences in the structural parameters between years are indicated by the mathematical expressions.

Suction (cm)	Hydraulic Conductivity ($mm\ h^{-1}$)	Macropores	Sorptivity ($mm\ h^{-\frac{1}{2}}$)
1.0	1992 > 1991 = 1990	3.0 to 1.5 mm: 1992 > 1991 = 1990	1992 > 1990
2.0	1992 > 1991 > 1990	1.5 to 1.0 mm: 1992 >> 1991 = 1990	1992 = 1991 > 1990
3.0	1991 > 1992 = 1990	1.0 to 0.74 mm: 1991 > 1990 > 1992	1991 > 1992 = 1990
4.0	1991 > 1992 = 1990		1991 > 1992 = 1990

The unsaturated hydraulic conductivity relationship was determined for the soil by the method of Campbell (1974)[6]. This method estimates the full hydraulic conductivity curve from the saturated conductivity, the water content at saturation and the slope of the water characteristic curve. The form of the equation is:

$$K = K_s\left(\frac{\theta}{\theta_s}\right)^{2b+3}$$

where
K = hydraulic conductivity (mm/h)
K_s = saturated hydraulic conductivity (mm/h)
θ = soil water content (%)
θ_s = saturated soil water content (%)
b = slope of the $\log\psi - \log\theta$ curve.

The saturated conductivity of the soil at the surface was assumed to be given by the disk permeameter results at an applied suction of 3 cm - equivalent to a matric potential of 0.3 kPa. On this basis, the disk permeameter results for the project give an average saturated conductivity value of 51 mm/h with a standard deviation of 15 mm/h. The saturated water content was obtained from the regression line shown in the previous section. A value of 83.5% corresponds to the adopted suction of 0.0003 MPa. The gradient of the soil water characteristic curve (b) is also taken from the regression curve in the previous section, and has a value of 6.4003. The resulting hydraulic conductivity curve for the trial soil has the form:

$$K = 51\left(\frac{\theta}{83.5}\right)^{15.8006}$$

and is shown in the following diagram:

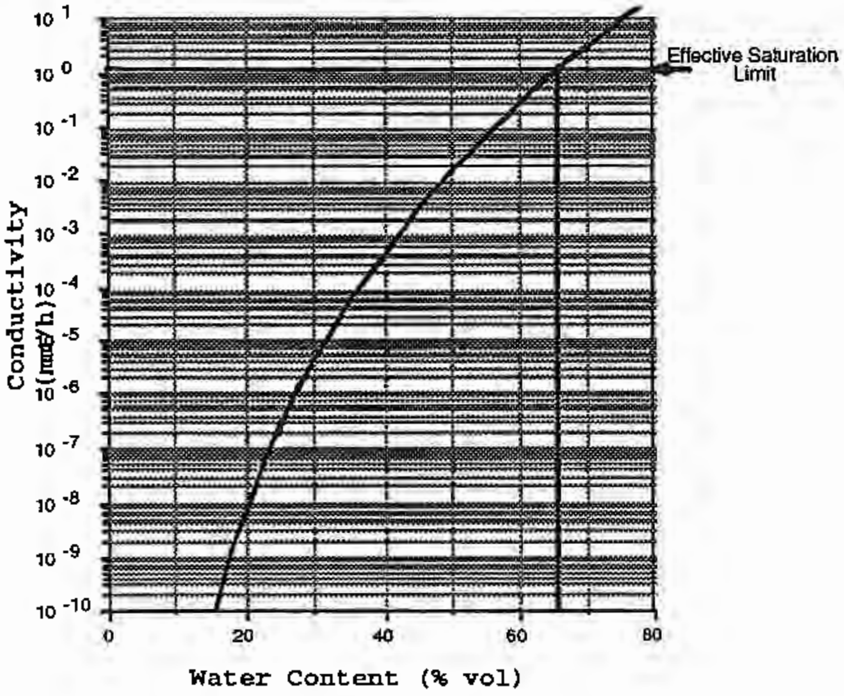

Figure 7. Plot of calculated hydraulic conductivity against water content.

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[6] Campbell, G.S. (1974) A simple method for determining unsaturated conductivity from moisture retention data. Soil Sci., 117(6):311-314.

It is noted that the voids in a heavy clay soil remain effectively saturated to a lower level of about 5 kPa. The hydraulic conductivity should therefore remain constant above this level. Figure 7 indicates an upper level on the conductivity of the soil, based on this approximate limit. This upper limit in the conductivity will be tested against measured data once the full tilled soil model is available. The required submodel has been written to simulate the soil's hydraulic conductivity at all water contents in the tilled soil zone.

3.7. Soil Temperature

Factors controlling soil temperature have been studied in detail, with hourly temperature values taken at the surface and at four different depths in the profile between 4 May 1990 and 19 July 1992. The necessary relationships have been developed to calibrate the previously developed ASTC model of Porter & McMahon (1987)[7] to cotton in south-east Queensland.

The empirical relationships between air and soil surface temperatures required for the ASTC model have been established for a bare tilled surface and for a growing cotton crop. They can be summarised as follows:

Cotton crop:

$$T^c_{mn} = 6.593 + 0.764 T_{mn} \qquad (r^2 = 0.82)$$

$$T^c_{mx} = 0.217 + 1.813 T_{mx} - 0.380 T^c_{mn} + 0.359 S - 0.380 L \qquad (r^2 = 0.74)$$

Bare fallow:

$$T^b_{mn} = 3.334 + 0.972 T_{mn} \qquad (r^2 = 0.93)$$

$$T^b_{mx} = 11.056 + 0.943 T_{mx} - 0.327 T^b_{mn} + 0.843 S - 0.018 W + 0.128 R \qquad (r^2 = 0.62)$$

where T_{mn} = daily minimum air temperature (°C)
T^c_{mn} = daily minimum temperature on surface in a cotton crop (°C)
T^b_{mn} = daily minimum temperature on surface in a bare fallow (°C)
T_{mx} = daily maximum air temperature (°C)
T^c_{mx} = daily maximum temperature on surface in a cotton crop (°C)
T^b_{mx} = daily maximum temperature on surface in a bare fallow (°C)
R = daily rainfall (mm)
S = daily solar radiation (MJ/m^2),
L = leaf area index of crop
W = total daily windspeed (km/h)

These equations allow the daily maximum and minimum surface temperatures to be estimated from standard daily air temperatures as recorded at most weather stations. The model then calculates hourly soil surface temperatures by scaling the relevant one of the following curves with the maximum and minimum values.

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[7] Porter, M.A., & McMahon, T.A. (1987) A computer simulation model for soil temperatures in Australian cereal cropping. Soil Tillage Res., 10:131-146.

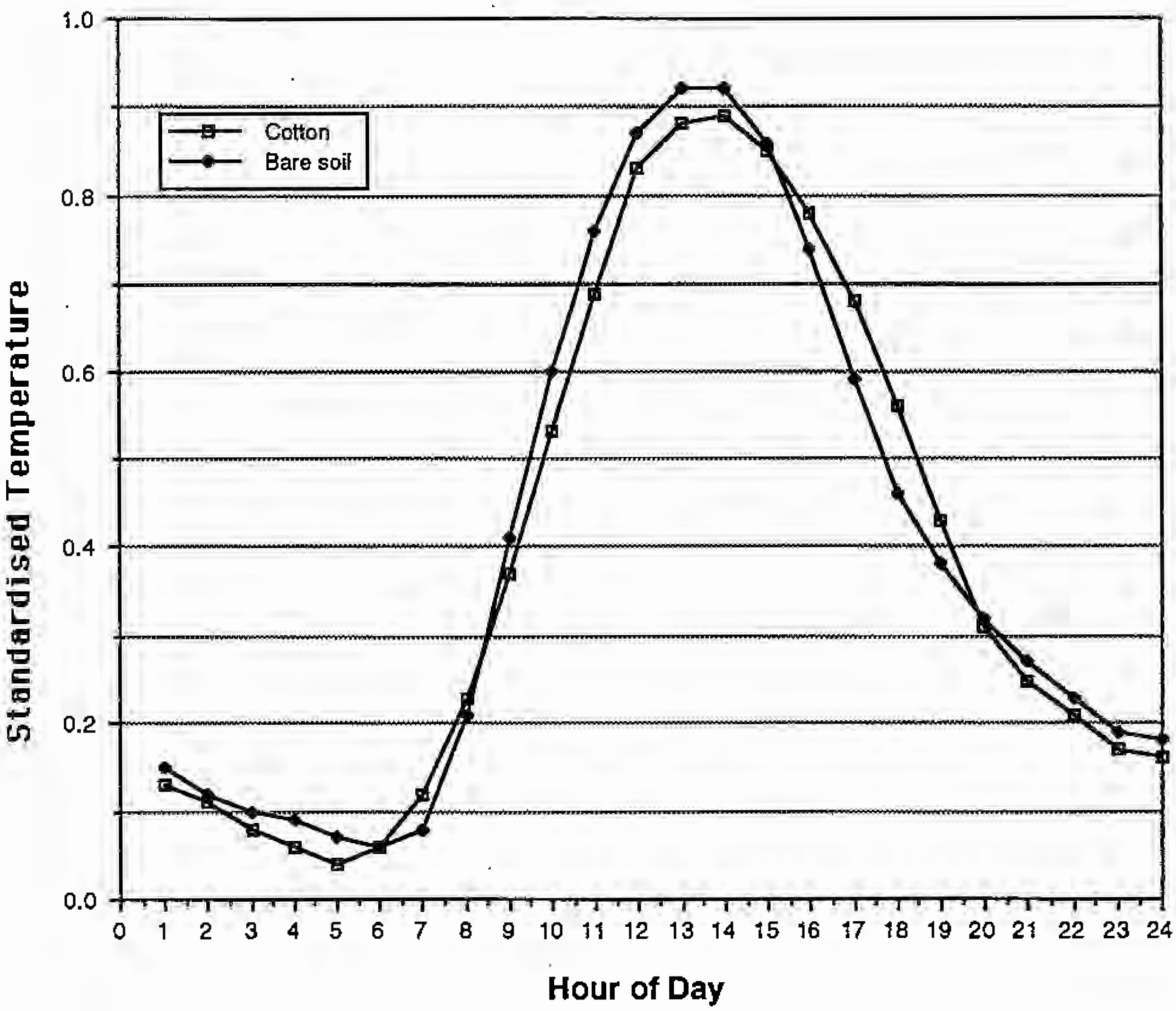


Figure 8. Standardised temperature curve for a cotton crop on the Darling Downs.

Finally, the ASTC model uses the 1 dimensional heat flow equation to calculate the temperature profile in the soil from the values estimated at the surface.

3.8. Soil Strength

The soil strength results are given in Section 3.2 of the Laneways subproject report. Additional information available includes the following penetrometer profiles taken over the field. These penetrometer measurements were taken to assess seedbed variability. They are not used in the tilled soil model.

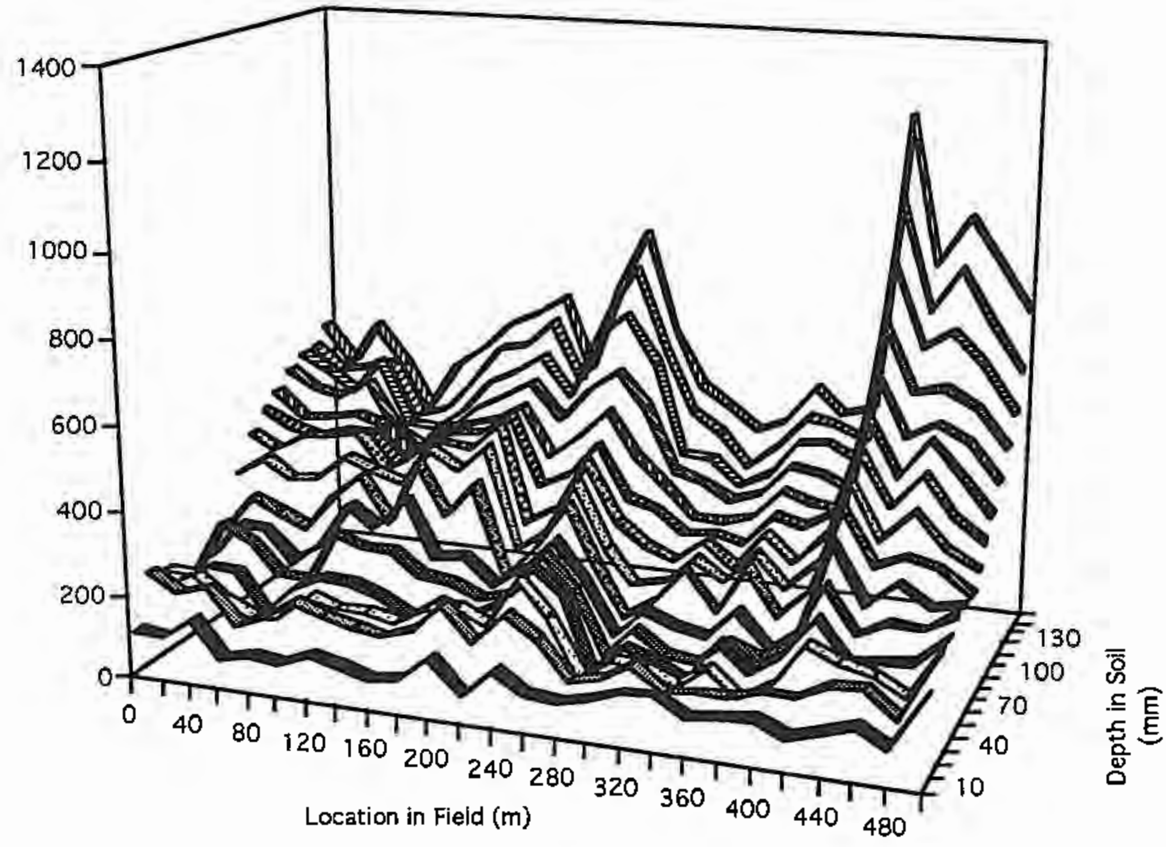
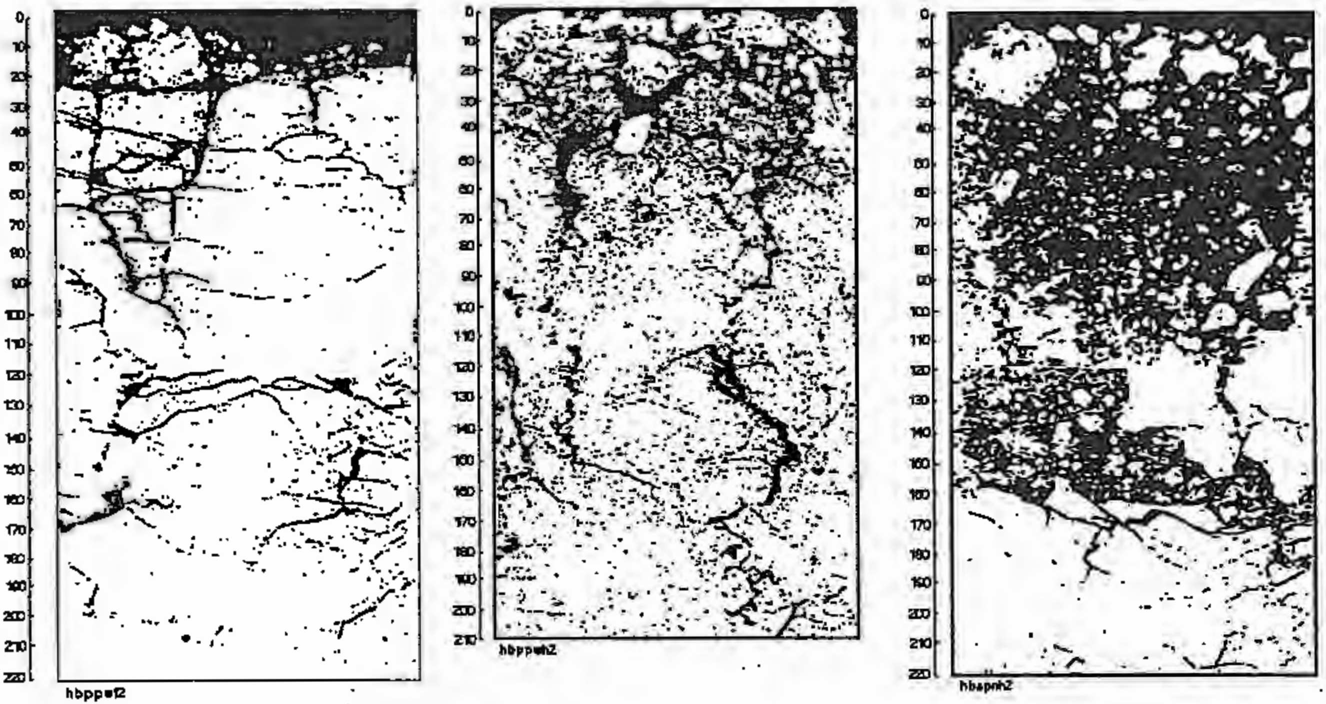


Figure 9. Average penetrometer readings in tilled zone of beds over length of field.

3.9. Soil Macrostructure

Extensive sampling was undertaken in the project to allow the soil macrostructure to be established through the SOLICON image analysis system. About 70 samples were taken on 11 different occassions between September 1990 and April 1993 to compare the soil structure in hills and furrows and to assess the change in structure with time. The profiles sampled were chosen so that the structure in hills adjoining a laneway, in hills remote from a laneway, and in both wheeled and non-wheeled furrows could be compared. Results were presented at the 1992 Australian Cotton Conference (Pillai-McGarry and McGarry, 1992).

Analyses of the samples shows that the structure in the pemanent beds improved during the project with the exception of a period in 1991 when a tillage working (middle busting of hills) in wet soil destroyed some of the gains made to that time. This result is evident in the following images (Figure 10). Figures 10a and 10b are from an immediately adjoining furrow and hill. The furrow has dense and platy structure to 220 mm, whereas the hill has crumb-like topsoil to 50 mm and below that there are many interconnected cracks with extensive porosity between. The sample shown in Figure 10c was taken in a cotton hill one week after the pass of a middle busting tine that had been used to prepare the beds prior to the 1991-92 season. At the time of cultivation the soil water content in the 180 to 240 mm zone was just at plastic limit. The subsequent compaction from 160 mm to depth can be seen in the image.



a) A wheeled furrow, and

b) The immediately adjoining hill, just before picking (1991)

c) A hill one week after the pass of a middle-busting tine, just before the start of the 1991-92 season.

Figure 10. Three digital images of soil structure taken from the cotton paddock on Condamine Plains. In all images the air spaces (pores) are black and the soil solid is white. The depth axis is in millimetres.

3.10. Surface Condition

The soil's surface condition is defined by its random roughness and the rainfall - runoff behaviour. These values were monitored in the project during the period from October 1990 to September 1991. A total of 47 readings were taken from hills both adjacent to and remote from traffic laneways. Figures 11 and 12 illustrate the basic information obtained for the tilled soil surface in the hills, and the associated runoff behaviour:

The runoff behaviour is summarised in this project by the volume of water stored on the surface at runoff initiation and at maximum capacity. The random roughness of the surface is represented by the standard deviation of the heights of the grid points after the overall bed profile is removed from the calculation. The random roughness should therefore be implement and weather dependent. That is the roughness of the surface will depend on the implement last used and on the weather conditions encountered since the tillage working, but not on the overall size or shape of the beds.

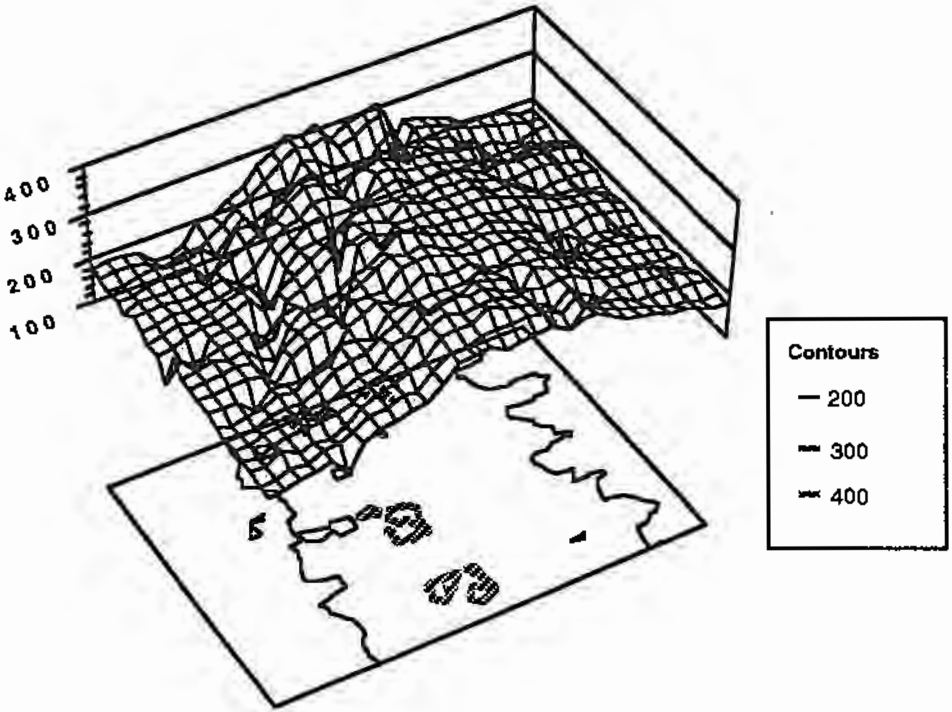


Figure 11. Tilled surface profile for a Wheeled Hill #5 on 8/5/91.

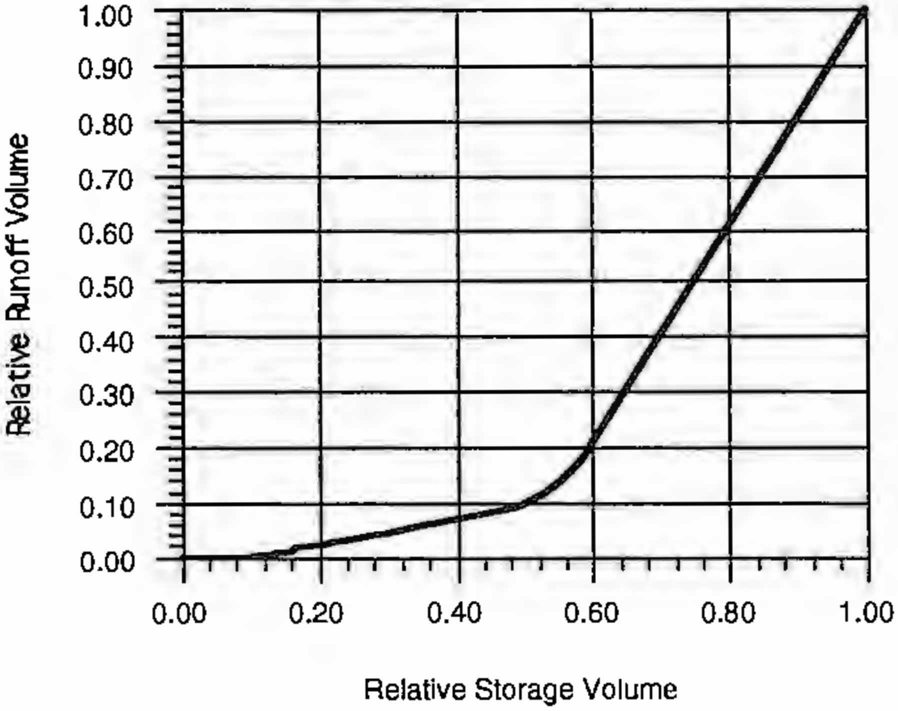


Figure 12. Storage - Runoff behaviour for Wheeled Hill #5 on 8/5/91
(Total surface storage capacity is 21.95 mm.

The data indicated only minor differences in the surface condition of hills adjacent to and remote from laneways, as shown in Figure 13. The standard deviations used in this plot are for the actual grid point readings and so include the overall bed shape. The regression line shown has a coefficient of Determination of 0.82.

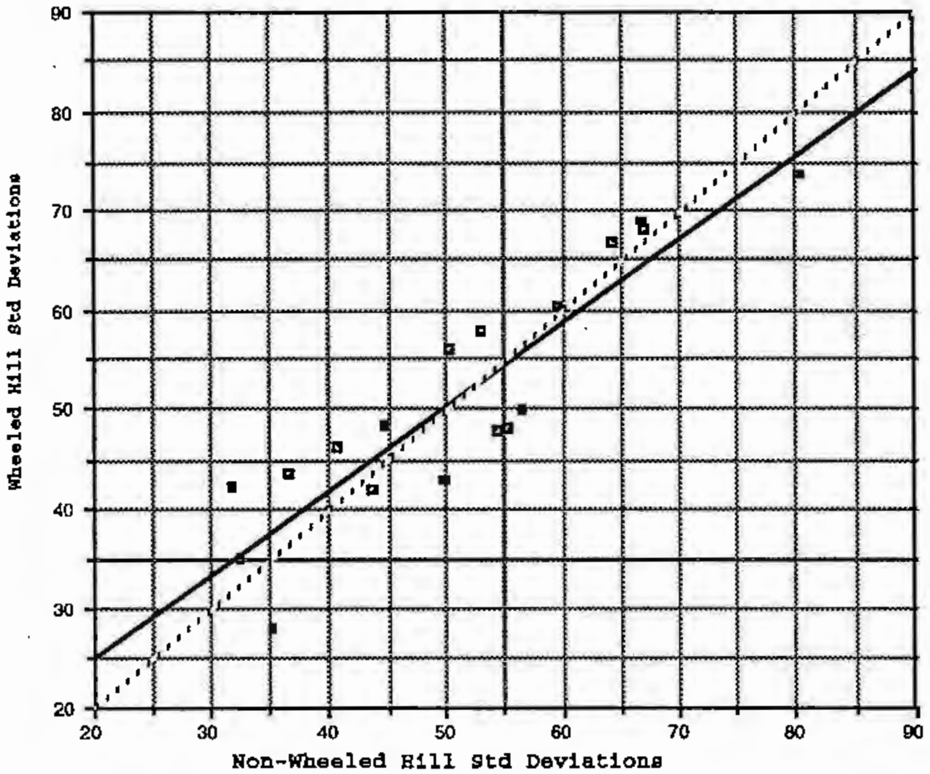


Figure 13. Comparison of standard deviations of profile heights for wheeled and non-wheeled hills.

The random roughness of the hills is weakly related to the period of time and the amount of rain following tillage. An adequate subroutine to simulate the surface condition in the model is still being developed for these data, but will be completed in the near future.

4. Conclusions

An extensive data base of measured soil structural properties has been established for tilled soil in a controlled traffic environment on a representative cotton growing soil on the Darling Downs. The development of an improved soil structure in the absence of direct wheel compaction over the period of the project has been identified. The dynamic relationships between key soil properties has also been established for this soil type.

The soil structure has been successfully quantified in terms of the soil bulk density, its water content and water potential, its sorptivity and hydraulic conductivity, the surface condition and the physical macrostructure. Necessary relationships to model the soil temperature have also been established.

The relationships derived in this project are suitable for inclusion in the proposed model of the tilled soil. Many of the subroutines of this model have been written, and the information is available for the remaining ones will be completed in due course.

The data base of soil properties from this project will be of enduring use. It will form a suitable baseline for any future studies of soil properties on the trial site. It will also be available for comparative studies at other locations.

The computer model is suited to future studies on minimum tillage requirements within a controlled bed environment. It is intended to use the model to assess the amount of tillage required to satisfy the soil based requirements for creating a good seedbed for cotton on the Darling Downs. The findings from such studies would be of direct practical use for the industry.

It is concluded that all of the key objectives of this subproject have been met.

5. Publications Resulting From the Project.

5.1. Conference Papers

Pillai-McGarry, U. & McGarry, D. (1992). Farming with compaction. Proc. of 6th Aust. Cotton Conf., Broadbeach, Qld., 12-14 Aug.

Porter, M.A. (1992) Controlled traffic and guidance systems Proc. of 6th Aust. Cotton Conf., Broadbeach, Qld., 12-14 Aug.

Porter, M.A. (1992) Managing soils to avoid compaction problems in cotton growing. Proc. of 6th Aust. Cotton Conf., Broadbeach, Qld., 12-14 Aug.

5.2. Articles

McGarry, D. & Porter, M. (1991) Soils and engineering research and development priorities. The Aust. Cottongrower. 12(2):49-50.

Porter, M. (1991) Soil management and the cotton industry. The Aust. Cottongrower. 12(3):54-55.

Porter, M. (1991) Modelling tilled soil and the effects of weathering. The Aust. Cottongrower. 12(3):56-57.

5.3. In Preparation:

Porter, M.A., Density differences between permanent beds and wheeled laneways on a swelling clay soil.

Porter, M.A., Soil temperatures for sowing cotton on the Darling Downs - a probabilistic approach.

Porter, M.A., A comparison of ASTC model parameters for Queensland and Victoria.

Porter, M.A., Tilled surface condition and soil infiltration on a swelling clay soil.

Laneway sub-project

1. Aims

The aims of the laneway sub-project, as defined in the project proposal, included:

- quantifying the dynamic stresses occurring in field soils under current wheel loadings,
- duplicating the actual field loadings in laboratory tests under a range of soil conditions (water content, density, previous work history, etc),
- developing guidelines for establishing wheel laneways in cotton growing,
- relating soil strength conditions in compacted laneways to trafficability potential, and
- conducting a field evaluation of the potential life of controlled traffic laneways, and of their erosion potential.

In general these goals have been achieved. The findings of the project have led to an extension of the investigations, with CRDC project USQ3C dedicated to extending the above mentioned aspects of soil compaction research.

2.0 Methods

2.1 Dynamic Stress Measurement

When a tyre runs over the soil a combination of stresses is generated. The magnitude and the direction of these stresses vary, depending on the position of the tyre, type of tyre and inflation pressure of the tyre.

The stresses can be separated into normal stresses and shear stresses in three orthogonal directions (X, Y and Z). In order to monitor these stresses a special soil stress transducer which can sense stresses in six different directions was developed at the USQ. The three extra directions (in addition to the orthogonal directions) are necessary to calculate the shear stresses on the soil. The sensor is used in conjunction with a dedicated high speed datalogger which is capable of logging each sensor at 250 Hz.

A reliable installation method was developed specifically for the sensor, so that a number of stress profiles could be obtained under a range of equipment and under different operating conditions. The tested farm equipment and conditions are representative of the cotton industry in South-East Queensland. The conditions were chosen such that they would reflect those under which some soil compaction would occur. Fortunately, these conditions also facilitated installation of the sensor.

2.2 Laboratory Testing

The response of the soil to stresses depends on its strength and its previous history. The soil volume can change in three different ways: through compression, expansion or with no volume change at all. The mode of volume change followed in any one case is determined by the ratio of the shear stress to the normal stress, the stress history of the soil and the soil condition (expressed in terms of degree of saturation, void ratio or water content).

The response of the soil to stresses was investigated in the laboratory. A special shearbox was developed to reproduce complex stress loadings similar to those in the field. The shearbox is rectangular in cross section and deforms as a parallelogram. A normal stress is applied to the top of the sample by means of a computer controlled, stepper motor driven ram. A shear stress is applied to the bottom of the shearbox by a similar device. During operation the stresses applied are monitored through load cells connected to data acquisition boards in a computer.

The shearbox was used in a range of different shear only tests to establish those parameters that describe soil behaviour. To date, a combination of normal and shear stresses has not been succesfully applied to a soil sample because of difficulties in interpretating shearbox readings.

Strength parameters have been established for the field site to describe soil behaviour. These values allow soil response at the depth of stress measurements to be predicted. Once the shearbox is capable of applying the combination of normal and shear stresses, the predictions will be verified by experiment.

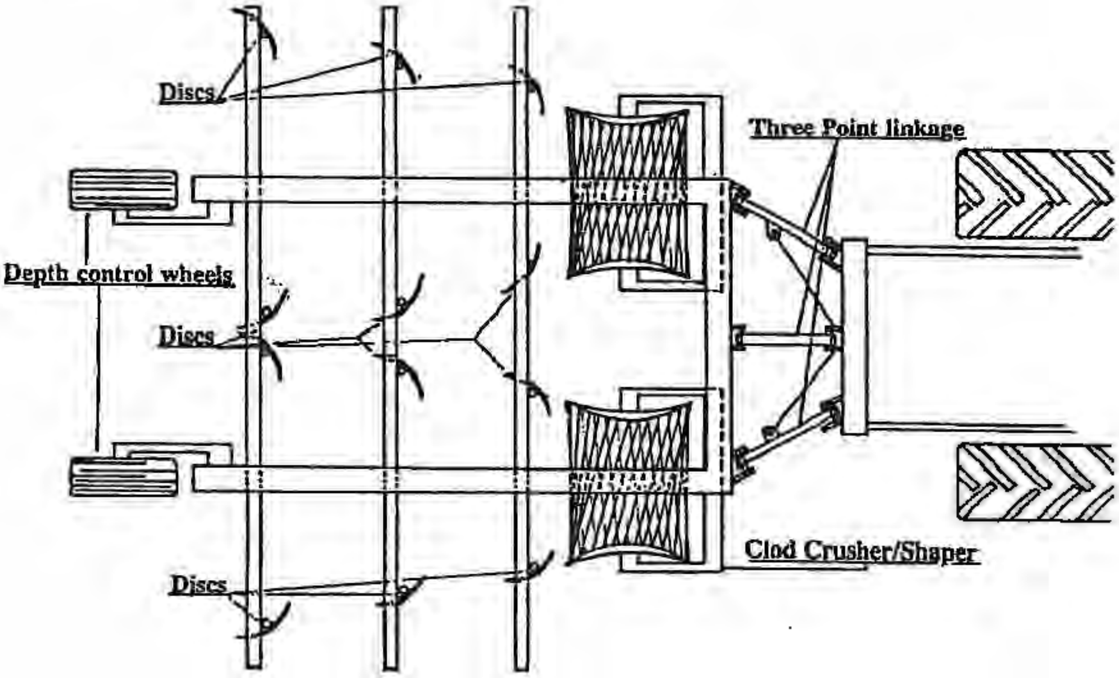
2.3 Field Experiments

It is known that soil strength is directly related to soil water content. Our preliminary work showed the strength of the soil at any water content can be improved with the inclusion of a binding material such as cotton trash. These two considerations led to the establishment of laneways on an experimental scale at the trial site. A permanent one (1) meter bed system had been used for several years prior to installation of these laneways. The laneway design was modified during the project as described below.

2.3.1 Season 1991-1992

A split plot experiment with two replicates was established in 1991 just before pre-watering. The treatments included normal recessed wheel tracks as a control treatment together with semi-elevated wheel tracks (set at a level higher than the irrigation furrow) and elevated wheel tracks (higher than the adjacent beds). The laneways were installed with a laneway builder. This implement was designed and build at the USQ. It was mounted in front of a tractor and used discs to rake the soil from the side and deposit it in front of the tyres. The tractor functioned as a roller to compact the laneways. Figure 1 shows the top view and the longitudinal cross section of the implement.

a). Top view



b) Longitudinal cross section

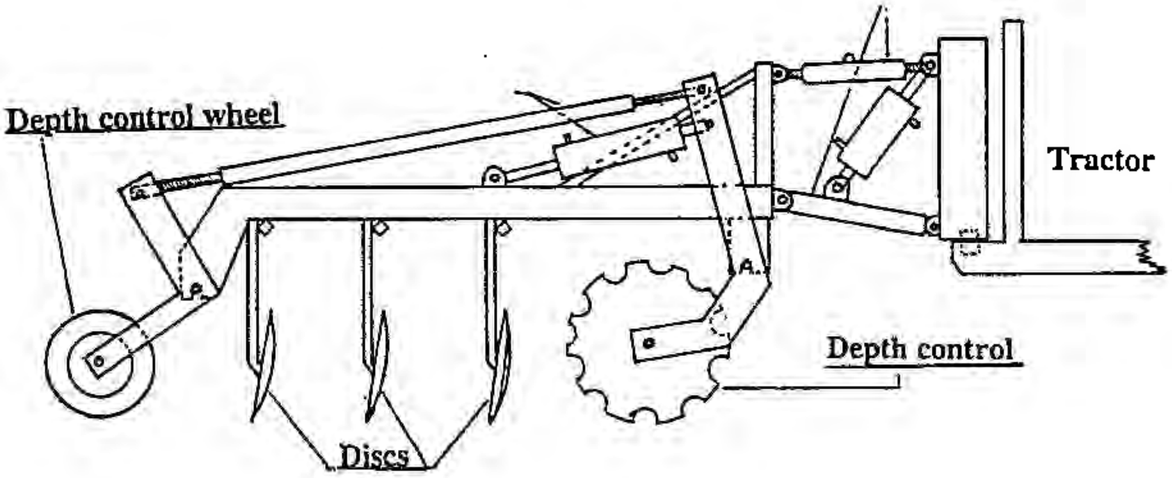


Figure 1 Design of the lane way builder

Further treatments included trials of cotton trash and gypsumadditives to the soil in the laneway. Cotton trash which had been raked aside after the previous seasonwas applied by hand to the soil surface. The gypsum was applied to the wheel tracks using a conventional spreader with disabled spinners. Soil strength in the different wheel tracks was assessed with a drop cone penetrometer. Plant performance and water extraction were monitored throughout the season.

2.3.2 Season 1992-1993

The experiment was relocated to a different field for the 1992-1993 season. Three treatments were trialed in this season. They included 2-metre wide beds, 2-metre wide beds with raised wheel tracks and 1-metre beds as a control treatment. The laneways in this year were installed with conventional equipment rather than the laneway builder. This change in procedure was intended to minimise disruption to farm management. A Lilliston speed wheel was used to deposit soil in the required position after the orientation of the speed wheels was suitably adjusted. Four replicates, each with an area of 0.6 ha, were installed. Plant performance and water extraction were monitored throughout the season in the top, middle and bottom of the field. Water extraction was monitored with a neutron probe in the wheel track, plant line and the non-wheel track. Other measurements included sampling for root densities in different locations relative to the plant line. In addition to this, detailed soil deformation measurements were under taken at planting, 5 days after rainfall and 5 days after irrigation.

The deformation measurements employed match sticks as position indicators. The sticks were inserted in a smooth wall of a trench which was dug perpendicular to the wheel track. The sticks were placed in an accurate grid pattern of 50x50 mm, 1.1m wide and 0.4 cm deep. After refilling the trench, the tractor drove across the trench and deformed the soil. The trench was then carefully re-excavated and the position of the sticks mapped onto a sheet of plastic held by a steel mounting frame. The change of the position of the match sticks relative to the original position was measured in the office.

2.4 Computer Simulations of Soil Compaction

Direct measurement of the compaction process is a very difficult exercise because of the nonhomogeneity of the strength profile and the complexity of the response behaviour of field soils coupled with the varying stress loads applied to the soil. Compaction can be more conveniently and practically simulated by a computer model. The availability of fast and powerful computers and reliable dedicated software makes this option very attractive.

The University of Sydney, Centre for Geo-Mechanical Research, has developed a computer program to model soil response to applied stresses. This software was purchased for use in the project.

The program, AFENA, uses a finite element methodology. The analytical procedure divides the soil medium into little segments or elements. When a load is applied to a few elements at the soil surface the resulting stresses are distributed to other elements further away from the load. The magnitude of the transmitted stresses is a function of the stress-strain relationship of the soil. During a simulation, the program continues to distribute the stresses until certain equilibrium criteria are satisfied. Indications of stress distributions and soil deformations are obtained after a simulation run. Figure 2 is an example of a segmented soil profile. The loaded nodes are indicated by arrows.

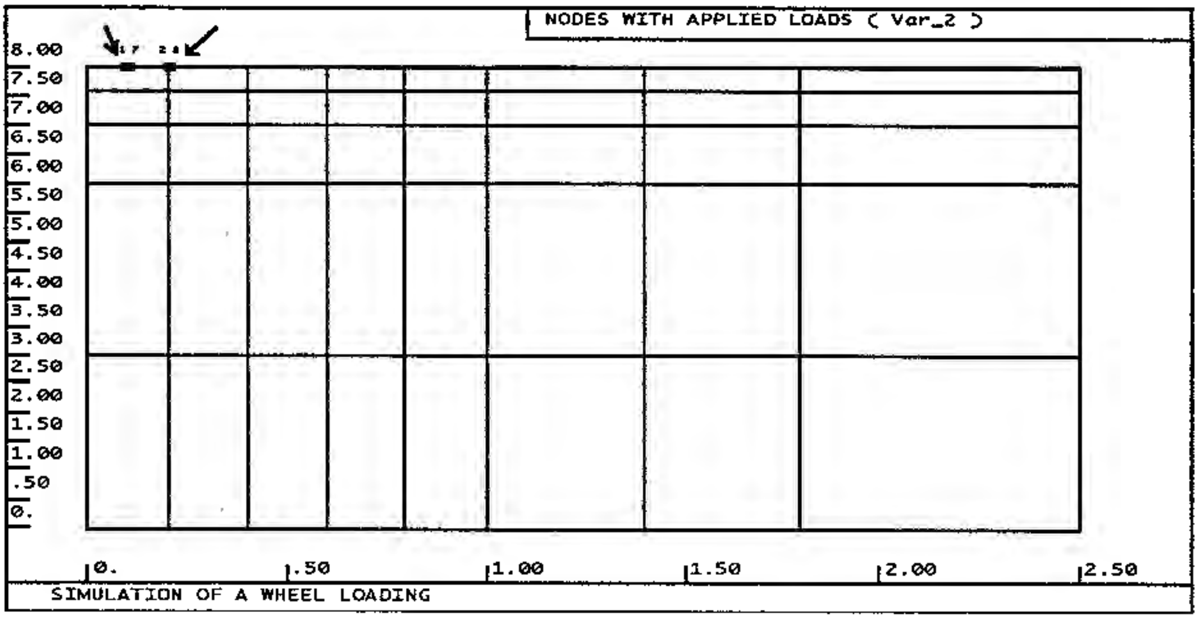


Figure 2. Example of the soil profile divided into segments. Arrows indicate the loaded segment which simulates a tyre.

3.0 RESULTS

3.1 Dynamic Stress Measurement

The combination of stresses imposed on the soil by agricultural equipment was measured on several occassions. Traditional stress theory holds that the average ground pressure is equal to the sum of the average inflation pressure and the carcass stiffness. However the pressure distribution at the tyre/soil interface is by no means uniform. Depending on the type of tyre, pressure concentrations of twice the inflation pressure can occur on the centre line of even smooth tyres. Most tyres have a more complicated pressure distribution that is related to the lug pattern. Nevertheless the average ground pressure forms an adequate basis for most compaction studies.

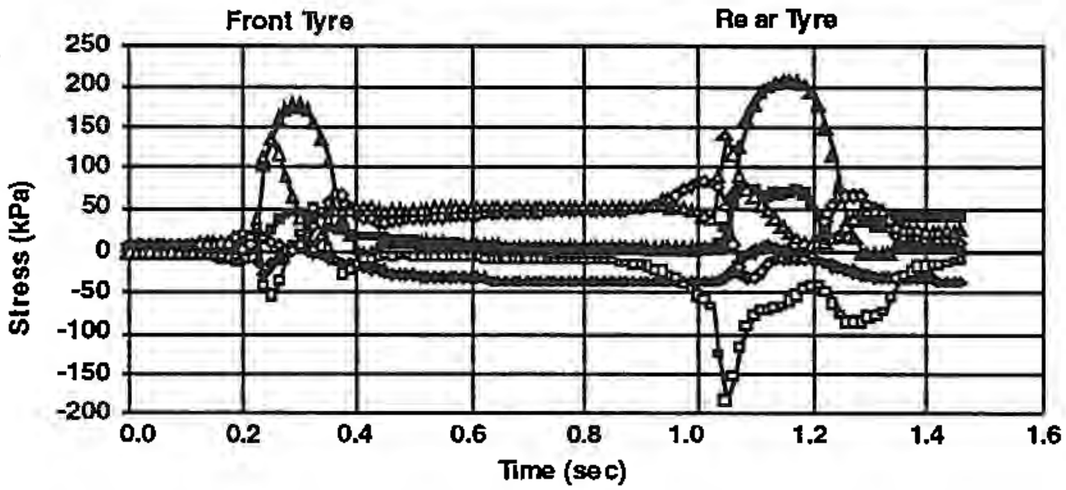
Figure 3 shows the results of stress measurements underneath a John Deere 4650 with an inter-row cultivator attached. The measurements were taken in the tail drain with a dry top soil and a moist sub-soil. The sensor was installed 15 cm below the surface. The tractor passed over the sensor a number of times with the tyres at different horizontal displacements.

Figure 3*a* portrays the stress changes under the tyre centre line. The increase in the normal stress *ZZ* is very pronounced and significant. This is the stress in the vertical direction. The horizontal stresses *XX* and *YY* remain fairly low. Negative stresses on the graph occur because installation of the sensor leaves residual stresses in the profile, and these were deducted from the total measured values. The order of magnitude of the maximum vertical stresses corresponds very well with the sum of the inflation pressure (175 kpa) and the carcass stiffness (20 kpa).

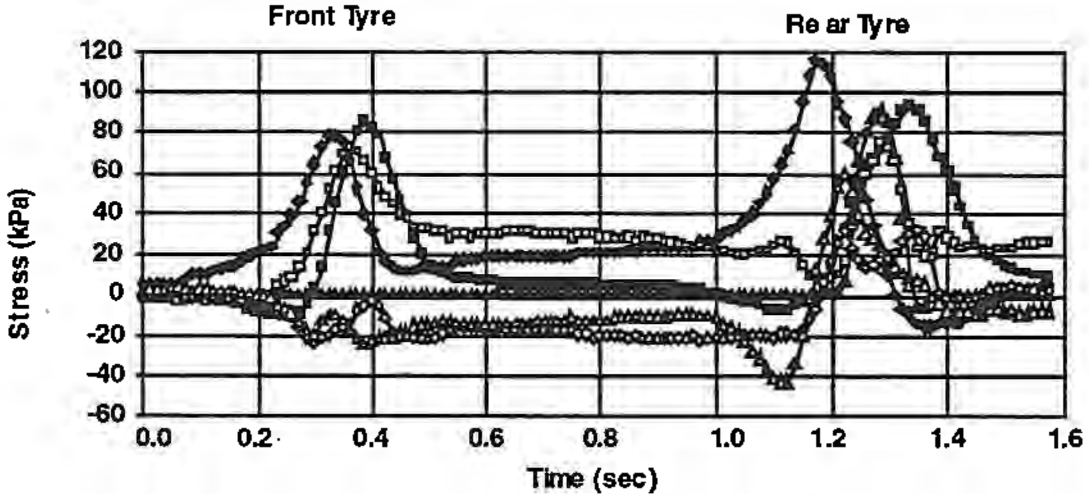
The change of direction (shown by the graph crossing the horizontal time axis) in all three shear stresses under the front tyre is expected for a rolling tyre which does not exert any draft. As the tyre approaches, a shear stress (*yz*) facing sideways away from the centre line is measured. Before the middle of the tyre reaches the position above the sensor the shear stress changes direction. This soil behaviour is often observed under tyres. In front of the tyre centre there exists an area where soil is moved forward. Behind that area but still before the tyre centre the soil is moved backward.

A similar soil stress pattern exists underneath the rear tyre. Due to the size of the tyre there is an area underneath the tyre centre where the shear stresses remain rather constant. This is maintained until the shear stresses change again as the tyre moves further forward.

a) Stresses at centre line of tyre.



b). Stresses at a distance of 20 cm from the centre line.



c) Stresses at a distance of 40cm from the centre line.

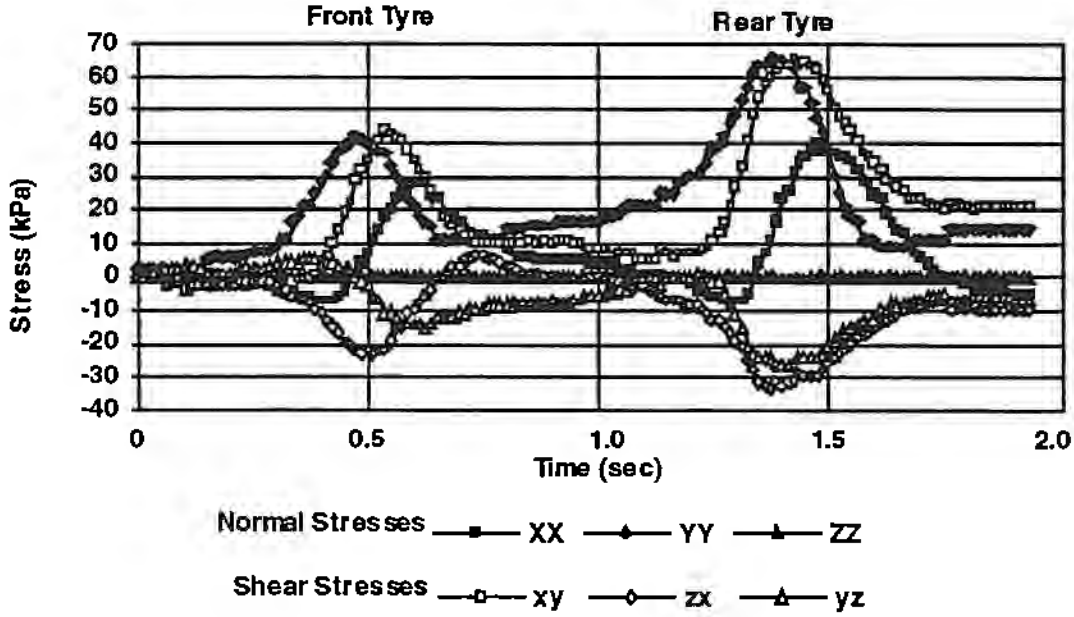


Figure 3 Stresses at 15 cm depth under the tyres of a JD 4650.

Figure 3*b* displays the stresses that develop under the edge of the tyres, 20 cm from the centre line.

The maximum stresses are less than those in Figure 3a and the contribution of the horizontal normal stresses (*XX* and *YY*) to the stress state has increased. The direction of the shear stresses does not change as the wheel passes and remains positive, indicating a general backward (*xy*), a little inward (*zx*) and upward (*yz*) oriented shear stress pattern. This pattern implies that some vertical upward displacement on the side of the tyre and side ways displacement can be expected when the soil is weak enough.

The stress state in the soil 40 cm away from the centre line at a depth of 15cm is given in Figure 3c.

The vertical stress, *ZZ*, has disappeared from this graph with an associated increase in the significance of the horizontal stresses, *XX* and *YY*. The shear stresses indicate a general backwards (*xy*), sideways (*zx*) and downward (*yz*) oriented pattern with no change in direction. The magnitude of the stresses has again been reduced. Some sideways displacement can therefore be expected when the soil is weak enough.

The previous stress figures indicate a rather complex picture for the state of stress in the soil. These stresses are direction dependent but a mathematical transformation of the stress state can be used to remove this dependence. The transformed stress state is described by two stress invariants, *P* and *Q*. *P* is the mean normal stress and *Q* is the octahedral shear stress. Both have been calculated for the three situations described above.

When *Q* is displayed as a function of *P* an indication of the stress path that occurs under a rolling tyre is obtained. Figure 3d portrays this relationship for the 3 different distances to the centre line of the tyre.

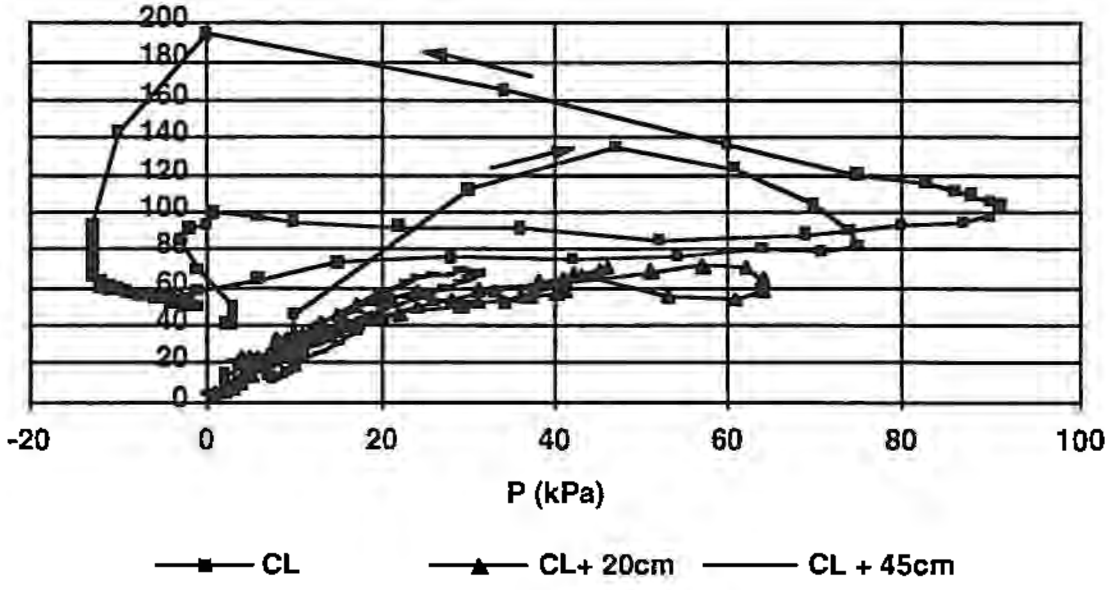


Figure 3*d*. P/Q stress path under JD 4650 at different distances to the centre line (CL)

Under the centre line the shear stress, *Q* increases rapidly and remains relatively constant followed by a rapid increase of the mean normal stress, *P*. At a distance of 20 cm from the centre line the *Q* as well as the P increase linearly up to a value of *Q* = 50 kpa where *Q* remains constant and the P increases. The same initial behaviour was found for a distance of 45 cm from the centre line but the plateau at which Q remain constant does not occur.

The P/Q paths are interpreted as follows. In the centre line under tyres the shear stress increases rapidly without any normal stress present. This may lead to a rapid soil shear failure in front of the tyre but the instantaneous increase of the normal stress compresses the soil immediately. Therefore any soil shear failure will not be visible.

Soil behaviour at the side of the tyres is governed by the constant ratio of P and Q. This indicates that soil failure is not likely to happen as the soil usually can resist this constant increase of both Q and P. However when the soil is very wet even this P/Q ratio will prove to be excessive and shearing failure of the soil will occur.

The measurements therefore indicate that no soil compaction will normally occur outside the width of the tyres. However the soil might still deform due to the small stresses P and Q under wet conditions and create unfavourable conditions for plant growth.

Similar types of stress paths were consistently obtained on all the occasions that measurements were done. Table 1 gives an overview of the results obtained during these measurements. The table indicates the type of machine, type of tyre and inflation pressure, depth of the sensor, distance of the sensor to the centre line, the magnitude of the different maximum stresses and the overall shape of the stress path.

A static measurement under the John Deere 4650 was made to assess the dynamic component in the stress measurements . Figure *3e* portrays the combination of stresses that occur in the centre line of the tyre when the tractor comes to a stand still with the rear tyre above the sensor.

Again the vertical stress, *ZZ*, is dominant. There is a difference of 30 kPa between the maximum dynamic stress and the maximum static stress. This would suggest that 30kPa can be attributed to the dynamic nature of the stresses. This should be taken into consideration when simulations are done on the computer. The shear stresses that initially develop are all reduced to very small values when the tractor stops.

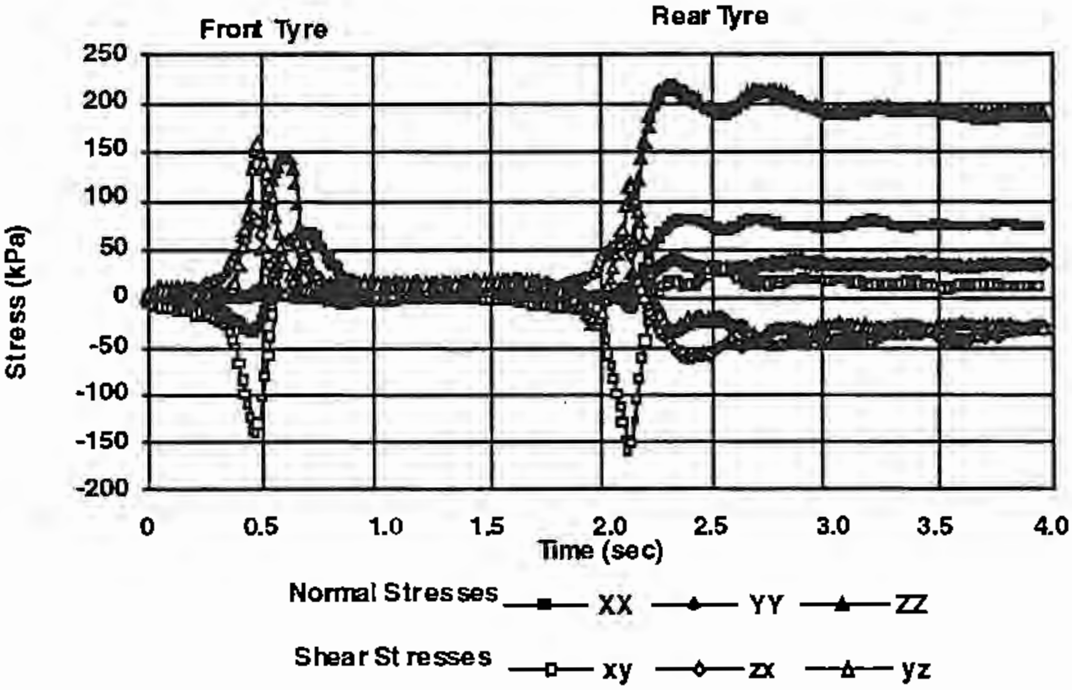


Figure *3e* Dynamic and static stresses appearing under the centre line of the tyres of a JD 4650 tractor. Depth of sensor=15 cm

Table I Maximum stresses under the tyres of different types of machinery, tyre seizes and inflation pressures, depths and distances to the centre line

Equipment	Tyre	Pressure (kPa)	Depth (cm)	CL (cm)	XX (kPa)	YY (kPa)	ZZ (kPa)	xy (kPa)	zx (kPa)	yx (kPa)	P (kPa)	Q (kPa)
JD9950	18.4 R38	267	15	20	75	80	0	70	-55	-65	40	95
		267	15	50	25	50	0	30	-30	-30	20	50
		267	25	0	25	45	250	-140	100/-40	40/60	105	110
		267	25	45	10	30	0	-15	70	30	14	60
JD4650	18.4 R32	172	15	0	70	40	210	-180	80/-40	140	90	190
		172	15	0	70	10	160	150	40	90	65	140
		172	15	20	90	110	90	80	30	60	65	70
		172	15	40	40	65	0	65	-30	-25	30	65
JD3640	12.4 R46	206	20	0	25	40	135	-90	50	70	60	100
		206	20	15	35	75	15	40	-5	-25	35	38
		206	20	25	15	40	0	40	-20	-25	18	45
		206	20	0	50	50	105	-50	25	45	65	50
		206	20	0	60	50	140	-40	25	45	55	75
		206	20	0	55	50	135	-40	-30	40	80	60
JD3640	13.6 R38		15	0	0	60	175	-40	-100	-80	80	120
			15	25	60	110	240	-70	100	140	110	150
			15	45	60	70	0	80	20	20	35	70
			25	0	5	5	50	-70	40	40	30	70
			25	25	10	70	110	-35	30	20	47	50
			25	45	90	105	15	55	55	55	60	70
			40	0	10	20	65	-40	20	-25	35	40
			40	25	35	35	22	20	35	15	30	30
JD3640	13.6 R38		25	5	60	60	120	-60	60	40	80	50
			25	5	160	100	200	-40	20	50	140	80
JD4650	18.4 R32		15	0	50	-50	270	-150	70	110	50	180
			15	0	30	0	250	-120	60	110	70	150
JD9940	18.4 R38	220	15	25	200	210	60	70	150	140	100	80
		220	15	25	150	170	30	65	135	95	75	130
JD9940	18.4 R38	220	30	20	90	85	5	60	-65	-65	45	95
		220	20	0	20	20	140	-100	90	140	48	130
		220	20	0	30	30	100	-90	110	130	40	130

3.2 Laboratory Testing

3.2.1 Soil Behaviour

The Critical State model of soil behaviour describes soil compressibility and soil strength by two functions. These are: the compression function, described as:

$$V = \Gamma - \lambda \ln P$$

where: V = Void Ratio
λ = Slope of compression curve
P = Mean Normal Stress (kPa)
Γ = Empirical constant

and the function that describes the internal friction of the soil:

$$Q = M P$$

where: P = the mean normal stress.

Q = the octahedral shear stress.

V, P and Q are measured during the shear tests. The three variables that are important are: Γ, λ and M. and are found to be moisture dependent.

In compaction studies some basic relationships have to be established between soil properties. For clay soils a relationship exists between the maximum attainable density and water content. The density can be expressed as a function of void ratio, which is the ratio of volume of voids to the volume of solids. A relationship exists also between the void ratio and the degree of saturation (S). The degree of saturation is the percentage of void space filled with water.

When the compressive stress on a soil is smaller than that experienced previously the soil is said to be over-consolidated. The ratio of the applied compression or normal stress to the maximum normal stress previously experienced is the over-consolidation ratio (OCR). The mode of soil behaviour, (expansion, compression or no volume change) depends largely on the OCR during shearing. The Critical OCR (OCR_{crit}) is defined as the OCR at which the soil neither compresses nor expands.

Figure 4*a* shows the minimum void ratio at the start of the shear tests after the soil has been compressed by a pre-determined normal stress. The maximum applied stress was 310 kPa. The minimum void ratio can be described as a parabolic function of the water content. Thus a given void ratio can be related to two different water contents. However when the void ratio, V, is related to the degree of saturation, S, a unique relationship between V and S is established, as portrayed in Figure 4b

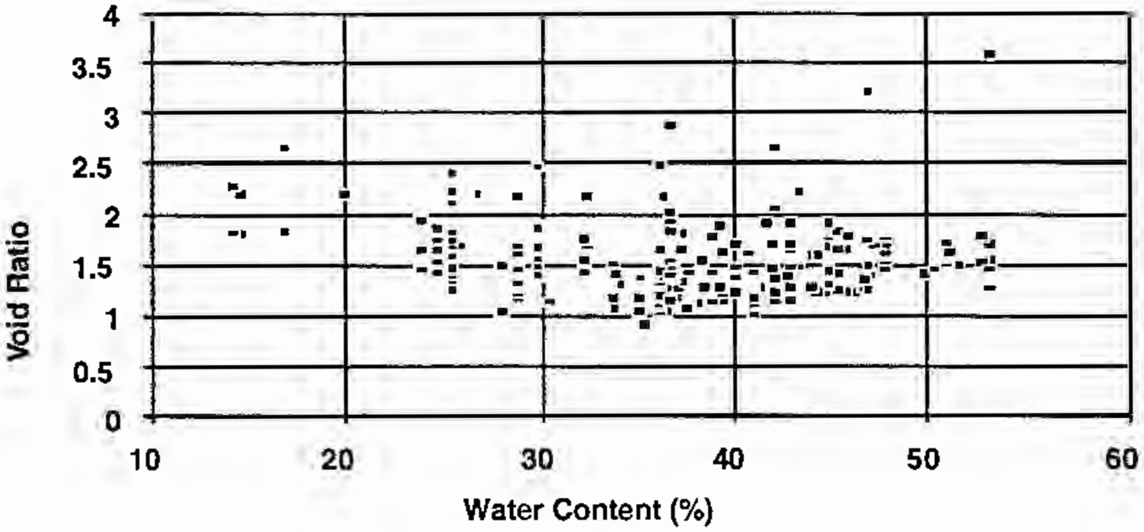


Figure 4a. Relationship between Void Ratio and the soil water content (%)

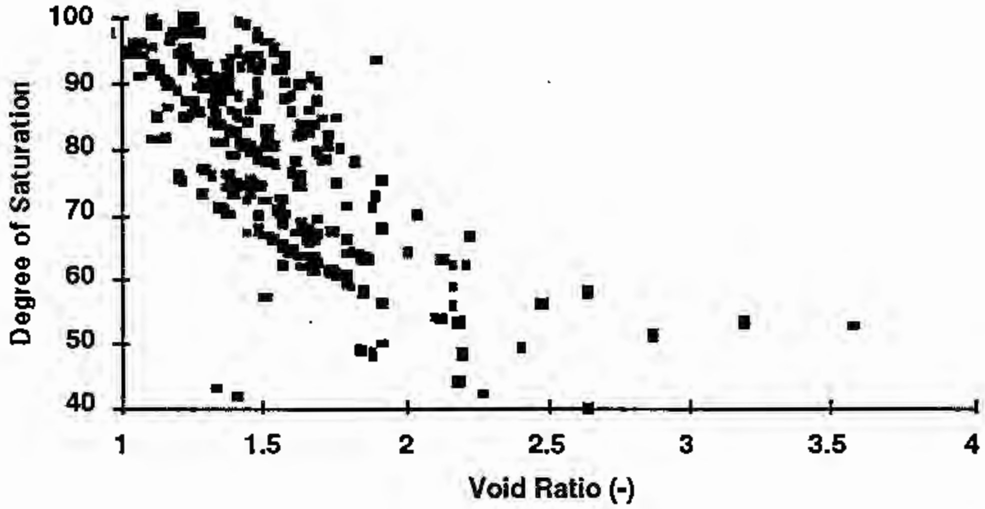


Figure 4b Relationship between Void Ratio and Degree of Saturation

When the slope of the compression curve, λ, is related to the degree of saturation, S, of the soil sample at the beginning of the compression it is found that the steepest slope exists when the soil is 55-70% saturated. This is displayed in Figure 4c. From the relationships described in figure 4a and 4b it can be found that the corresponding water content is in the range of 30-40%. Soil at that water content is most compressible, and would thus be at the optimum water content for compaction.

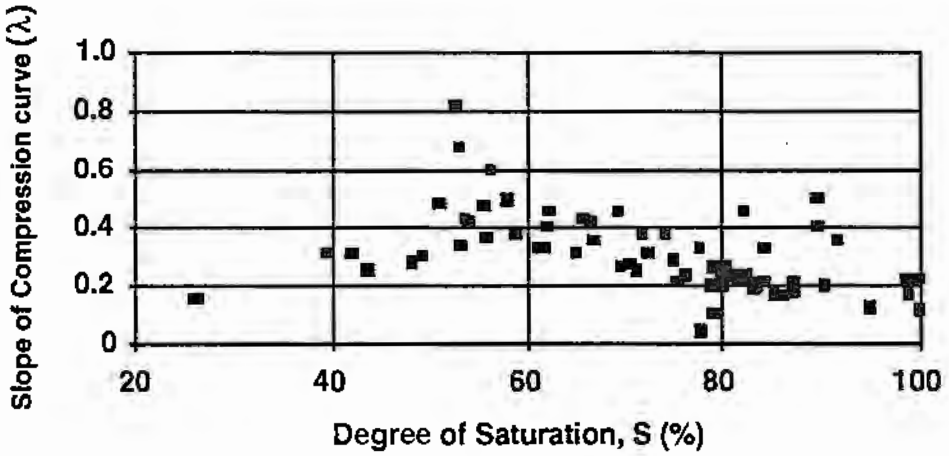


Figure 4c. Relationship between the slope of the compression curve (λ) and the degree of saturation (S)

These findings agree with the civil engineering practice of compacting the sub-base of a road body at Optimum Moisture Content (OMC). For the Black Earth the OMC is around the 30-32% water content.

The slope of the P-Q relationship, M, for field soils which are compressed and sheared at a compression stress of 310kpa is portrayed in Figure 4*d*. The slope reduces with an increase in the degree of saturation , indicating that the soil becomes weaker as it gets wetter.

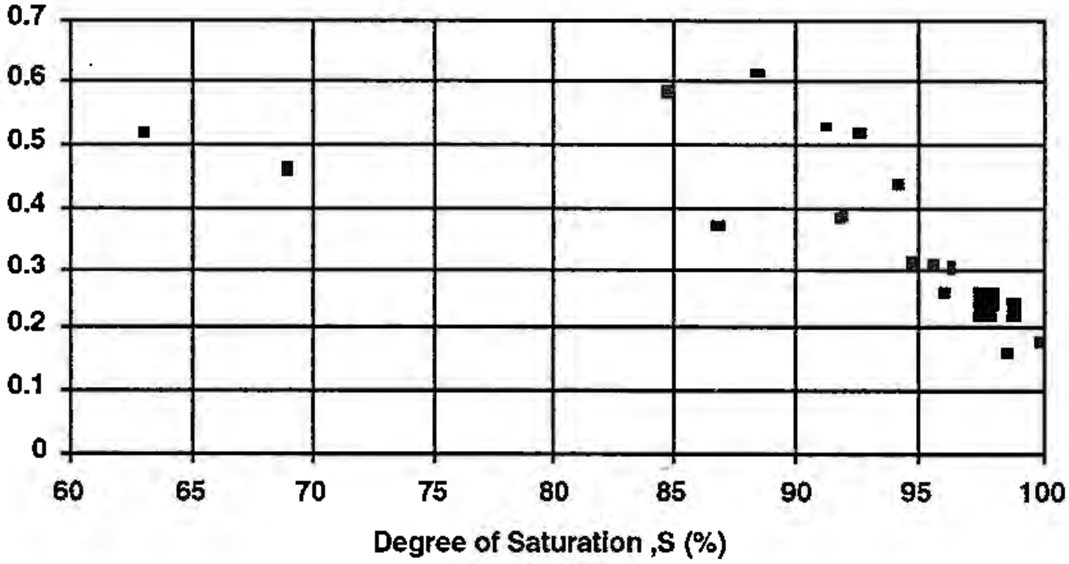


Figure 4d The influence of degree of saturation (S) on M, the slope of the P/Q relationship

The OCR_{crit} is also a function of the degree of saturation as Figure *4e* indicates. The changes in void ratio that occur during the shear tests at different OCR values are shown. The volume changes clearly reduce on this graph as the soil gets wetter.

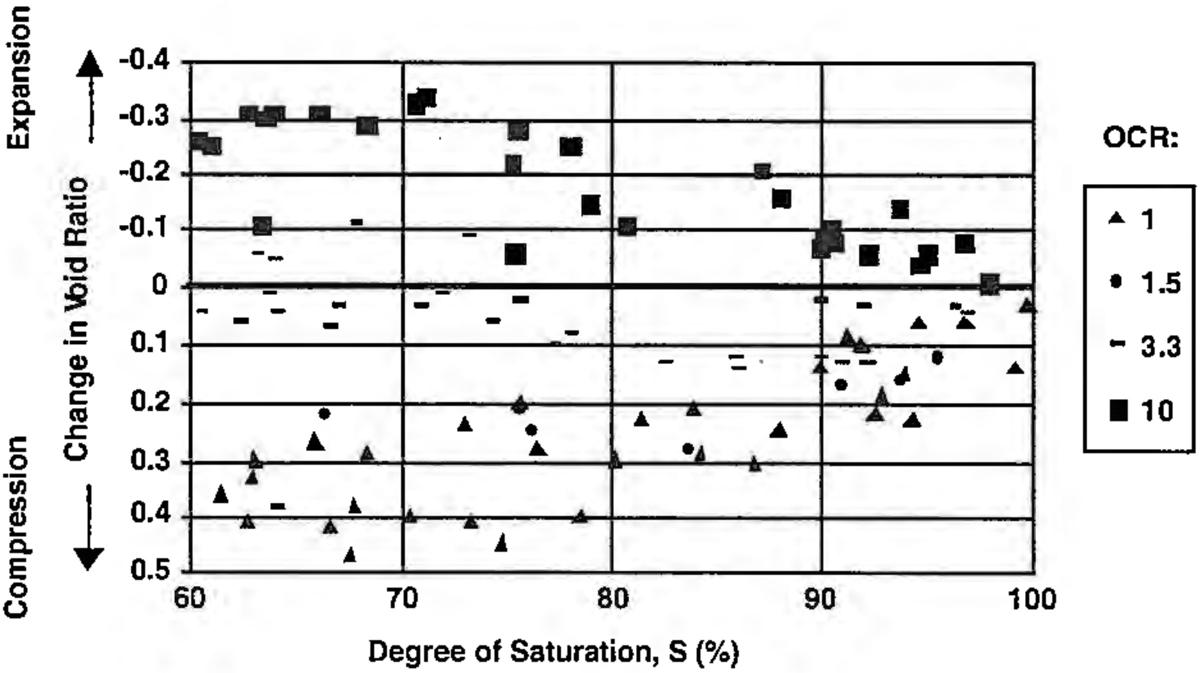


Figure 4e. Change of Void Ratio (V) during shear tests as a function of the Degree of Saturation (S) and Over-Consolidation Ratio (OCR). Positive values indicate compression while negative change expansion.

The soil behaviour changes at a degree of saturation greater than 75% . Shearing with an OCR of 3.3 starts to bring about a void ratio decrease rather than no void ratio change at values of S above 75%. As the soil becomes more saturated the volume changes decrease during shearing at all OCR's. The 75% degree of saturation can be related to void ratio and soil water content through figures 4*a* and 4*b*. These figures show that the transition occurs at a void ratio of 1.4 or a water content of 32%-42% which is just above the plastic limit of the soil. In practice farmers will work the soil just below or around the plastic limit. The shear tests confirm the loosening effect of these tillage practices from a soil mechanical perspective.

The point could be made that an implement which induces stresses corresponding to an OCR of 3.3 will neither compact nor compress at a soil at S<75%. This would represent a marginal tillage operation and at S>75% the soil will start to compact. It is unlikely that tillage implements that can induce an OCR of 10 exist, because such an implement would expand the soil even near saturation (S=95%), and this is not frequently observed.

3.2.2 Cotton Trash

The soil strength can be increased with the addition of cotton trash. Several different soil tests were carried out to prove this effect. Figure 5 shows the influence of cotton trash on the soil strength by means of triaxial testing. The lines indicate the points of failure.

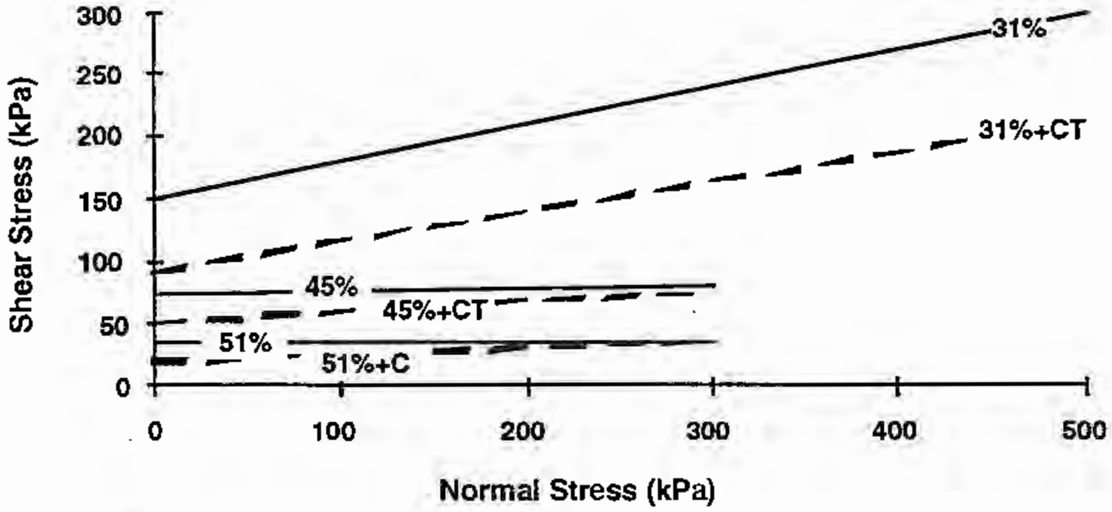


Figure 5 The influence of cotton trash on the soil strength at different water contents. The broken line (- - - - -) +CT indicates "with cotton trash"

The slope of the failure line does not change significantly but the intercept on the Y-axis is greatly affected by the addition of trash. The upward shift of the failure line indicates that the soil is able to resist higher shear stresses at the same normal stress before failure occurs when cotton trash is included. The effect is reduced with an increase in soil water and would only be of practical use below 31% water content.

3.3 Field Laneway Experiments

3.3.1 1991-1992 season

The laneways installed prior to pre-watering underwent a lot of subsequent deformation in the period following sowing. The elevated laneways completely flattened and became level with the adjacent beds. An associated problem occured with the permanent beds. They were also reduced in height when loose soil was taken to build up the wheel tracks. This resulted in minor flooding of the beds on several occasions. During planting it became obvious that guidance of the tractor was a limitation to using elevated laneways. Planting depth in the raised wheel track treatment was insufficient and a re-watering was necessary in order to ensure proper establishment. The crop in the treatment with the elevated laneways therefore experienced a delay in initial development.

Observations during field work after rain and after irrigations indicated the existence of differences in soil strength between the elevated laneways and the recessed wheel tracks. Measurements with the drop cone penetrometer, however, did not reveal any statistically significant differences between factors (laneway geometry) or sub-factors (cotton trash, gypsum and control). The results of average depth of penetration tests from several different tests are given in Table II. The water content and penetrations in this table are averaged from all experimental values.

Table II Drop cone penetration (cm) and the water content (%) of the top soil from several occasions.

Occasion	%	cm
End '90/'91 growing season	28.2	2.51
20 days after pre-watering and before planting	45.9	4.38
After planting	48.1	2.12
7 days after suppl. irrigation	41.1	3.1
5 days after rain (30mm)	43.3	3.2
2 days after rain (55mm)	52.3	5.1
5 days after rain (10mm) and irrigation	46.0	4.3

Drop cone penetrations were related to the irrigation-furrow cross sectional area as shown in Figure 6. The furrow base was used as a reference level for all profile measurements. Any decrease in soil strength (as given by a higher penetration reading) is accompanied by a general slumping of the bed profile, and hence a relatively larger furrow size.

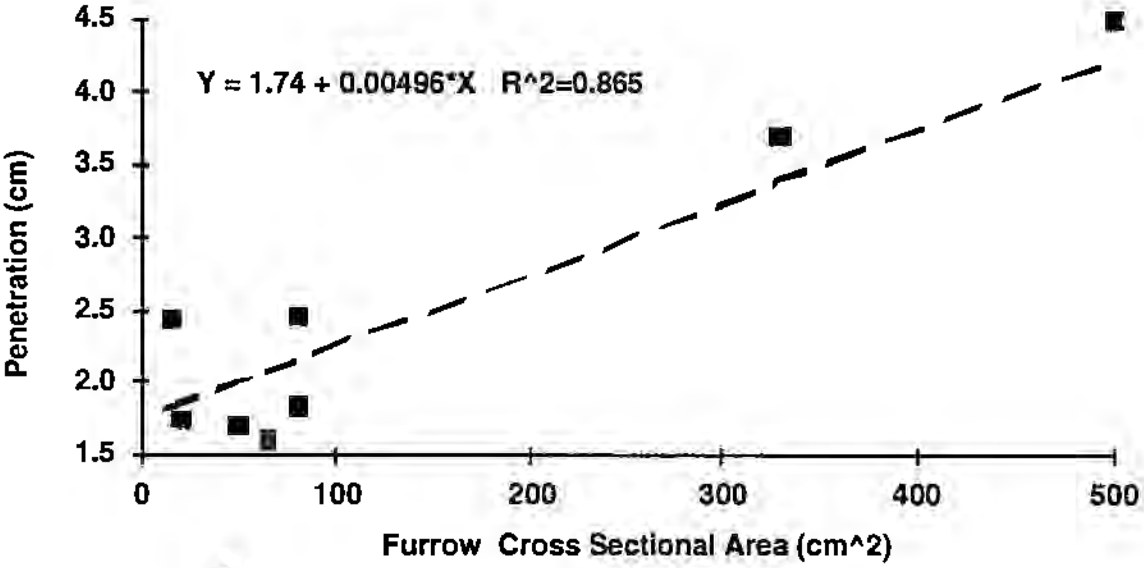


Figure 6 Relationship between Drop-Cone penetration and the Increase in Furrow Cross Sectional area.

The results in Table II can be used with this graph to determine the furrow size during the experiment. Analysis of this information shows that a significant increase in the furrow area can be expected 2 days after 55 mm of rain due to soil deformation. The deformation that occurs is also a function of the wheel loads of the equipment used but this has not been taken into account in the above relationship. An attempt will be made in the future to relate surface deformation or wheel rut development with sub-soil deformation and drop cone penetration.

In every replicate of each factor the yield from a section of one metre of plant row was taken. The yield from these sections was expressed as relative yield , being the ratio of the yield to the highest yield occurring in any of the sections. Adjacent to each of these sections the moisture extraction was followed with neutron probes. The total moisture extraction over a depth 20 - 60 cm was calculated and also expressed in terms as relative moisture extraction, being the ratio of the moisture extraction to the highest moisture extraction, occurring in any of the sections. The results of these observations are indicated in Figure 7.

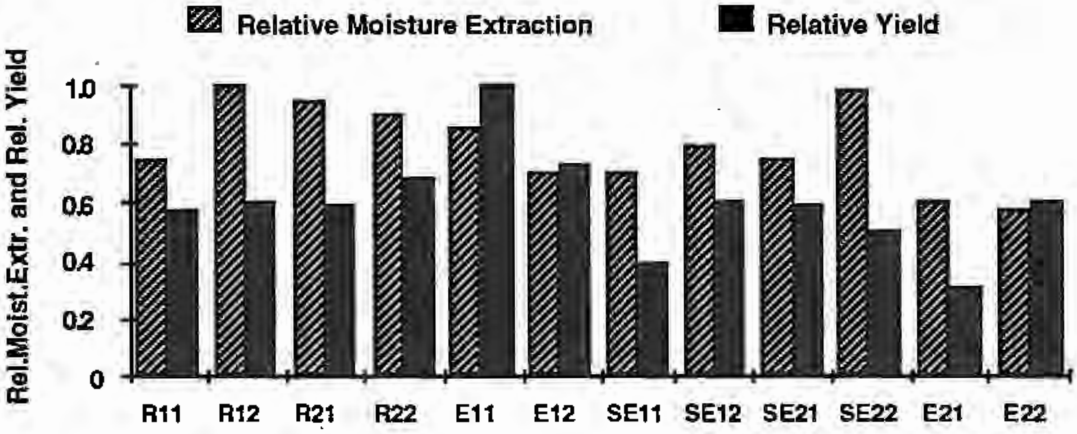


Figure 7 Relative yield and relative moisture extraction in the experiment. R=Recessed Laneway, SE=Semi-Elevated, E=Elevated

No statistically significant differences across the replicates in the yield were found between the recessed, semi-elevated and elevated laneways. However moisture extraction in the elevated laneways was significantly lower (5% level) than in the recessed laneways but not in the semi-elevated. When the yield is expressed as a ratio of weight to millimetres extracted soil moisture, the elevated laneways are significantly different from both other treatments with a change of occurrence of 99.9%.

The elevated laneways treatment had suffered from poor plant establishment due to a shallow planting depth but the overall results from the '91/'92 field experiment showed that the aspect of the raised wheel tracks should be further researched. In the '91/'92 experiment no allowance was made for a comparison between the raised wheel tracks and a 2 metre bed configuration. A comparison between these two bed systems was considered necessary, and planned for the '92/'93 season.

In contrast to the laboratory results, no difference in soil strength was found when cotton trash was included in the field, so it was decided not to proceed with this option. During the '91/'92 season it was also found that a significant amount of re-growth occurred in those sections that had been strengthened with trash. In order to profit from the inclusion of cotton trash a larger body of soil should be strengthened with the cotton stalks. This could probably he achieved over some years in a back-to-back cotton rotation.

3.3.2 1992-1993 season

The installation and maintenance of the treatments did not pose any difficulties during this season. The coorperating farm uses a 1 metre standard bed system and some effort was required in setting up equipment to handle 2m beds and 2m beds with Raised Wheel Tracks (RWT). Some difficulties were encountered in staying on the centre of the RWT during planting, again highlighting the need for steering guidance. Driving on the RWT's demands constant attention from the operator. During picking the automatic depth control of the pickers could not cater for the RWT's and manual control was required. This should not create any difficulties in the future since re-adjustment of the depth controls are easy to make.

Differences between the treatments were observed in:
- the rates of crop development,
- the root densities relative to the plant row,
- the raw cotton yield, and
- the soil displacements under the same timing of operations

A phenelogical summary of the trials is given in Figure 8. The treatment with the raised wheel tracks developed at a different rate to the other treatments.

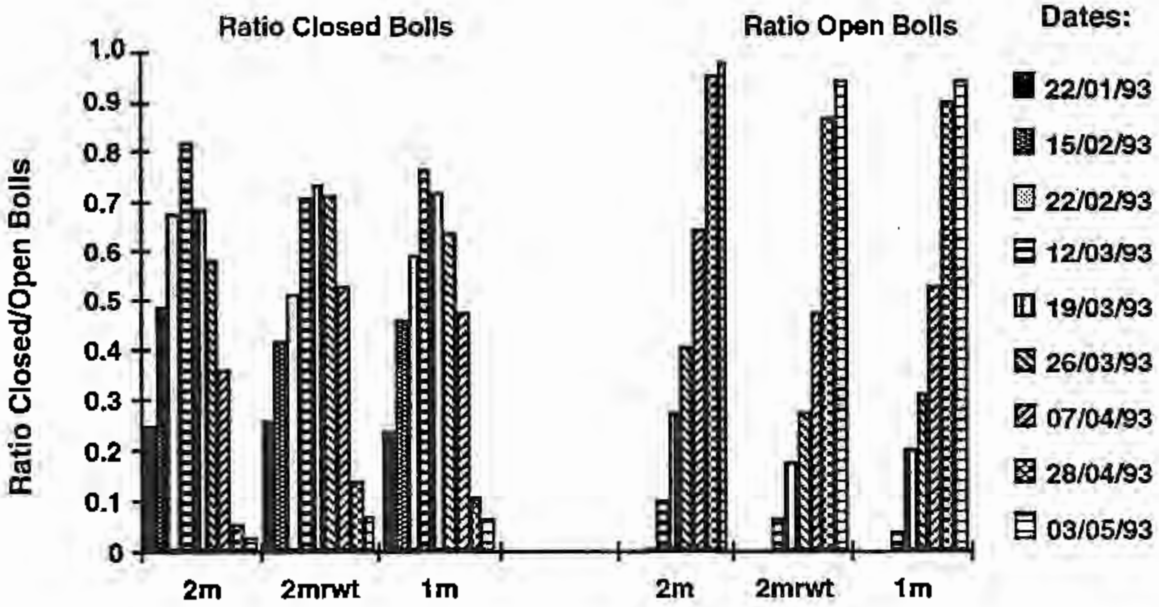


Figure 8 Ratios of Closed Bolls and Ratios of Open Bolls in the three treatments. The results are averages from three observations.

The Ratio Closed Bolls is the number of closed bolls divided by the total number of fruiting sites (squares, closed and open bolls). Similarly the Ratio Open Bolls is the number of open bolls divided by the total number of fruiting sites (squares, closed and open bolls).

The conventional 2 metre beds (2m) rapidly opened the bolls after the 12th of March. The 2m RWT was slower in its development. The Ratio of Open Bolls in figure 8 also shows that the 2m treatment was ahead of the other two treatments with the 2m RWT trailing behind. On the 3rd of May, two weeks after defoliation, the 2m beds had opened 97% of the bolls whereas both the 1m and the 2m RWT treatment had opened 94 % of the bolls. These data are averaged over three sampling sites.

Early February root density samples were taken in the centre of the 2m bed, the wheel track of the 2m RWT and the centre of the 1m bed. The top 15 cm was sampled with a spade. The roots were washed from the soil after the soil was air dried and crushed. It proved to very difficult to separate other organic matter from the roots. The previous crop had been soya beans and the stubble had been burned. This resulted in very small black particles of the same size and weight as the roots. Consequently the weight of the root samples were affected by the presence of foreign organic matter. It was assumed that the introduced error affected all samples equally. Two samples were taken at both the bottom and the top of the field. Figure 9 portrays the amount of roots per gram of soil. It can be seen that there is a significantly higher amount of roots present in the RWT as compared to the centre of the 2 metre bed or the centre of the 1 metre bed. Visual observations also showed a clear difference between these sampling sites.

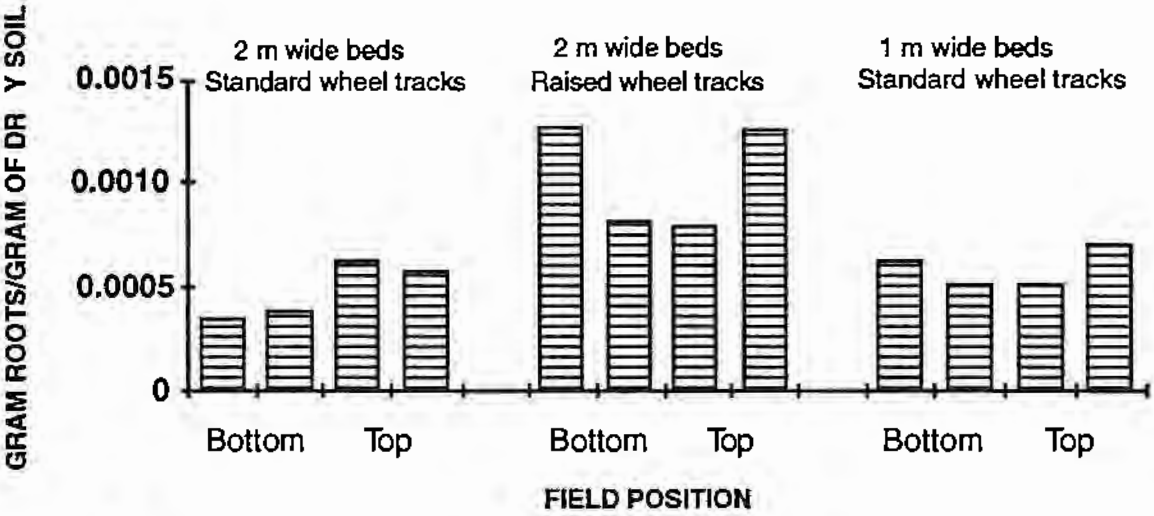


Figure 9 Root Densities (gm organic matter per gm soil) in the top 15cm of the profile. Samples are taken from three treatments at two different sites, Top and Bottom of the field.

From these observations it is concluded that the presence of wheel tracks, provided they have good drainage properties, does not hamper root growth. The last inter-row cultivation had been carried out at the end of November. On that occasion the soil in the centre of the 2m bed was disturbed whereas the raised wheel track was left undisturbed. It is very unlikely that this operation would have affected root growth at a later stage.

On three occasions after irrigation and rainfall soil moisture samples were taken in the wheel track furrows and the raised wheel tracks. On all these occasions the raised wheel tracks were drier than the other wheel tracks. On several occasions after rainfall it was also observed that the raised wheel tracks provided very good drainage for the centre of the beds. Small gullies developed from the wheel track to the furrow. This might have contributed to a better root development in the raised wheel track when compared to the centre of the 2 metre beds. No measured data to support these observations are available.

At the end of the experiment the yield in all four replicates in all the treatments were recorded with portable scales and are reported in Table III. Assumed gin turn-out was 38%.

The yield in the conventional 2 metre beds are significantly lower than the rest, while the 2mRWT are statistically significantly higher than the 1 metre beds. This result is supported by the number of open boll/metre count described previously.

The various measurements indicated that the crop in the raised wheel tracks had the benefit of a larger supply of soil moisture and matured later. This contributed to a larger yield. These results also confirmed the findings of the '91/'92 trial (Figure 7).

Table III. Yield of the four replicates in the three treatments, Condamine Plains, '92/'93. Assumed gin turn-out =38%

Treatment	Weight (Ton)	Bale/Acre
2m	2.29	2.79
2m	2.31	2.81
2m	2.33	2.84
2m	2.34	2.85
2mRWT	2.67	3.25
2mRWT	2.48	3.02
2mRWT	2.51	3.05
2mRWT	2.55	3.10
1m	2.47	3.01
1m	2.48	3.02
1m	2.47	3.01
1m	2.48	3.02

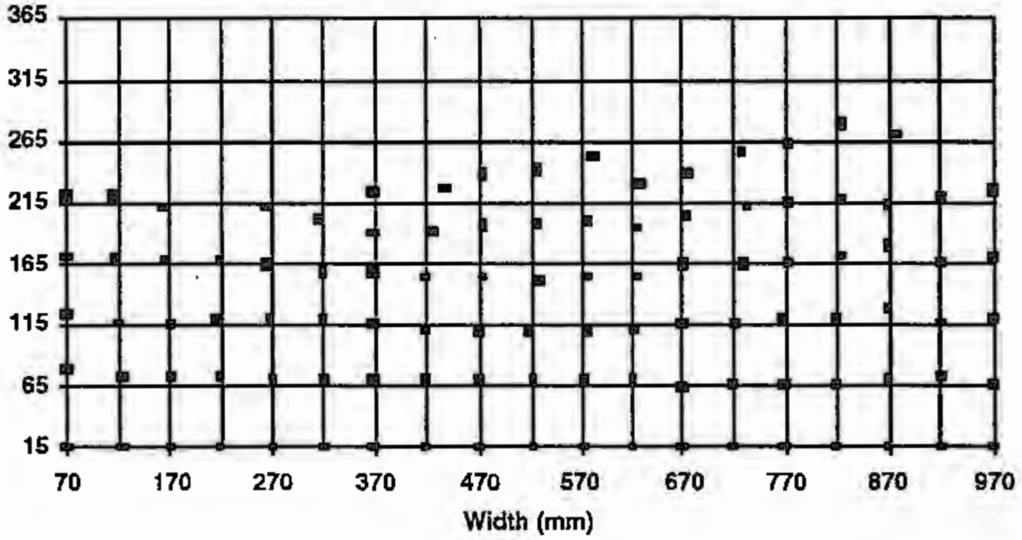
3.3.3 Soil Deformations

The soil deformation under field traffic was extensively studied in this project. Due to the lack of rain there was no restriction on field access. Planting was the only operation carried out under moist conditions but even then the top soil was very dry. The grower was asked on two occasions to enter the field when the soil was still reasonably wet so that the required measurements could be made with a wet soil. Typical results from these measurements are shown in Figure 10.

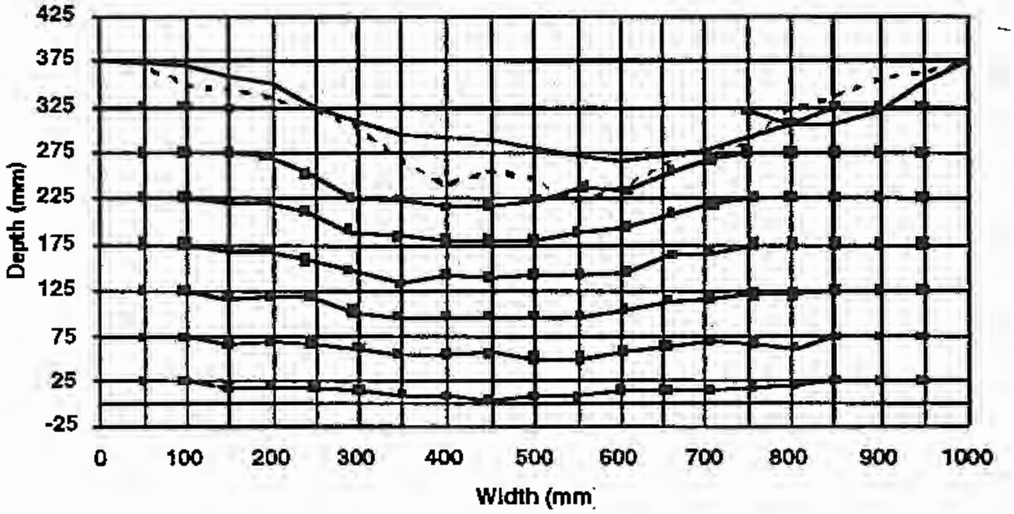
The deformation in the recessed wheel track that occurred during planting is portrayed in figure 10*a*. Some non-uniform displacement to the sides of the furrow occurred but no sideways displacements into the root zone. The displacements overall were minimal. This would suggest that from a compaction point of view planting could have been initiated earlier.

The second trial occurred 7 days after heavy rain (145mm fell in 5 days). Figure 10*b* shows the displacement which occurred in the recessed wheel track. Figure 10*c* indicates the deformation which occurred in the raised wheel track. The tractor was a JD 4650 equipped with a small cultivator. The solid line in the following figures indicates the projection of the original soil surface on the plastic sheet. The broken line indicates the projection of soil surface after wheel passage.

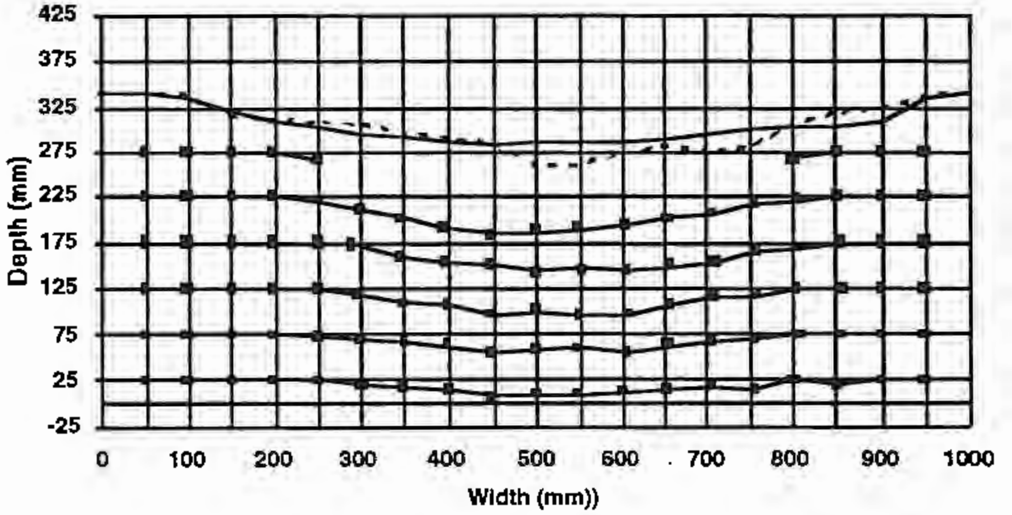
a) Deformation in a reccessed wheel track during planting



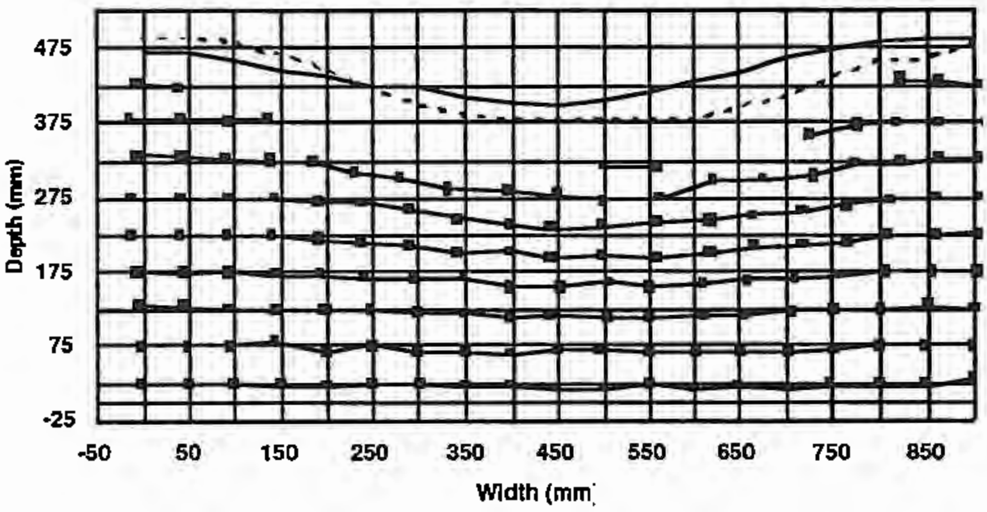
b) Deformation in a recessed wheel track 7 days after rain



c) Deformation in a raised wheel track, 7 days after rain



d) Deformation in a recessed wheel track 5 days after irrigation.



e) Deformation in a raised wheel track 5 days after irrigation .

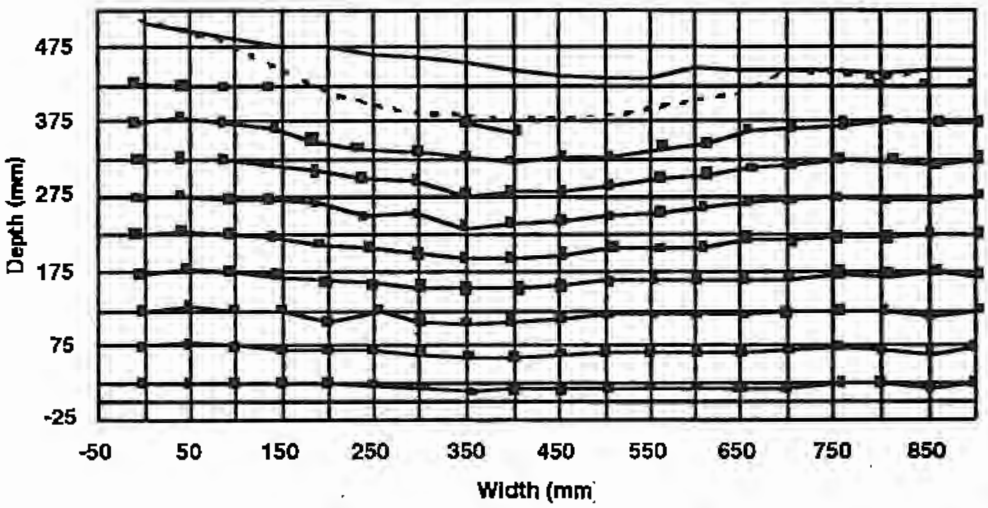


Figure 10. Deformation measured in wheel tracks after planting

The third and last trial occurred 5 days after irrigation. A JD 4755 tractor was used in these experiments with no implements attached. Figure 10*d* portrays the displacements that occurred in a recessed wheel track and Figure 10*e* the deformation that occurred in the raised wheel track.

The results in Figure 10 show that a lack of side ways displacement occurred on the second occasion compared to that which occurred on the third occasion. The soil moisture on the second and third occasion at depths of 0-5cm and 5-10cm were respectively, 31%, 47% and 44%, 52%.

Even though the soil was displaced, soil compaction as measured by changes in bulk density might not have occurred on the third occasion that measurements were taken. Laboratory testing indicated that the soil becomes in-compressible at higher water contents. However soil deformation can take place with no compaction, and deformation is then characterised by smearing of the clay. An investigation into the orientation of the clay particles as the result of traffic under wet conditions will be initiated as part of a follow up project.

Soil deformation with no associated change in bulk density is characterised by large side-ways displacements. When the sum of the total horizontal displacements (H) is divided by the sum of the total vertical displacements (V) a ratio is obtained that indicates what the contribution of the horizontal displacement is to the total displacements. Table IV gives the H/V ratio's obtained on several occasions.

Table IV Ratios of the vertical and horizontal displacements for different treatments on two different occasions

Timing	Treatment	H/V Ratio	No of Replicates
7 days after heavy rain	2m	0.22	1
7 days after heavy rain	2mRWT	0.22	1
5 days after irrigation	2m	0.68	1
5 days after irrigation	2m	0.70	2
5 days after irrigation	2m RWT	0.44	1
5 days after irrigation	2m RWT	0.44	2
5 days after irrigation	1m	0.58	1
5 days after irrigation	1m	0.58	2

Not much side ways displacement occured with traffic 7 days after major rainfall.

When the field has to be trafficked under wet conditions e.g. a wet pick, as simulated by the traffic trial 5 days after irrigation, it can be seen that the contribution of the side-ways displacement to the overall deformation is far greater than it is 7 days after heavy rain.

Under these very wet conditions the measured side-ways displacements are less when raised wheel tracks are used. This can be partly attributed to the initially rather flat wheel track but differences in soil moisture in the top 10 cm between treatments contributed also to a different distribution of the deformations. The raised wheel tracks were drier than the recessed wheel tracks. Even though the wetting-up profile under irrigation is different from rain fall, it was noted that the raised wheel tracks remained dryer than the recessed wheel tracks after heavy rain.

3.4 Computer Simulation Of Soil Compaction.

The AFENA package has been used in initial simulations of the trial soil profile.

The loading function on the loaded nodes was that measured in the field. This contrasts with previous soil compaction simulation studies. They tend to assume a constant load applied on the element and then to use the calculated deformation as an indicator for the real deformation. However soil deformations can be separated into elastic and plastic deformations. The elastic deformations are recoverable deformations whereas the plastic deformations are not recoverable. The latter cause soil compaction. These plastic deformations have been measured in the field and are displayed in Figure 10. They will be used to refine the input parameters which were initially derived from the soil mechanical tests. Detailed and reliable results are not yet available but this area is the subject of a follow up project.

4.0 Conclusions

The following conclusions are separated into the key areas researched in this sub-project.

4.1 Dynamic Stress Measurement

The dynamic component adds about 15% to static stress levels in the soil from farm machinery.

Vertical stress is the major contributor to the stress state in the soil under the centre line of a tyre. Any reduction in this stress component will reduce compaction. The P-Q stress path indicates the significance of the shear stresses that develop at a distance of 45cm from the centre line as the tyre moves over the soil. The response of the soil to these stresses is entirely dependent on the soil strength. This emphasizes the importance of our future stress path controlled shear test program.

4.2 Laboratory Testing

The soil is most compressible at a degree of saturation of 65%. This corresponds to a water content of about 30%, at which level most of compaction can be expected to occur.

As the soil gets wetter and weaker, deformations still occur but in the form of shearing instead of compression. At a 75% degree of saturation a major change in soil behaviour occurs and the soil is compressed when sheared with an OCR of 3.3. This corresponds to a water content of roughly 35-40%. Cultivations should be carried out below this water content.

4.3 Field Experiments and Laneway Performance

Raised wheel tracks have performed well over the last two seasons and provide method for soil compaction control with no observed yield penalty.

A guidance system would be required to eliminate management problems associated with implement steering on raised wheel tracks.

5.0 Publications Resulting From the Project.

5.1 Refereed Publications

Harris, H and D.M. Bakker, 1993. A Soil Stress Transducer for Measuring In-Situ Soil Stresses. Accepted for publication in Soil and Tillage Research

Harris, H and D.M. Bakker, 1993. A Servo Controlled Simple Shearbox. Accepted for publication in Soil and Tillage Research

5.2 Conference Papers

Bakker, D.M and H. Harris. 1992. The Measurement of Critical State Parameters for a Black Earth. Proceedings Agricultural Engineering Conference, Albury, NSW, Australia

Bakker, D.M and H. Harris. 1992. Design and Implementation of Laneways in Irrigated Cotton Farming. Proceedings Agricultural Engineering Conference, Albury, NSW, Australia

Harris, H and D.M. Bakker. 1992. A Soil Stress Transducer and Its Use for Measuring the Stress State Under Tyres. Proceedings Agricultural Engineering Conference, Albury, NSW, Australia

5.3 Poster Paper:

Bakker, D.M and H. Harris. 1992. Soil Management for Laneways in Controlled Traffic in Cotton Growing Areas. 4th National Soils Conference, Adelaide

5.4 Articles

Harris, H. and D. Bakker. 1991. Designing and installing stable laneways. The Australian Cottongrower, May - June. No. 3 Vol. 12

Bakker, D. M., H. Harris and M. Porter. 1993. Control of compaction in permanent bed farming. The Australian Cottongrower, Jan. - Feb. No. 1 Vol. 14

Bakker, D. M. 1993. Cotton stalks and soil strength. The Australian Cottongrower, Jan. - Feb. No. 1 Vol. 14

Guidance sub-project

1. Aims

The primary aim of this sub-project was to establish a suitable system for automatic guidance of farm machinery for growing cotton.

Specific objectives were defined as follows:

(i) to evaluate previous research findings and available equipment components,

(ii) to recommend a suitable basis for a guidance system for use on cotton machinery, based on the previous evaluations.

(iii) to design and develop a system to automatically steer any agricultural machine to a desired level of accuracy while performing a range of functions.

The first two of these objectives were met in full. The third objective was partially achieved with the specification of a suitable system for guiding farm tractors. A substantial amount of extra work is required to prove this system under field conditions, and to commercialise the system. A separate project was therefore instigated to complete this work, in partnership with the CRDC, cooperating farmers, and a tractor manufacturer.

In general the developed system is considered to have great potential for commercial exploitation within the cotton industry.

2. Methods

2.1 Initial Evaluations

Previous industry effort has been directed at controlling the implement rather than the tractor, (eg Orthman Tracker series, Truetrack system) with the implement free to move relative to the vehicle. Such systems do not adequately control the location of the tractor wheels; a serious flaw in controlled traffic farming systems. This project sought to achieve accurate guidance of the tractor itself in a way that would allow the implement to follow the tractor's path.

The methodology adopted in the project was to initially establish a list of tasks required of a guidance system in order to make controlled traffic work, and then to propose a system based on available components where possible. Several guidance mechanisms were evaluated for suitability of use in growing cotton. Results were gathered from experimental systems based on three of these alternatives.

Experimental trials of two guidance systems were performed during the first stages of the project. These consisted of a Leader Cable system, and the Microcom[1] Ultrasonic Row Guidance system. The Leader Cable system uses transducers to detect a magnetic field around a buried cable (that carries an electric current), while the Microcom System uses an ultrasonic sonar sensor to determine the position of the crop row

A subsequent series of trials was conducted with a camera-based vision system. This system was developed at the U.S.Q. specifically for the project and employed a PC for both vision processing and control implementation. Frame sequential image analysis methods enabled changing features to be tracked, giving estimates of the system states which were used in a variable-structure control algorithm for steering.

Results of the work done to date are presented and other sensory inputs considered below.

2.2 System Assessment.

For some time the "Controlled Traffic" concept has been growing in economic important to the cotton industry, with an increasing awareness of the effect that soil damage has on crop growth. It is desirable for the tyres on all farm machinery to travel down the same path during every operation so that the compactive effects are confined. Such techniques maximise the uncompacted soil area adjacent to the wheel tracks if applied correctly, with the primary cause of failure being operator inability to ensure that the wheel tracks do not drift over time.

A suitable automatic guidance task for cotton growing must meet a range of goals for different operations. The goals were established by identifying machinery tasks likely to place pressure on a driver attempting to accurately steer the vehicle. The tasks were identified as :

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[1] Use of particular trade names is for descriptive purposes only, and does not imply any endorsement of the product.

i) LISTING: The tractor and implement must be guided along straight parallel rows. The field is bare at this stage but a requirement remains for the laneway locations to be re-established from the previous season.

ii) PRE-PLANTING TILLAGE and SPRAYING OPERATIONS, plus PLANTING. A bare furrow is evident, with wheels of the vehicles needing to pass accurately along the same path as the listing rig.

iii) INTER-ROW CROP CULTIVATION. In addition to controlling any compactive effects, accurate steering control will contribute to
   - Plant damage minimisation, and
   - Mechanical weed control,

iv) PICKING. Heavy cotton pickers cause a high percentage of the damage that occurs to a field during a season. The guidance system should also enable the pickers to follow the established wheel tracks.

v) POST HARVEST operations. Tractors and implements must be controlled in such operations as they often occur during the wetter period of the year when the soil is most susceptible to compaction.

Two existing systems were initially trialed to establish their ability to meet these task requirements. The Leader Cable Guidance and Ultrasonic Guidance systems were selected on the basis of their existing performance in other industries, and on the performance claims of sensor manufacturers.

2.3 Leader Cable Guidance.

A wire guidance system works by detecting the magnetic field around a buried wire that has been electromagnetically excited by an electric current. The location of the wire is estimated by gauging the relative strength of the electromagnetic field as detected by two transducers mounted on the moving vehicle. Signals produced by the transducers are used to control the hydraulic steering and to therefore keep the tractor on the desired path. The attraction of this approach is that it is widely used in many industrial applications and suitable equipment is readily available. Figure 1 shows the concept diagrammatically.

As the sensor mounted on the vehicle moves either side of the wire, different voltages are induced in the two coils. The difference between these voltages can be used to establish the position of the combined sensor relative to the wire. The distance from the sensor to the centre line of the wire increases as the voltage difference increases as shown in Figure 2.

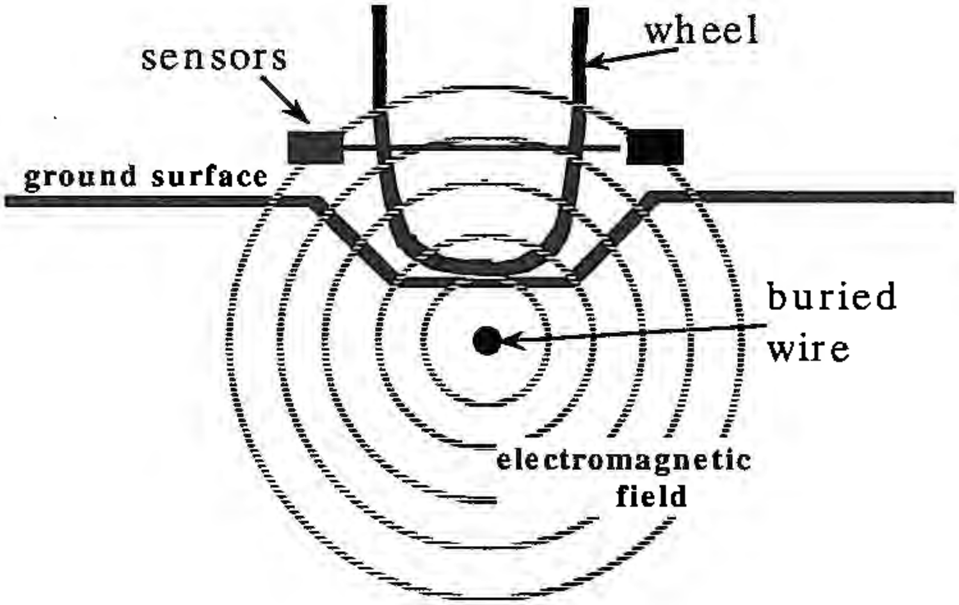


Figure 1: Diagram showing buried wire, magnetic field, and sensor.

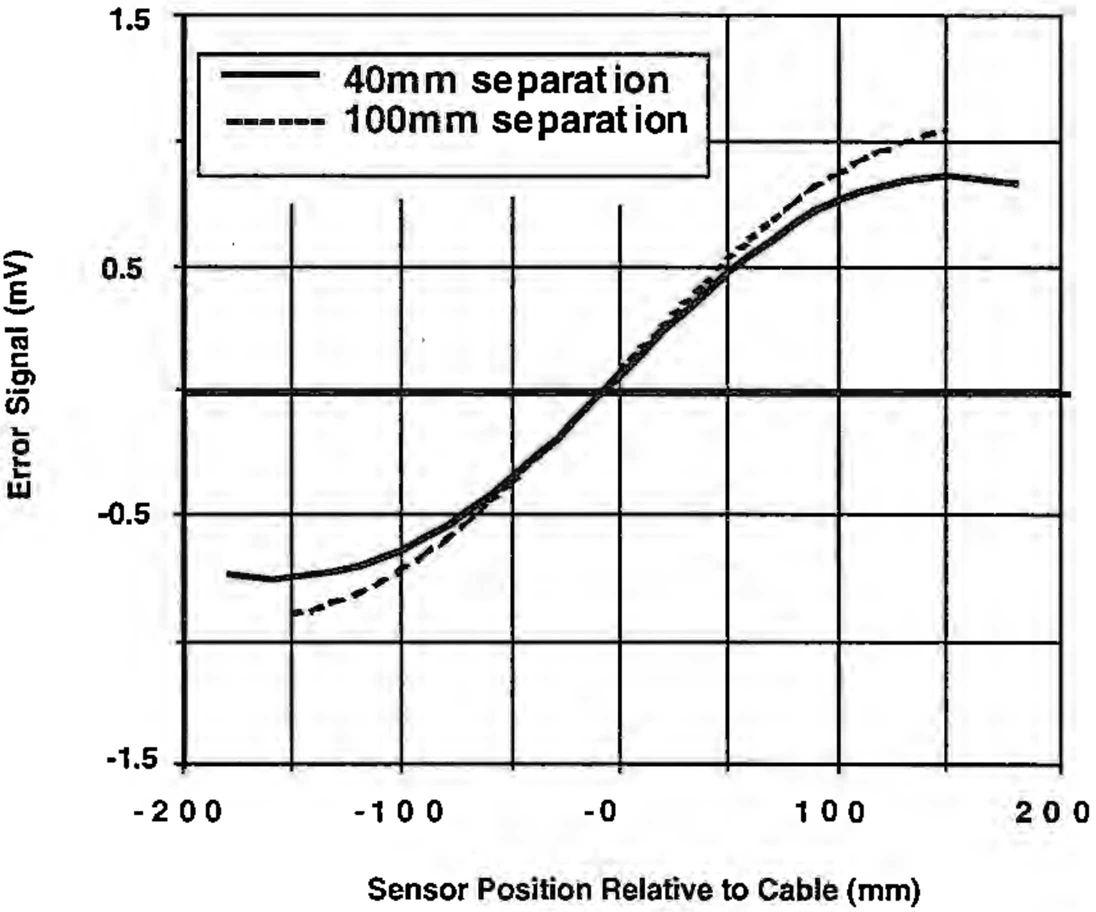


Figure 2: Voltage difference between sensor coils with sensor at 218 mm above ground surface.

Figure 2 shows that if the resultant voltage is positive, the vehicle is to the right of the wire, and if it is negative, to the left. This information was used as an input to the two control systems trailed.

The comparison of the voltages coming from the sensor block was performed by two different methods. Analogue component comparators in a simple circuit were used in the initial test series while computer analysis and control were employed in the later series.

The sensors were mounted on two test vehicles using a bracket attached to the steering wheels. Figure 3 shows the basic concept used. The positioning of the sensors in front of the wheels provided for immediate mechanical feedback to the system control loop and so minimised instability and steering wander caused by constant overcorrections of direction.

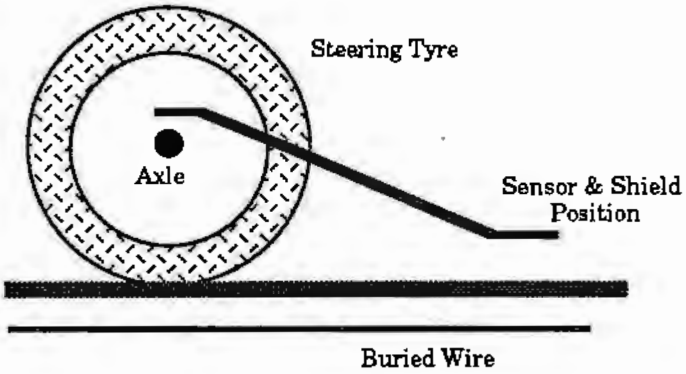


Figure 3: Sensor holding device.

Signals from the sensors were amplified to a level that over-rode any signal interference and then were analysed by the system. The required corrective signals were then sent to the stepper motor on the steering motor. This control was obtained through the used of two LM308N amplifiers, a LM339N comparator, and two relays.

Initial field testing of the system showed that it performed adequately, but weather and electrical failure prevented quantitative results from being obtained. It seemed that the system lacked robustness and was prone to failure.

Later in the project, the performance of this system was considerably improved by incorporating it into a broader system using multiple sensor analysis. A computer was used to coordinate the information provided by several transducers. in an approach commonly referred to as "Sensory Integration". Once the computer was installed its analogue/digital board was used to replace the voltage comparator circuit with a simple controlling program. The control algorithms were then able to be modified quickly during operation with the motor able to be effectively driven through software. The analogue control system used in the first tests gave direct on/off linear control and used mechanical feedback for stability. The computer based system was able to provide more flexibility in control. As a result, a proportional control algorithm was employed in the tests, with steering angle feedback supplied by a potentiometer connected to the steering mechanism.

With the sensors and computer mounted on the tractor, the operator was able to adjust steering gain and sensitivity for different operating speeds.

Output from the program was directed to the motor control board, where a cordless drill drove the steering mechanism on the tractor. Gears and a toothed belt were used to give a reduction of approximately 5:1 on the drill shaft so that the steering reaction was not too abrupt. The steering wheel was removed from the small David Brown tractor for these initial tests with the multiple sensory system.

A tensioned loop of wire was laid for testing the system. Tests were done at different speeds, with different separation distances and different gain settings. Each of the tests performed were replicated with different gains and sensitivity settings.

The CRDC review team initially expressed concern about likely effects of soil movement on the buried wire, and the apparently difficult task of maintaining such a system over large cropping areas. These concerns are valid and it is unlikely that a leader cable system will be adopted by the industry until a system is developed that clearly overcomes them. The work of this project has established that a leader cable system is capable of meeting the technical requirements of farm machinery guidance, however, and any further work by others must concentrate on the practical aspects of laying the cable and maintaining system reliability.

It was concluded in this project that other technologies would provide a more acceptable approach to automatic machinery guidance.

2.4 Microcom Ultrasonic Guidance

The Microcom Row Guidance System is a commercially available automated steering control device for agricultural implements. It is intended to guide either an implement or a tractor along crop rows.

The system works on the same principle as an echo sounder. A non-contact ultrasonic sonar system is used to determine the position of the machines in relation to the crop rows (Figure 4). It measures distance by sending out short pulses of sound waves, and measuring the time for the echo to come back from the soil ridge or plant row. The difference in measured times between the sensors is used to determine whether the transducers are centralised over the soil ridge or plant row.

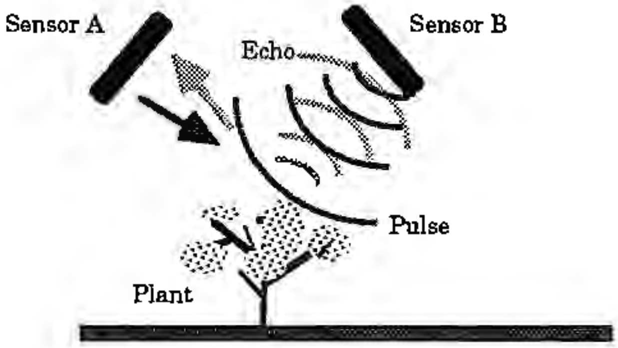


Figure 4: Sensor position and signal path to determine plant location

As a deviation in crop position occurs, the control apparatus detects any positional errors and then makes automatic adjustments by sending control signals to the appropriate hydraulic actuators. In the case of this project, the signal from the unit actuated a bi-directional stepper motor that was linked to a parallel steering circuit on the tractor. The amount of deviation is indicated on the LED bar graph located on the front of the unit. Incorporated is a left and right bias control to adjust for slopes and off-centre rows.

The most attractive feature of the Row Guidance System in the original evaluation was its potential ability to track small objects on the ground surface, such as stalks and seedlings. Alternatively, in the 'Row' mode, the system had the ability to track soil ridges, basically ignoring and averaging out the error signal from small surface weeds, and thus allow correct planting in the soil row.

The complete system as used in the tests included the following components:

(i) Microcom Sensors
(ii) Microcom Control Unit
(iii) Parallel Steering Circuit
(iv) Stepper Motor and Control Circuits.

The unit was purported to provide tracking benefits in most row crops, including corn, cotton, sorghum, and soy-beans. The unit being intended to operate during cultivation, spraying, harvesting, and planting in order to prevent plant damage and increase efficiency generally.

2.5 Vision Based Guidance

A third approach was trialed during the last few months of the project. Some testing was done on the concept of guiding a tractor by using a camera to follow the same physical features that guide a human operator. A camera, frame-grabber board, computer, feedback mechanism, and electric motor were used to steer the tractor. Figure 5 below shows the equipment on the tractor.

As this testing was not part of the original schedule developed after the initial systems evaluation process. It was conceived largely as a result of the limitations discovered in the leader cable and ultrasonic systems. Consequently, insufficient time was available to obtain conclusive results of the systems capabilities. The testing completed did however show that the concept of vision based guidance offered a potentially superior solution to either the leader cable or ultrasonic technology. This work was used to plan a full follow-on project to establish the system performance and develop suitable prototypes.

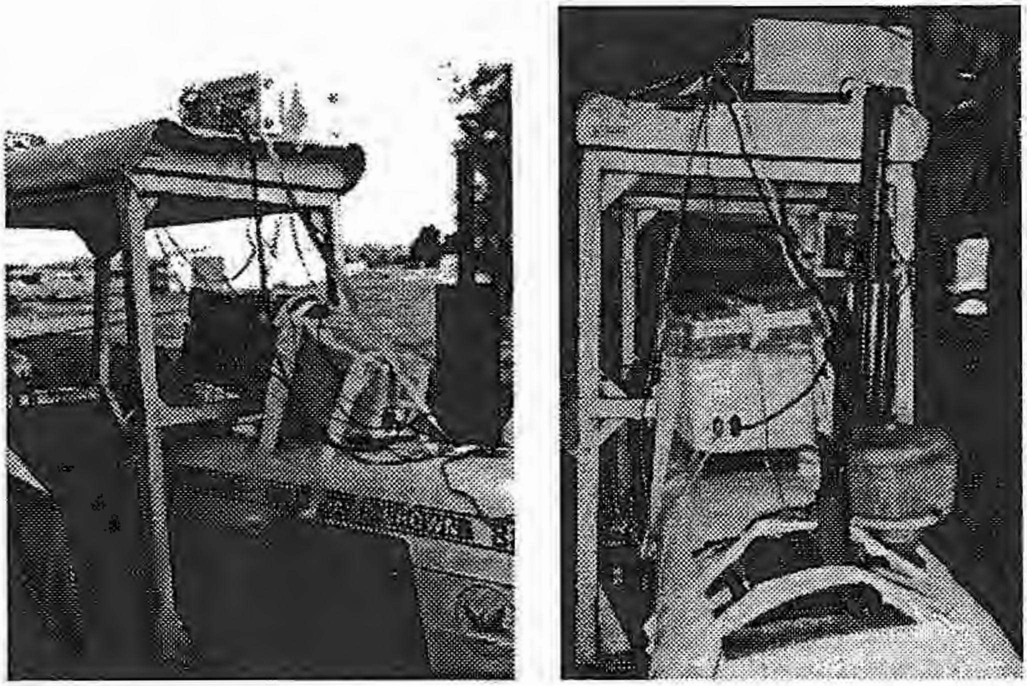


Figure 5: Prototype vision acquisition equipment mounted on tractor. The video camera is shown attached to the bonnet of the tractor. The computer is attached to the roof with the monitor located in front of the driving position.

3. Results

3.1 Leader Cable Guidance

A typical error plot achieved in the field tests is shown in Figure 6 below. The graph shows the position error, or deviation of the tractor from the required course, against the position of the tractor along the row. The error in steering was about ±20 mm for most of the row, but the tractor strayed by 50 mm at about the middle of the row. This error range occurred at a test speed of 3.2 km/h.

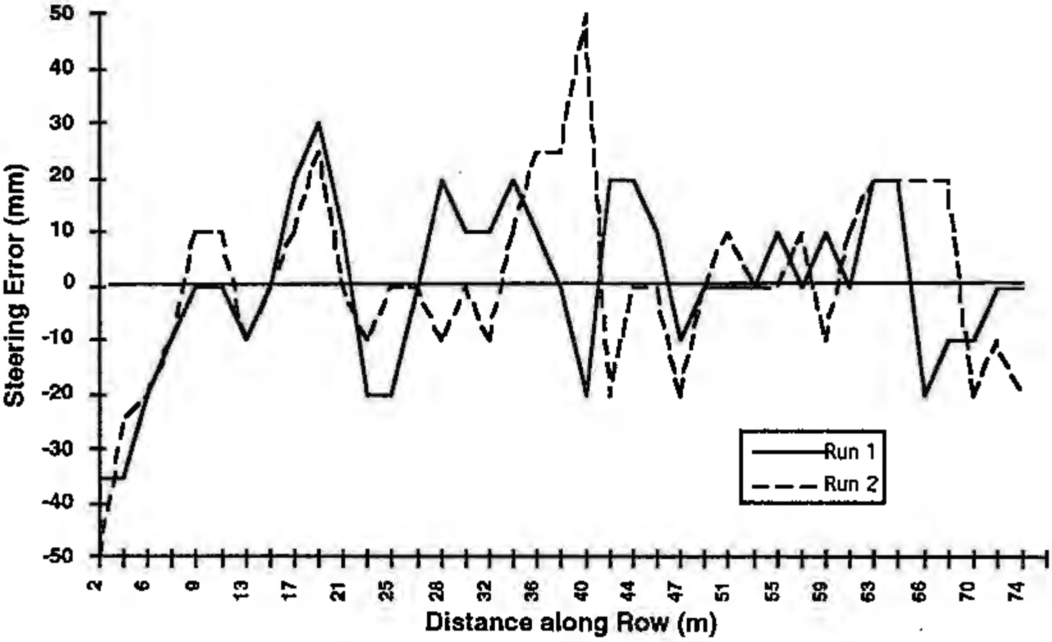


Figure 6: Wire Guidance Test at 3.22km/h.

Results of the test series showed that wire guidance of farm machinery could work very well. The control system implemented here could have been further tuned to attain stable control at speeds greater than the 6.44km/h achieved, but other considerations previously discussed meant that the buried leader cable concept was not developed further. It was necessary to show that such a system would work, and this has been achieved. Practical considerations and a lack of acceptance by industry will limit the application of this technology in the foreseeable future even though the acceptable level of accuracy is achievable.

The identifiable limitations on the systems acceptance include:

i) the problem of preserving wire integrity. Any break in the wire, especially if buried, will be difficult to locate for repair,

ii) the problem of possible disturbance and breakage of the wire as a result of tillage operations and ground swelling/shrinking movement,

iii) the possible problem of rodent damage to the wire,

iv) the cost of installing a system of wire across a whole farm.

3.2Microcom Ultrasonic Guidance.

Initial results from the ultrasonic system were disappointing, with the degree of steering control achieved being much less than expected. Both high and low gain commercially available sensors were calibrated and then field trialed on the small U.S.Q. tractor to confirm system performance.

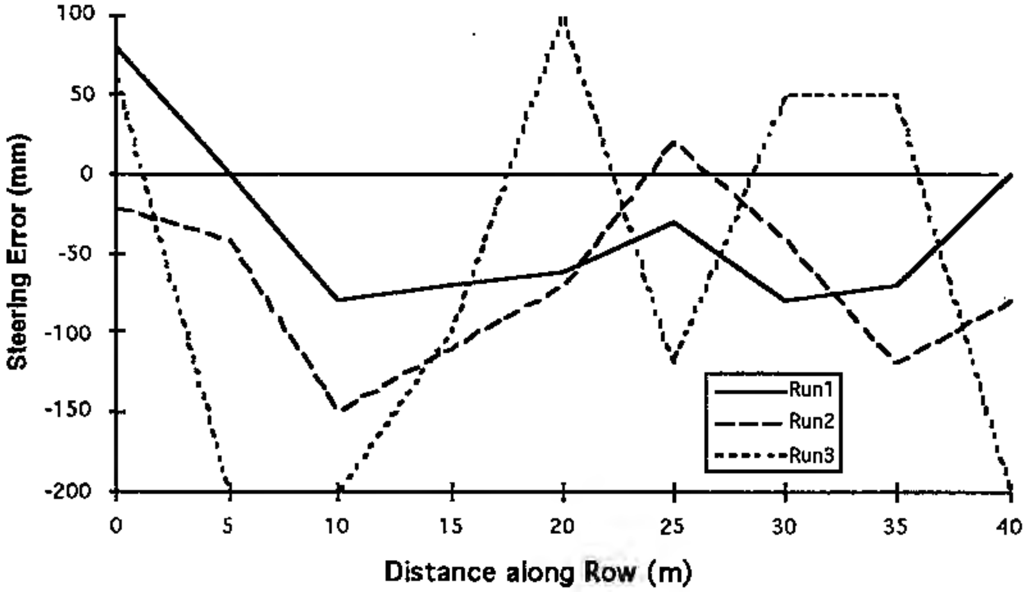
A John Deere tractor was subsequently provided for field trials by the local dealer. This provision allowed the adjustable rig to be attached to the front of the tractor type most used by cotton growers and further tests were performed with cotton and soybeans. These tests were performed over several days. All tests were video taped to record and quantify the system's performance. In general the results confirmed the initial trials, although some improvement was gained by fine tuning the system.

Typical values obtained during the testing can be seen in Figure 7 below. These results apply to a small crop of soybeans approximately 15cm high and a small crop of cotton. Sensors were set in a 762mm triangular pattern aimed at the base of the plants.

There is no real consistency in these results, or others from the test series. A total drift of 300mm is too much for a cultivator guidance system.

In summary, the trials showed that although the sensors did 'see' the crop to an extent, the signals were not consistent or precise enough to achieve the required degree of steering control. The performance characteristics displayed were erratic, to the point where the results or behaviour of the system could not be trusted. Further controlled testing and evaluation established that the ultrasonic beams were reflecting off the soil behind the plant rather than the plant itself. The sensors had particular difficulty detecting small plants, the crop stage where accurate guidance is essential.

a) Small soybean crop a tractor speed of 5.6 km/h



b) Small cotton crop with atractor speed of 7.2 km/h

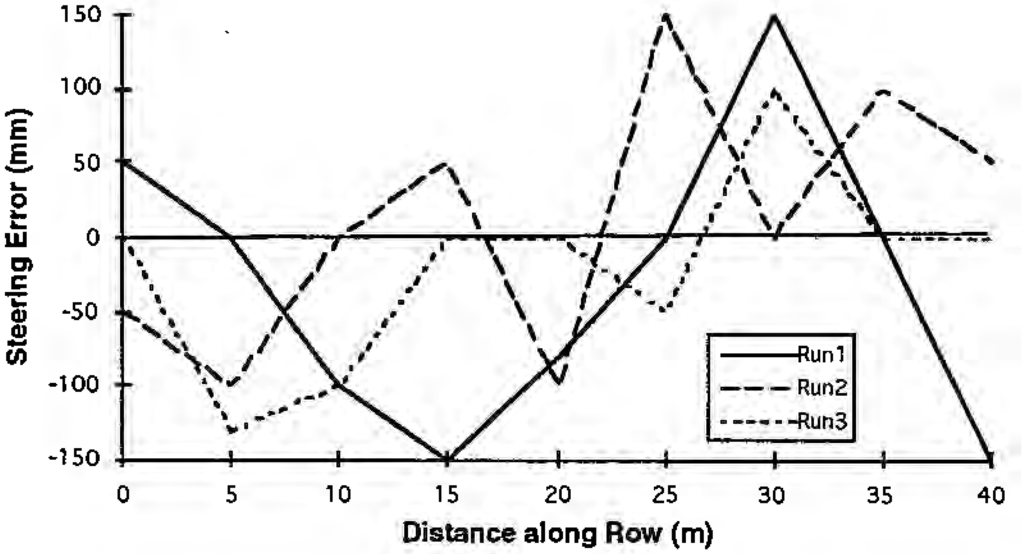


Figure 7: Ultrasonic test results for two crop types

3.3 Vision Based Guidance

The tests done on some rows of sorghum at the Agricultural Field Station showed that a vision based system will work and will achieve the desired level of steering control. Results obtained at low speed with very basic equipment showed that a tractor could be steered automatically down the crop rows to an accuracy of some ±75 mm. Given the basic level of equipment employed in these tests, this result was an exceptional achievement.

Based on these results, a separate project has been funded by the C.R.D.C. to commercialise a vision based system for use in the cotton industry.

4. Conclusions

The results from this sub-project indicate that it is possible for a farm tractor to be kept on a desired path using the leader cable system. The ultrasonic devices tested gave steering errors that could not be tolerated, however, and they would not provide a useable system for the cotton industry without considerable extra development.

The results from tests with prototypes of both systems show that there is a real need for better system control. It is concluded that no one sensor based system will provide the level of steering guidance required in controlled traffic farming. Work was therefore begun on a computer based system to meet this need. The required control can be provided using Sensory Integration to combine the information of a number of transducers and avoid the drawbacks of each individual one. By taking inputs from various sensors such as visual devices, wire guidance, electronic compasses, beacons and the like, the computer can 'decide' which information requires action to attain the best steering control under all possible conditions.

It is concluded that successful farm machinery guidance can be attained, based on a central system employing a vision acquisition device. This system will analyse images fed to the computer through a camera mounted on the vehicle. Physical features can be followed adequately, with tests done to date showing good performance characteristics. Other sensory information would supplement the vision information to provide the required system reliability.

The work done on the concept of sensory integration has led to a new project, in which we shall be commercialising a guidance system for the cotton industry. Development is well under way, with J I Case offering us the use of a tractor, and programming currently being done. By the end of 1995 we hope to see the final designs being used in the field.

4. Publications

4.1 Conference Papers

Schoenfisch, M.K and Billingsley J. (1993). A Comparison of automated guidance systems for a variety of operations in the growing of cotton. Proc. Conf. on Robotics in Agriculture. Brisbane, Qld July.

Billingsley J. and Schoenfisch, M.K. (1993). A vision-guided agricultural tractor. Proc. Conf. on Robotics in Agriculture. Brisbane, Qld. July.