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2/89 to 6/90

PROCEDURES FOR THE EVALUATION OF SOIL PHYSICAL CONDITIONS IN THE FIELD TO ASSIST LAND MANAGEMENT FOR COTTON PRODUCTION (DAN 46L).

A final report prepared for the

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FINAL REPORT

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PART 1 EVALUATION OF TECHNIQUES FOR SOIL STRUCTURAL ASSESSMENT IN THE FIELD

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SUMMARY

Introduction

Soil compaction in the cotton industry has been identified as a major limitation to crop growth. This led to the establishment of several CRDC funded research projects dealing with the management of soil compaction. However, it has proved difficult to diagnose this problem in the field. In mid-1987 the Macquarie Valley Soil Management Service was set up to aid growers with their soil management decisions; they found that in about 30% of cases, it was difficult to make recommendations about the degree of soil compaction. A majority of this uncertainty was due to poorly defined techniques for assessing soil condition.

The aim of this project was to evaluate, and where necessary refine, the techniques currently available for soil structural assessment in the field. The techniques for the assessment package, where possible, have to be rapid and repeatable, with low degrees of operator subjectivity. They will help farm agronomists, consultants and extension personnel to make better soil management decisions, and monitor the changes in structural condition from year to year. The package will be incorporated into the **SOILpak** manual.

Several sites were chosen in the Macquarie and Namoi Valleys on a number of different types of grey cracking clays. At each of these sites there were two treatments - undamaged and damaged. This ensured that the techniques for measuring soil structure were tested over a wide range of different soil types and soil conditions. The soil and plant characteristics measured included bulk density; air-filled porosity; soil strength (penetrometers); root morphology; plant development; yield; cation exchange capacity (CEC); exchangeable cation percentages; electrical conductivity (ECe); pH; clod shrinkage; nutrient content; organic matter; and soil structural description using traditional survey schemes.

This report summarises results obtained from 6 farms in 1989/90. They are presented as a series of case studies. Once results from the 1990/91 season have been collated as part of project DAN 50C, they will be combined with the 1989/90 data to provide detailed conclusions. Some promising techniques have been identified. Soil strength and root morphology measurements fit the required criteria of being rapid and easily repeatable, as well as accurately describing the soil condition. There are limitations with these techniques, but further analysis and sampling should overcome them.

Summary of Key Results

1 Most promising techniques for use by advisory staff in the field are penetrometers and root morphological characteristics.

2 Soil smearing may not have significant effects on plant growth. It was previously thought to have a very detrimental effect on plant growth.

3 Crop management can override the effects of soil compaction on plant growth.

Future Research Recommendations

1 More experiments are required to further refine the procedures for soil physical assessment.

2 The 'Rimik' penetrometer and Handheld penetrometer need to be calibrated for the different types of grey clay in the Macquarie and Namoi Valleys.

3 Further adjustments to the modified Peerlkamp Soil Assessment Scheme made by Dr Tom Batey (soil husbandry consultant and lecturer Aberdeen, Scotland) are required for the Australian grey cracking clays.

4 When using the above procedures, the location and intensity of soil sampling within cotton fields needs to be established.

5 Critical limits for cotton root development under a range of moisture regimes need to be determined for a broad range of cracking clays.

N.B. These future research needs are being addressed by the CRDC funded project DAN 50C.

Budget Summary

	Salaries $	Travel $	Operating $	Capital $	Total $
1988/89	8 207	2 717	1 156		12 080
1989/90	20 715	2 800	2 500		26 015
GRAND TOTAL					38 095

DETAILED REPORT

Objectives

The purpose of this project was to evaluate, and where necessary refine, methods for the assessment of the soil physical condition in the field. Where possible, they have to be able to be used rapidly and repeatably, with low degrees of operator subjectivity.

The information will be incorporated into the SOILpak manual. This is a decision-support system for soil management in the cotton industry which aims to:

1. Improve the efficiency of cotton production by promoting objective soil management.
2. Extend soil research data relevant to the cotton industry more effectively and rapidly.
3. Provide research planners with an improved way of defining their priorities.

Experimental Design

The experiment was carried out on six cotton properties:-

1. Auscott Warren, Macquarie Valley, NSW.
2. Elengerah, Macquarie Valley, NSW.
3. Carlisle, Macquarie Valley, NSW.
4. Buttabone, Macquarie Valley, NSW.
5. Auscott Narrabri, Namoi Valley, NSW.
6. Myall Vale Research Station, Namoi Valley, NSW.

At each site (one per property) there were 2 treatments:-

1	Undamaged treatment -	cotton grown under normal management operations for that property.
2	Damaged treatment -	cotton grown after imposition of smearing and compaction between depths of 5 and 15 cm below the hills. Damage was created by using a middle-busting tyne in the centre of the hill, and a tractor wheel passing over the hill.

Measurements

PRE-SEASON AUGUST 1989

1	Macroporosity	Rhodamine dye technique (3 replicates at depths of 5, 10, 15 & 20 cm)
2	Bulk Density and Air-filled Porosity	50 mm cores (3 replicates at depths of 15, 25, 35, 55, 75 & 95 cm)
3	Soil Description	MacDonald et al. Hodgson et al. McKeague et al. SOILpak
4	Laboratory analysis	Exchangeable cations, pH, electrical conductivity, organic matter, clod shrinkage, nutrients (measurements taken at 15, 25, 35, 55, 75 & 95 cm)
5	Soil Strength	Rimik Penetrometer (3 replicates every 1.5 cm to a depth of 45 cm) Chatillon Handheld Penetrometer (3 replicates at depths of 5, 10, 15, 20, 25, 30, 35, 55, 75 & 95 cm)

DURING SEASON 1989/90

1	Plant Growth	
2	Fruit Development	
3	Water Content Profiles	Neutron Probe (3 replicates per treatment)
4	Root Distribution	Grid Technique (January)

OVER ONE IRRIGATION CYCLE FEBRUARY 1990

1	Leaf Expansion	
2	Soil Strength	Rimik Penetrometer (3 replicates every 1.5 cm to a depth of 45 cm every 2 days)
3	Bulk Density and Air-filled Porosity	50 mm cores (3 replicates at depths of 0, 15 & 25 cm)
4	Oxygen Diffusion	3 replicates at 15 cm
5	Water Usage	Neutron Probe (reading taken every 2 days)

END OF SEASON APRIL 1990

1	Yield	
2	Root Morphology	root diameter root obliquity root "flatness" no. lateral roots

STRENGTH CALIBRATION FEBRUARY 1990

Three strength measuring devices- 'Rimik' penetrometer, Handheld penetrometer and shear vane- were calibrated near the Auscott Warren site.

Difficulties Encountered

1. In the Namoi Valley a hail storm in February 1990 severely affected the yield of both sites, which made it difficult to determine the effects of soil structural condition on final yields.

2. There were not enough sites in 1989/90 to make accurate comparisons between the Namoi Valley and Macquarie Valley. There was insufficient labour to study more sites. Further sites are required to obtain the necessary degrees of freedom for statistical analysis.

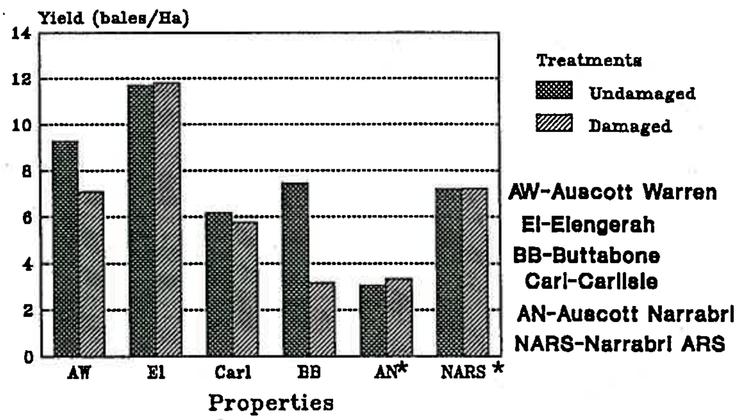
3. The simulation of soil compaction in the field was not effective at most of the sites. The aim of the project was to have two levels of compaction. However, the machinery used was not heavy enough (3130 John Deere tractor) and the moisture content of the soil, when driven over and smeared, was not sufficient to induce severe levels of compaction and smearing.

4. Differences in irrigation and fertiliser management between the properties have masked some of the expected differences in crop development and production due to compaction.

CASE STUDIES

The lint yields for the 'damaged' and 'undamaged' sites on each of the 6 case study properties are shown in Fig 1.

Fig 1. Lint yields for the 1989/90 cotton season; * denotes severe hail damage.



In the following sections the management details, selected soil structural measurements, cotton root morphology and soil chemical measurements are summarised for each of the properties. Some of the critical limits for these parameters are listed in Table 1.

Description of Root Morphological Parameters

Root Diameter - a measure of the diameter of the root every 10 cm; the ratio compares root diameter at one depth to another depth eg. ratio 1 = diameter (depth 1)/diameter (depth 2)

Root Obliquity - measures the angle of the taproot from the vertical as it grows down the profile; the ratio compares taproot angle within one depth interval to another depth interval eg. ratio 1 = angle (depth 1)/angle (depth 2)

No. lateral roots - the number of lateral roots growing off the taproot within different depths intervals;
the ratio compares the numbers of lateral roots between two depth intervals eg. ratio 1 = no. lateral roots (depth interval 1)/no. lateral roots (depth interval 2)

Flatness Ratio - this ratio describes how cylindrical the roots are eg. ratio (depth 1) = largest diameter (depth 1)/smallest diameter (depth 1) .

The higher ratios indicate larger degrees of compaction (Gerard et al., 1971), as do high root obliquity angles.

Table 1. Critical soil limits for cotton.

Soil Factor	**Critical Level**
Soil Strength	3 MPa
Electrical Conductivity (ECe)	> 7.7 dS/m; restricted plant water uptake
Sodium	Exchangeable sodium percentage (ESP) > 5; dispersion in water
Ca/Mg ratio	< 2; dispersion in water
Organic Matter %	> 4 % - high 2-4 % - satisfactory 1-2 % - low < 1 % - very low

1. BUTTABONE

Table 2. Management details for Field 6, Buttabone, Warren.

	undamaged/damaged treatments
soil type	sodic grey clay
slope	1:1725
cotton variety	Siokra 1-4
seed treatments	Terrachlor/Apron/Semevin
nitrogen applied	110 kg/ha
method of N application	side-dressed
pre-emergence herbicides	Treflan/Cotoran/Diuron
sowing date	first plant- 12-10-89 re-plant -26-10-89
sowing rate	16.9 kg/ha
pre-irrigation	13-9-89
number of crop irrigations	5
plant emergence	5-11-89
first square	8-12-89
first flower	8-1-89
first green boll	15-1-90
first open boll	1-3-90
defoliants used	Harvade/Catapult/Salt
harvest date	
yield	undamaged- 1675 Kg/Ha (7.44 bales/Ha) damaged - 708 Kg/Ha (3.15 bales/Ha)

Yield

There is a large difference in lint yield between the two sites, with the 'undamaged' site yielding 7.44 bales/Ha and the 'damaged' site yielding 3.15 bales/Ha (Fig 1).

Soil Strength

Fig 2a Soil strength measurements using handheld penetrometer at Buttabone.

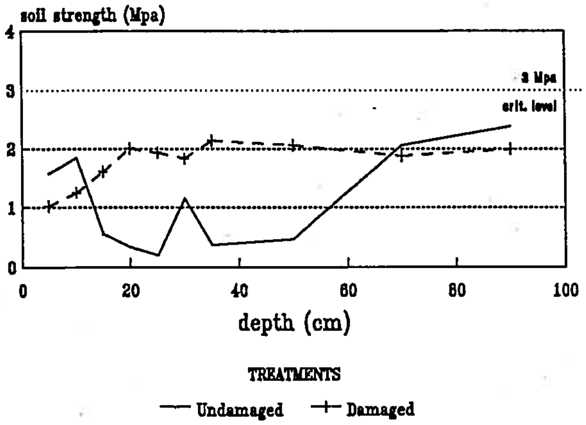
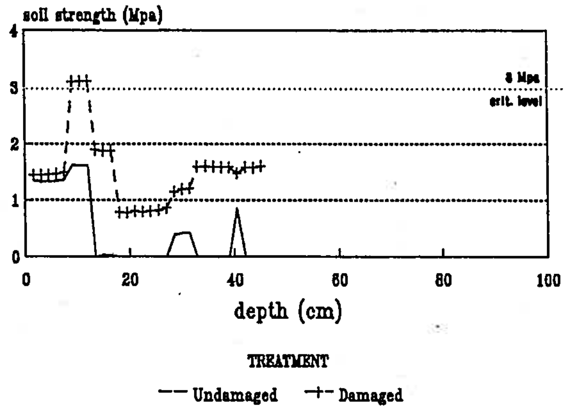


Fig 2b Soil strength measurements using Rimik penetrometer at Buttabone.



Using 3 Mpa as the critical soil strength for cotton root penetration (Taylor et al., 1963), it is possible to determine if the soil is limiting to plant growth. Fig 2a & b show the Rimik penetrometer and Handheld penetrometer strength measurements under the ridges at Buttabone. All the measurements have been corrected to a gravimetric moisture content of 20%, to enable comparisons between the different sites. The calibration formula is based on the Auscott Warren grey clays (see next section).

The Rimik penetrometer indicates that the 'damaged' site would encounter soil strength problems near the surface, while the 'undamaged' site should have unimpeded plant growth (Fig 2b). The handheld penetrometer follows the same trend but the readings do not exceed the critical limit of 3 Mpa (Fig 2a).

Root Distribution and Morphology

Fig 3a Root diameter changes with depth at Buttabone.

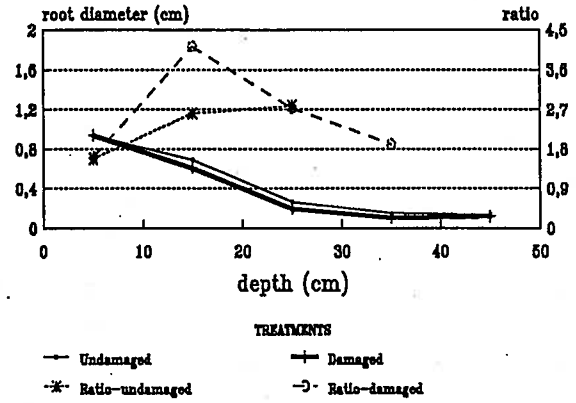


Fig 3b Root obliquity changes with depth at Buttabone.

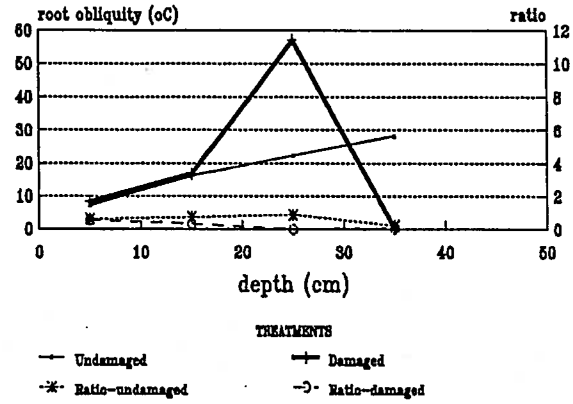


Fig 3c Changes in the number of lateral roots with depth at Buttabone.

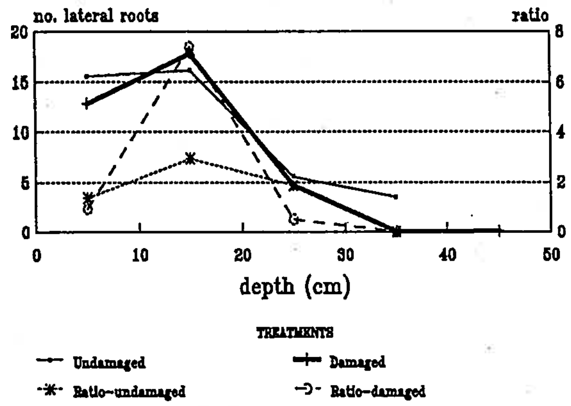
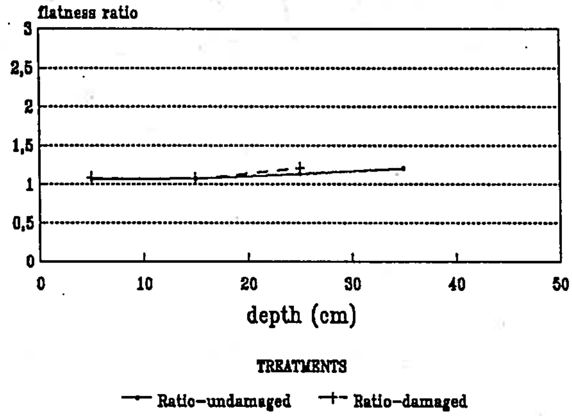
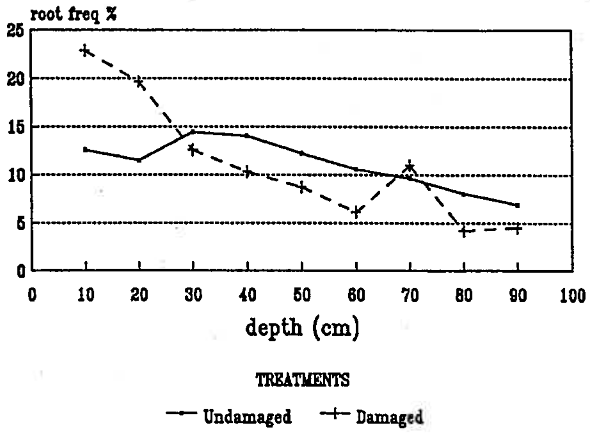


Fig 3d Root flatness at Buttabone.



The ratio of the number of lateral roots, the root diameter ratio and the actual values of root obliquity show differences between the 'damaged' and 'undamaged' sites at approximately 20 cm (Fig 3a,b & c). This corresponds with the area above the critical soil strength identified by the Rimik penetrometer.

Fig 4 Root distribution under the hills down the profile at Buttabone.



The root distribution (Fig 4) shows that the roots had some penetration difficulties with a greater percentage of roots at the surface of the 'damaged' site. This indicates the presence of an unfavourable growth zone for the cotton roots, and reinforces both the root morphological and soil strength measurements.

Summary

1. Yield differences indicated that the 'damaged' site had some structural problems.

2. Soil strength readings identified the problem area on the 'damaged' site.

3. Root morphology and root distribution measurements confirm the soil strength findings.

Table 3. Chemical properties relevant to soil structural stability at Buttabone.

Depth	Treatment	5cm	15cm	25cm	35cm	55cm	75cm	95cm
pH	undamaged	6.5	6.6	6.6	7.3	7.5	7.4	7.4
	damaged	7.2	7.1	7.1	7.7	6.8	7.1	7.2
ECe	undamaged	0.98	0.9	0.75	1.8	1.8	3.15	13.4
	damaged	1.43	1.43	1.5	1.95	1.95	2.33	3.30
ESP	undamaged	2.74	2.93	5.58	10.2	13.4	15.0	15.9
	damaged	2.54	2.57	8.36	8.00	9.17	12.12	13.5
Ca/Mg ratio	undamaged	1.67	1.57	1.27	1.25	1.26	1.36	1.21
	damaged	2.18	2.09	1.55	1.11	1.09	1.05	1.15
CEC	undamaged	23.9	23.9	25.0	25.1	25.0	22.6	23.3
	damaged	26.7	25.2	28.1	24.6	26.9	27.5	26.5
OM%	undamaged	1.03	1.27	0.84	0.8	0.55	0.69	0.43
	damaged	1.14	1.2	1.37	1.18	0.58	0.4	0.69
P	undamaged	-	-	3.8	2.4	4.6	7.6	7.9
	damaged	4.9	7.6	3.5	6.3	3.8	1.1	5.6
N%	undamaged	0.75	0.89	0.57	0.47	0.39	0.33	0.27
	damaged	0.79	0.79	0.78	0.65	0.41	0.40	0.37

* shaded area indicates problem areas

2. ELENGERAH

Table 4. Management details for Field 7, Elengerah, Trangie.

	undamaged/damaged treatments
soil type	grey silty clay (Macquarie alluvium levees and splays)
slope	1:1440
cotton variety	Siokra 1-4
seed treatments	Terrachlor/Apron/Semevin
nitrogen applied	144 kg/ha
method of N application	Anhydrous ammonia
pre-emergence herbicides	Treflan/Cotoran/Diuron
sowing date	29-9-89
sowing rate	16.5 kg/ha
pre-irrigation	8-9-89
number of crop irrigations	10
plant emergence	
first square	29-11-89
first flower	
first green boll	29-12-89
first open boll	21-2-90
defoliants used	
harvest date	
yield	undamaged- 2631 Kg/ha (11.69 bales/Ha) damaged - 2659 Kg/ha (11.82 bales/Ha)

Yield

Lint yields for the two sites ('damaged' and 'undamaged') on this property were very similar (Fig 1).

Soil Strength

Fig 5a Soil strength measurements using handheld penetrometer at Elengerah.

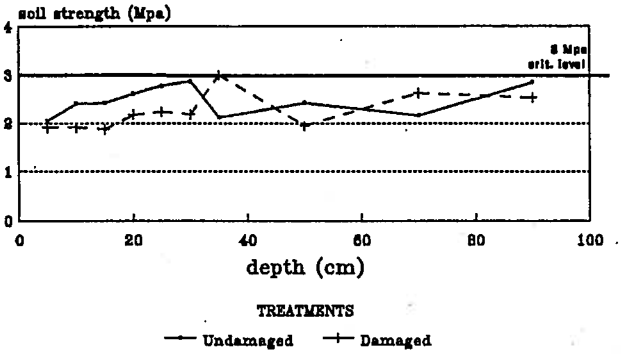
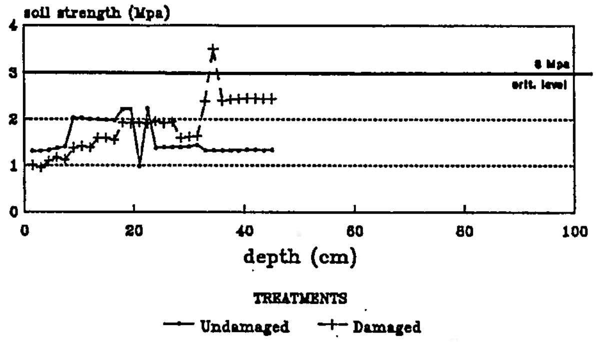


Fig 5b Soil strength measurements using Rimik penetrometer at Elengerah.



Between 30 and 40 cm below the soil surface the Rimik penetrometer (Fig 5b) showed that the 'damaged' site had readings greater than the critical limits for cotton root penetration. The Handheld penetrometer gave similar trends but the readings did not reach the critical level (Fig 5a).

Root Distribution and Morphology

Fig 6a Root diameter changes with depth at Elengerah.

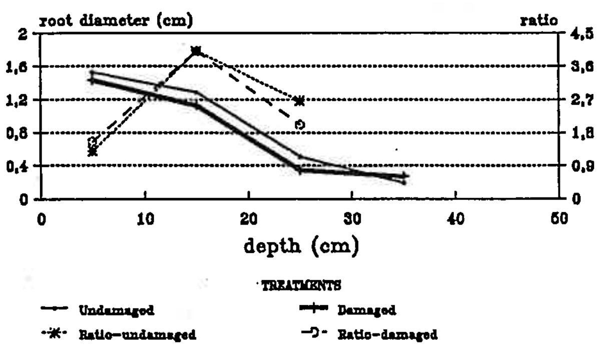


Fig 6b Root obliquity changes with depth at Elengerah.

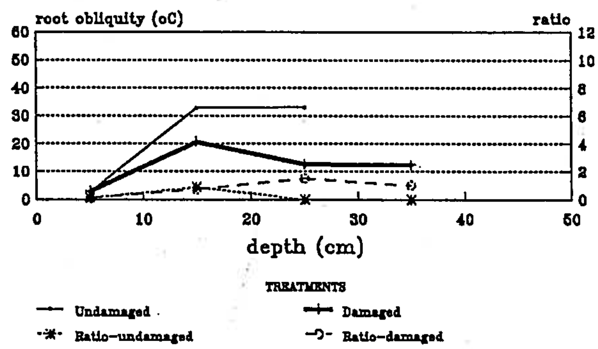


Fig 6c Changes in the number of lateral roots with depth at Elengerah.

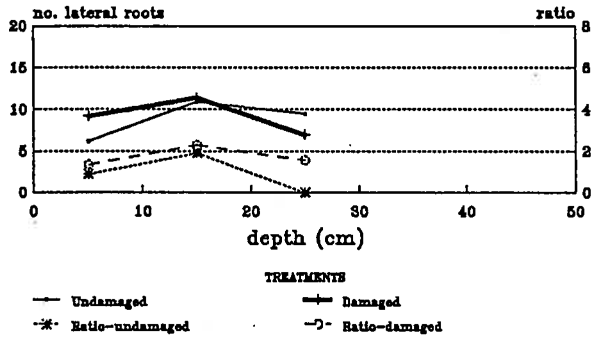
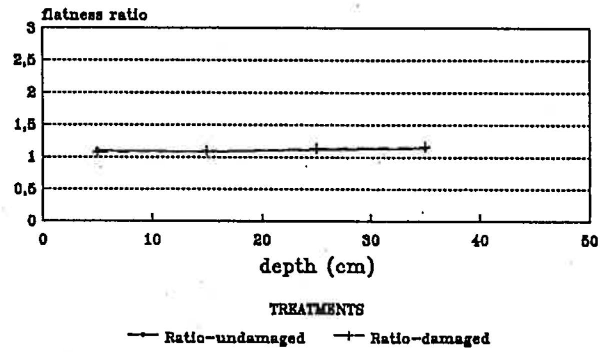
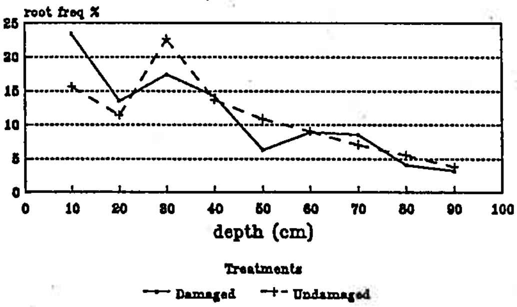


Fig 6d Measure of root flatness at Elengerah.



The suspected root restrictions indicated by the soil strength readings where not evident in the root morphological measurements (Fig 6a,b,c & d).

Fig 7 Root distribution under the hill down the profile at Elengerah.



The higher concentration of roots in the surface soil and then at 30 cm on both sites (Fig 7), appears to correspond to smear layers resulting from previous tillage operations. These may have held up root growth early in the season, but did not affect overall plant growth and subsequent yields.

Summary

1. Yield results indicate no apparent yield limiting differences in soil structural condition between the 'damaged' and 'undamaged' sites.

2. Soil strength readings indicated problems at about 40 cm depth on the 'damaged' site.

3. Plant root morphology showed no evidence of structural damage at either site.

4. Increased irrigation frequency, which keeps compacted soil in a relatively soft condition, appears to have helped the cotton plants to override any compaction effects.

Table 4. Chemical properties relevant to soil structural stability at Elengerah.

Depth	Treatment	5cm	15cm	25cm	35cm	55cm	75cm	95cm
pH	undamaged	5.8	5.5	5.6	5.5	5.6	5.9	7.7
	damaged	5.9	5.2	5.2	5.4	5.8	6.7	7.6
ECe	undamaged	1.13	1.73	1.13	0.45	0.6	0.53	0.6
	damaged	1.13	2.1	0.9	0.75	0.45	0.53	0.6
ESP	undamaged	1.65	1.05	2.12	2.54	2.24	2.21	2.32
	damaged	2.20	0.86	2.27	2.30	2.51	2.68	2.98
Ca/Mg ratio	undamaged	2.04	2.11	2.08	2.04	1.98	1.75	2.03
	damaged	2.08	2.03	2.05	1.94	2.08	1.98	2.07
CEC	undamaged	17.6	18.1	15.8	18.1	20.1	19.4	21.7
	damaged	17.7	18.6	16.8	16.7	18.5	20.2	22.2
OM%	undamaged	3.19	2.47	2.95	1.62	1.71	0.96	0.92
	damaged	2.93	3.04	3.16	2.77	1.32	0.68	0.93
P	undamaged	6.2	7.2	7.6	8.4	0.5	5.9	5.8
	damaged	0.4	5.0	7.4	2.6	3.1	4.8	6.9
N%	undamaged	1.62	1.63	1.53	0.81	0.7	0.24	0.38
	damaged	1.49	1.68	1.58	1.38	0.51	0.43	0.38

* shaded areas indicate problem areas.

3. CARLISLE

Table 6. Management details for Field 4, Carlisle, Trangie.

	undamaged/damaged treatments
soil type	grey clay (Old alluvium meander plain)
slope	1:955
cotton variety	Siokra 1-4
seed treatments	Terrachlor/Apron
nitrogen applied	
method of N application	Anhydrous ammonia
pre-emergence herbicides	Treflan/Cotoran/Diuron
sowing date	15-10-89
sowing rate	
pre-irrigation	25-9-89
number of crop irrigations	7
plant emergence	
first square	
first flower	5-1-90
first green boll	15-1-90 (approx)
first open boll	
defoliants used	
harvest date	
yield	undamaged- 1389 Kg/Ha (6.18 bales/Ha) damaged - 1296 Kg/Ha (5.76 bales/Ha)

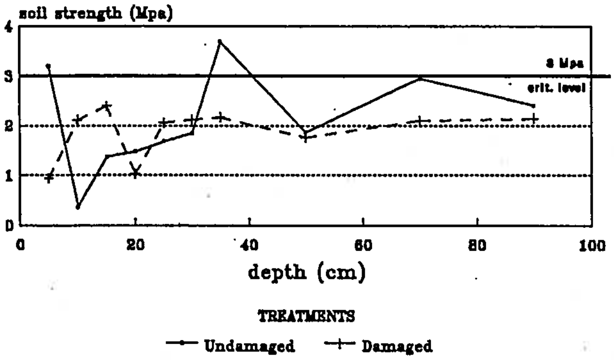
Yield

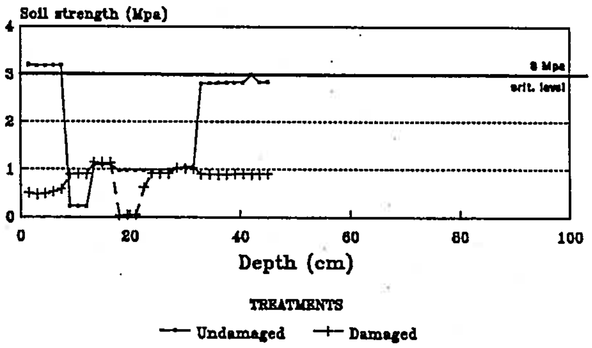
There was very little difference in lint yield between the two sites (Fig 1).

Soil Strength

Fig 8a Soil strength measurements using Handheld penetrometer at Carlisle.

Fig 8b Soil strength measurement using Rimik penetrometer at Carlisle.



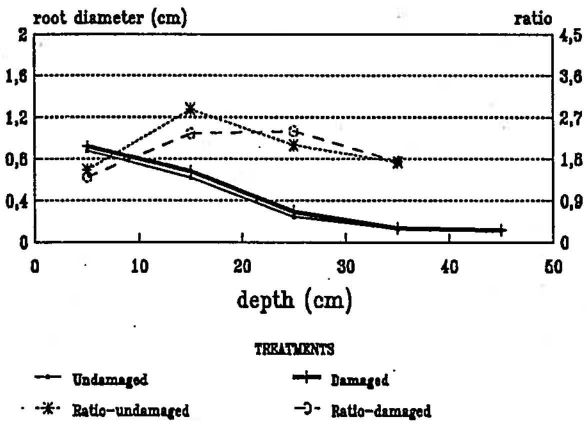


The Rimik and Handheld penetrometers indicate that there are potential soil strength problems at the surface and at 35-40 cm on the 'undamaged' site (Fig 8a&b).

Root Distribution and Root Morphology

Fig 9a Root diameter changes with depth at Carlisle.

Fig 9b Root obliquity changes with depth at Carlisle.



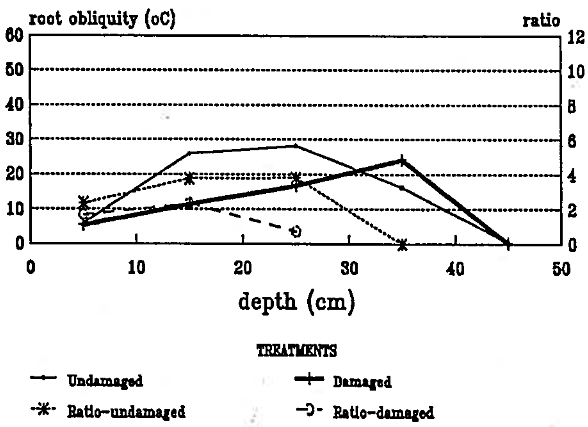
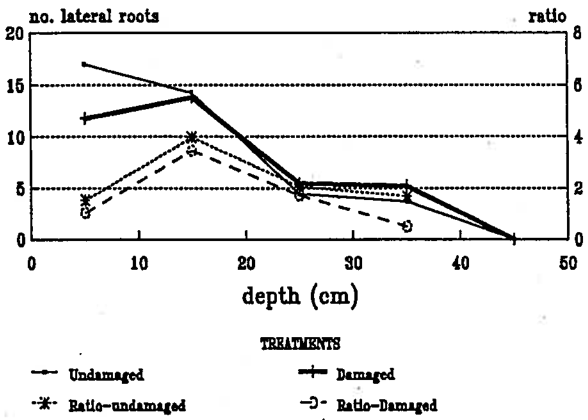
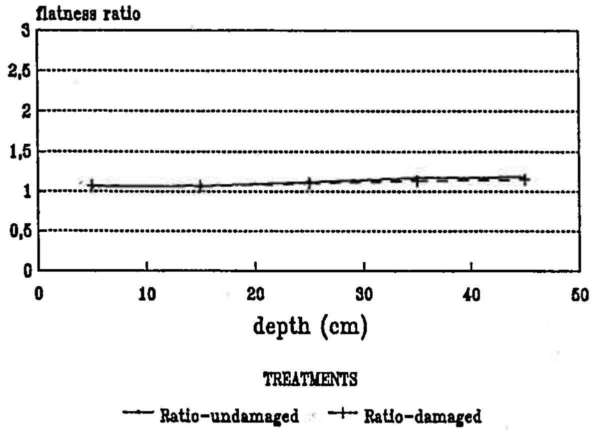


Fig 9c Changes in the number of lateral roots at Carlisle.

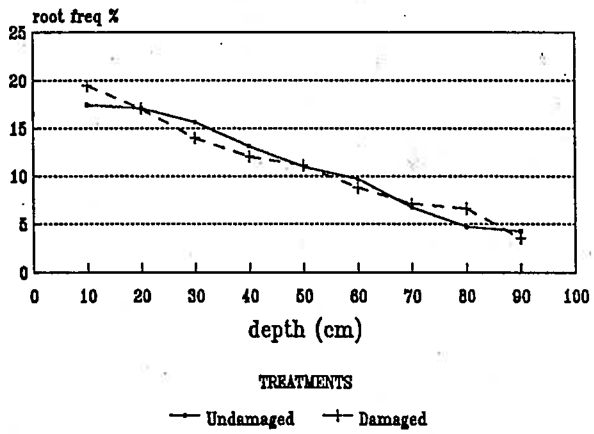
Fig 9d Root flatness at Carlisle.





The soil strength problems that were evident with the penetrometer readings did not affect the root morphological characteristics (Fig 9a,b,c & d). These measurements along with the root distribution (Fig 10) show that the roots were able to penetrate the potential problem layers.

Fig 10 Distribution of roots under the hills down the profile at Carlisle.



Summary

1. Yield and root morphology data give no indication of structural problems.

2. Soil strength measurements show that there could have been some restrictions to plant growth.

3. Frequent irrigation may have masked the effects of soil compaction.

Table 7. Chemical properties relevant to soil structural stability at Carlisle

Depth	Treatment	5cm	15cm	25cm	35cm	55cm	75cm	95cm
pH	undamaged	7.8	7.6	7.6	8.3	7.7	7.9	8.0
	damaged	7.7	7.6	7.5	7.6	7.6	7.9	8.1
ECe	undamaged	1.2	0.9	0.9	0.9	1.2	1.65	2.1
	damaged	1.43	1.2	0.98	1.05	1.28	1.95	2.33
ESP	undamaged	1.1	1.44	1.83	2.28	4.64	8.41	13.9
	damaged	-	1.55	1.48	2.52	4.18	9.96	13.8
Ca (meq/kg)	undamaged	21	19.9	19.8	20.7	19	18.3	12.8
	damaged	16.4	18.8	19.2	17.7	17.2	12.8	12.9
Ca/Mg ratio	undamaged	3.53	2.93	3.07	2.59	2.22	2.09	1.46
	damaged	2.01	2.98	2.92	2.53	2.32	1.17	1.26
CEC	undamaged	28.7	28.2	27.9	30.2	29.6	30.4	25.8
	damaged	27.0	26.7	27.3	26.4	26.6	27.4	28.0
P	undamaged	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
	damaged	1.4	1.6	0.9	0.7	<0.2	<0.2	<0.2
N%	undamaged	0.89	0.66	0.58	0.43	0.2	0.31	0.31
	damaged	0.41	0.85	0.64	0.52	0.41	0.37	0.32
OM%	undamaged	1.53	1.32	1.23	1.03	0.91	0.86	0.66
	damaged	1.31	1.31	1.05	0.83	0.74	0.77	1.53

* shaded areas indicate problem areas

4. AUSCOTT WARREN

Table 2. Management details for Field 35, Auscott Warren.

	undamaged/damaged treatments
soil type	grey clay (Old alluvium backplain)
slope	1:1900
cotton variety	Siokra 1-4
seed treatments	Terrachlor/Apron/Semevin
nitrogen applied	142 kg/ha
method of N application	Cold flo
pre-emergence herbicides	Treflan/Cotoran/Diuron
sowing date	2nd Oct 1989
sowing rate	18.4 kg/ha
pre-irrigation	17-9-89
number of crop irrigations	4
plant emergence	
first square	
first flower	26-12-89
first green boll	
first open boll	26-2-90
defoliants used	
harvest date	
yield	undamaged- 2091 Kg/ha (9.29 bales/Ha) damaged - 1594 Kg/ha (7.08 bales/Ha)

Yield

The 'undamaged' site had a higher lint yield than the 'damaged' site, suggesting poorer soil structure at the 'damaged' site (Fig 1).

Soil Strength

Fig 11a Soil strength measurements using Handheld penetrometer at Auscott Warren.

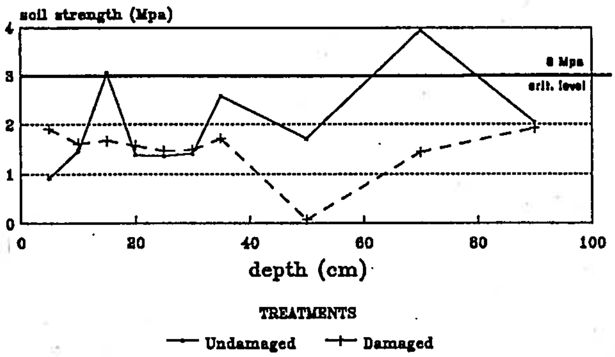
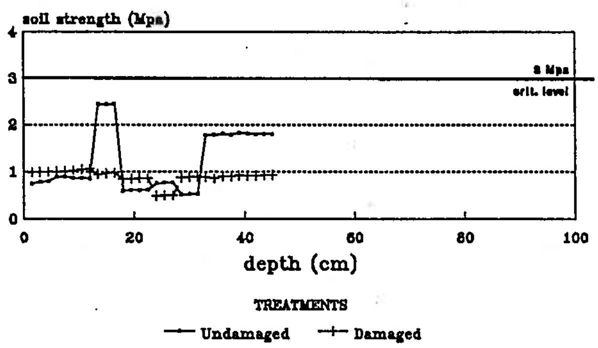


Fig 11b Soil strength measurements using Rimik penetrometer at Auscott Warren.



The Rimik penetrometer (Fig 11b) shows that the 'undamaged' site has a higher soil strength reading than the 'damaged' site, but neither of the sites actually reach the critical level. From these reading we would not expect any problems in cotton growth. The Handheld penetrometer (Fig 11a) gave different readings but the trend between the two sites is similar. However, at 60 cm the roots at the 'undamaged' site may have encountered problems.

Fig 12a Root diameter changes with depth at Auscott Warren.

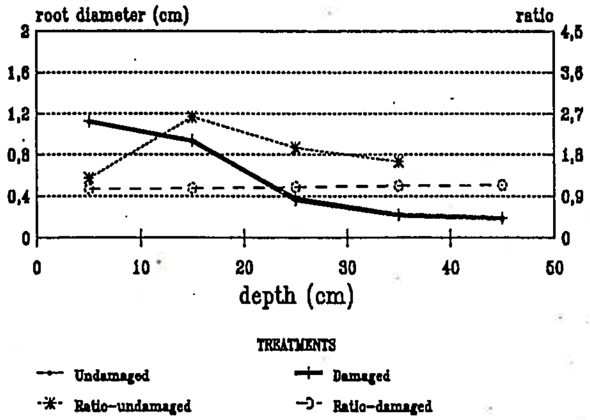


Fig 12b Root obliquity changes with depth at Auscott Warren.

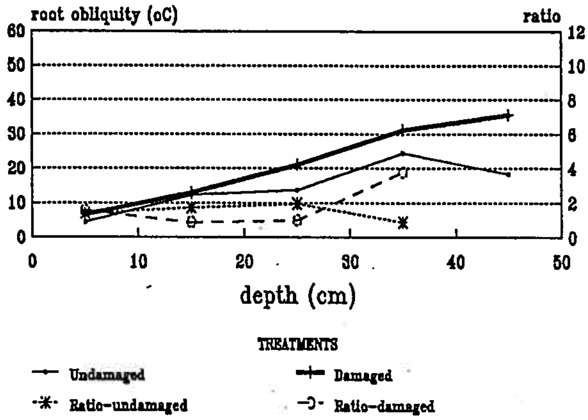


Fig 12c Changes in the number of lateral roots with depth at Auscott Warren.

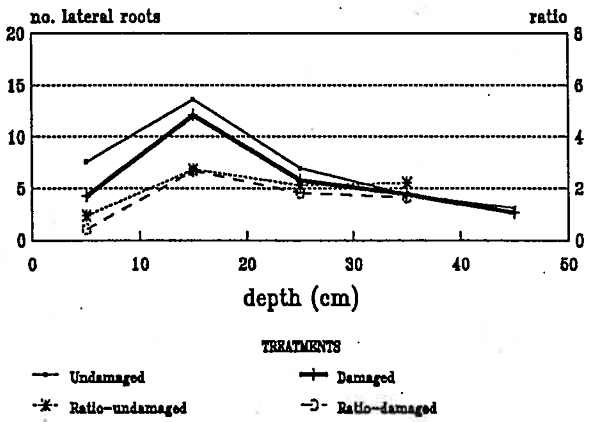
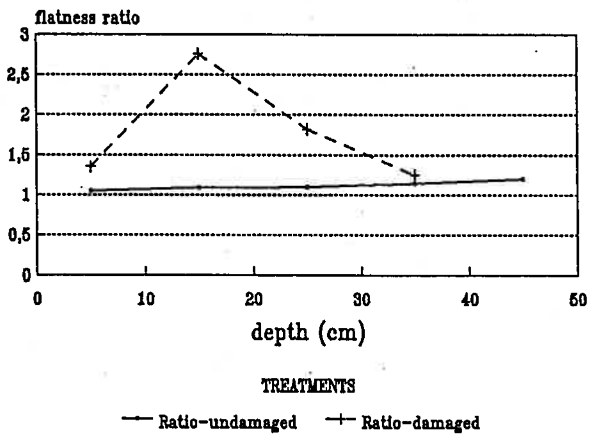
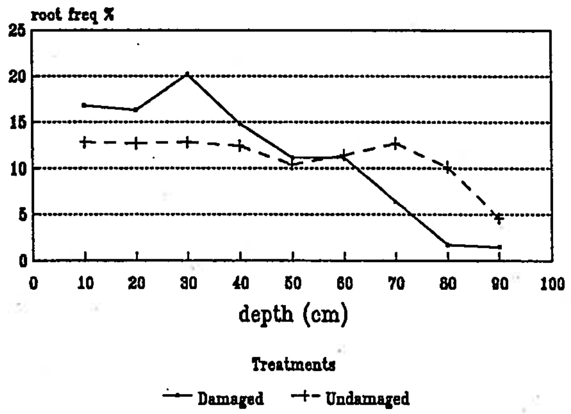


Fig 12d Root flatness at Auscott Warren.



Root diameter, root obliquity and the number of lateral roots indicate many similarities between the treatments (Fig 12a,b & c). However, the root flatness ratio does indicate there are soil problems at the 'damaged' site (Fig 12d).

Fig 13 The distribution of roots under the hill down the profile at Auscott Warren.



In the top 60 cm of the 'damaged' profile there is a high concentration of roots (Fig 13), suggesting that the cotton roots had difficulty penetrating the soil in this area.

Summary

1. Lint yields suggest that the 'damaged' site had a poorer soil condition than the 'undamaged' site.

2. Soil strength readings were similar for the 'damaged' and 'undamaged' sites.

3. Root flatness ratio and root distribution measurements indicate an adverse response by cotton plants to soil compaction at the 'damaged' site.

Table 3. Chemical properties relevant to soil structural stability at Auscott Warren.

Depth	Treatment	5cm	15cm	25cm	35cm	55cm	75cm	95cm
pH	undamaged	7.7	7.6	7.5	7.7	7.8	8.0	8.0
	damaged	7.6	7.6	7.7	7.6	7.6	7.8	8.0
ECe	undamaged	0.98	1.05	1.13	1.35	1.65	2.4	3.75
	damaged	0.9	0.98	1.13	1.2	1.35	1.73	2.4
ESP	undamaged	1.58	2.14	2.78	4.28	9.05	13.9	17.3
	damaged	1.86	1.63	2.95	3.8	5.03	10.45	13.4
Ca/Mg ratio	undamaged	2.9	3.29	2.77	2.42	1.81	1.43	1.23
	damaged	3.05	2.89	2.76	2.55	2.38	1.72	1.45
CEC	undamaged	23.2	22.0	21.7	25.1	22.5	24.1	25.5
	damaged	24.2	23.6	22.5	24.0	26.1	21.6	22.7
OM%	undamaged	0.97	0.96	0.83	0.65	0.97	0.44	0.52
	damaged	0.96	0.96	1.25	0.75	0.61	0.5	0.49
P	undamaged	<0.2	<0.2	<0.2	<0.2	<0.2	0.6	1.4
	damaged	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
N%	undamaged	0.53	0.47	0.47	-	0.3	0.27	0.27
	damaged	0.46	0.43	0.40	0.37	0.13	0.31	0.26

* shaded areas indicate problem areas.

5. AUSCOTT NARRABRI

Table 9. Management details for Field 15, Auscott Narrabri, Narrabri.

	undamaged/damaged treatments
soil type	
slope	
cotton variety	Siokra 1-4
seed treatments	Terrachlor/Apron/Semevin
nitrogen applied	155 kg/ha
method of N application	Anhydrous ammonia and Urea
pre-emergence herbicides	Trifluralin
sowing date	9-10-89
sowing rate	16.7 kg/ha
pre-irrigation	none
number of crop irrigations	3
plant emergence	24-10-89
first square	
first flower	28-12-89
first green boll	
first open boll	
defoliants used	
harvest date	
yield	undamaged- 686 Kg/Ha (3.05 bales/Ha) damaged - 749 Kg/Ha (3.33 bales/Ha)

Yield

There was very little lint yield difference between the 'damaged' and 'undamaged' sites (Fig 1). Hail badly affected this site in February 1990.

Soil Strength

Fig 14a Soil strength measurements using Handheld penetrometer at Auscott Narrabri.

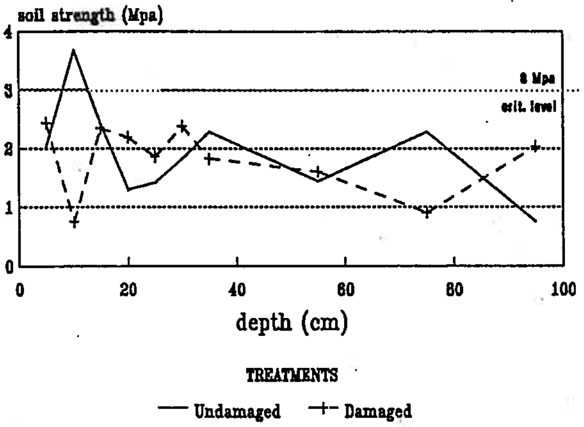
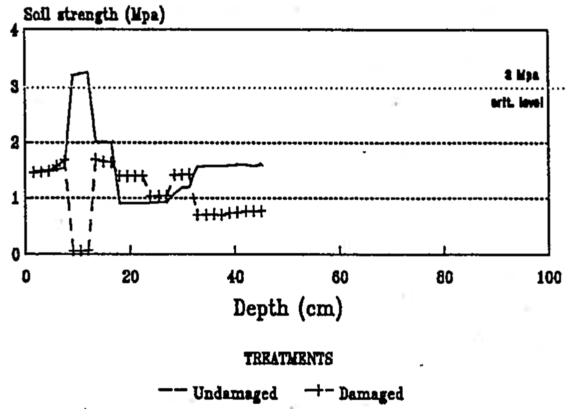


Fig 14b Soil strength measurements using Rimik penetrometer at Auscott Narrabri.



Both the Rimik and Handheld penetrometer showed similar trends (Fig 14 a&b). There is an unusual pattern for soil strength between 10 and 20 cm where the 'damaged' site has a sharp drop in soil strength and the 'undamaged' site has a large increase in soil strength. In this case it is possible that the tyne we used to impose a smear layer may have actually had the reverse affect and loosened the soil.

Root Distribution and Root Morphology

Fig 15a Root diameter changes with depth at Auscott Narrabri.

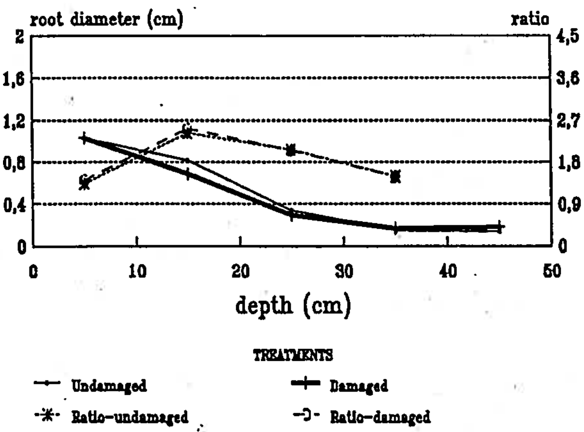


Fig 15b Root obliquity changes with depth at Auscott Narrabri.

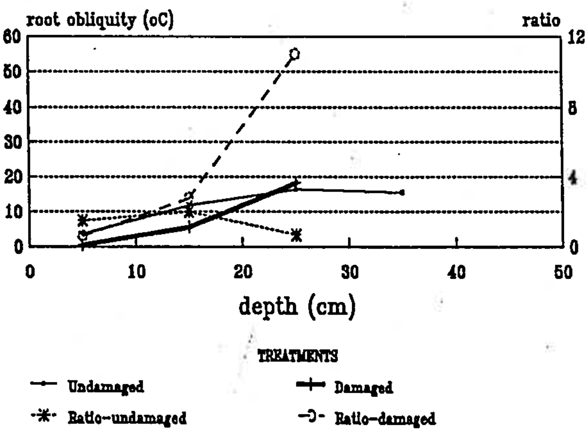


Fig 15c Changes in the number of lateral roots with depth at Auscott Narrabri.

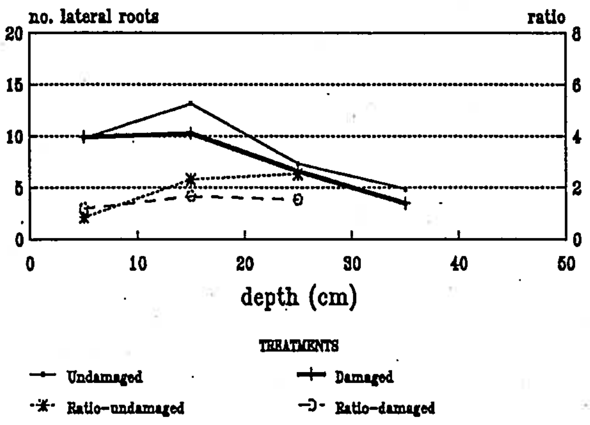
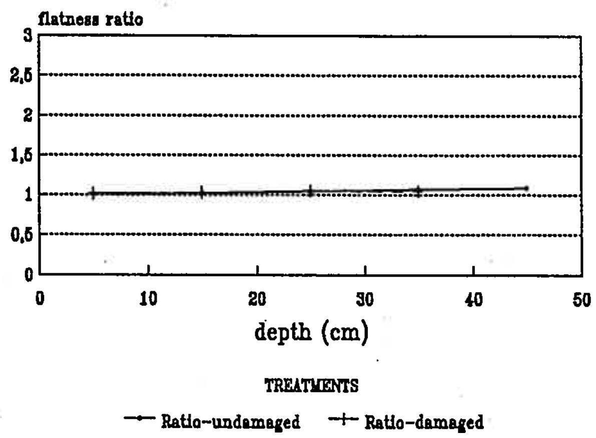
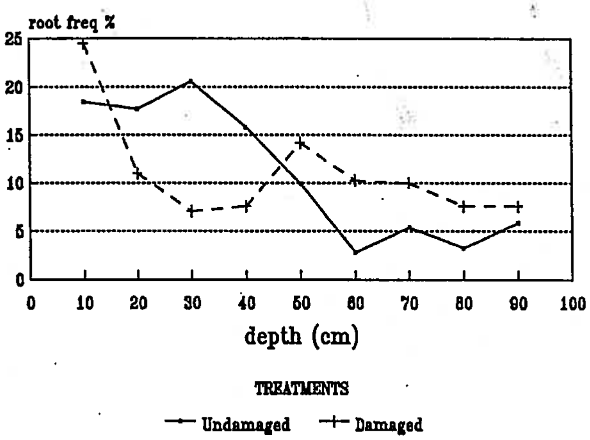


Fig 15d Root flatness at Auscott Narrabri.



Root morphology measurements do not indicate any difference between the two sites (Fig 15 a,b,c & d). The layer of higher soil strength at the 'undamaged' site did not affect the penetration capacity of the taproots.

Fig 16 Distribution of roots under the hill down the profile at Auscott Narrabri.



There is a site difference in the root distribution over the profile (Fig 16). The 'undamaged' site had a greater concentration of roots in the top 40cm, indicating that the root growth may have been hindered prior to moving through the zone of higher soil strength.

Summary

1. Yield and root morphology data do not show evidence of soil structural problems.

2. Soil strength and root distribution indicated that there were structural problems present in the soil.

3. This damage, being confined to near the surface, appears not have inhibited plant development once the roots had penetrated this layer.

Table 10. Chemical properties relevant to soil structural stability at Auscott Narrabri.

Depth	Treatment	5cm	15cm	25cm	35cm	55cm	75cm	95cm
pH	undamaged	7.3	7.3	7.5	7.8	8.0	7.9	7.5
	damaged	7.4	7.4	7.6	7.7	7.9	7.9	7.2
ECe	undamaged	0.9	0.9	0.98	1.5	2.25	2.55	1.13
	damaged	1.2	1.13	1.35	1.65	2.55	2.93	0.83
ESP	undamaged	3.15	3.99	5.06	8.62	11.5	13.46	-
	damaged	3.79	5.51	6.40	8.82	12.9	13.75	-
Ca/Mg ratio	undamaged	1.86	1.54	1.72	1.38	1.49	1.10	3.08
	damaged	1.80	1.75	1.74	1.55	1.30	1.16	1.72
CEC	undamaged	36.5	35.0	36.7	35.5	38.3	32.7	26.1
	damaged	34.0	33.0	38.2	35.0	34.1	32.0	33.6
OM%	undamaged	1.04	0.91	0.43	0.77	0.89	0.43	1.68
	damaged	1.25	0.79	0.96	0.87	0.77	0.59	1.22
P	undamaged	-	4.1	0.8	0.9	0.4	0.3	12.8
	damaged	3.4	2.5	2.3	1.8	1.3	34.7	28.7
N%	undamaged	0.53	0.45	0.36	0.34	0.29	0.27	0.53
	damaged	0.5	0.45	0.41	0.40	0.31	0.23	0.47

* shaded areas indicate problem areas.

6. MYALL VALE RESEARCH CENTRE

Table 11. Management details for Block 3c, Myall Vale Research Station (NARS), Narrabri.

	undamaged/damaged treatments
soil type	
slope	
cotton variety	Siokra 1-4
seed treatments	
nitrogen applied	
method of N application	
pre-emergence herbicides	Cotoran
sowing date	9-10-89
sowing rate	
pre-irrigation	31-8-89
number of crop irrigations	4
plant emergence	
first square	
first flower	
first green boll	
first open boll	
defoliants used	
harvest date	25-3-90
yield	undamaged- 1623 Kg/Ha (7.21 bales/Ha) damaged - 1627 Kg/Ha (7.23 bales/Ha)

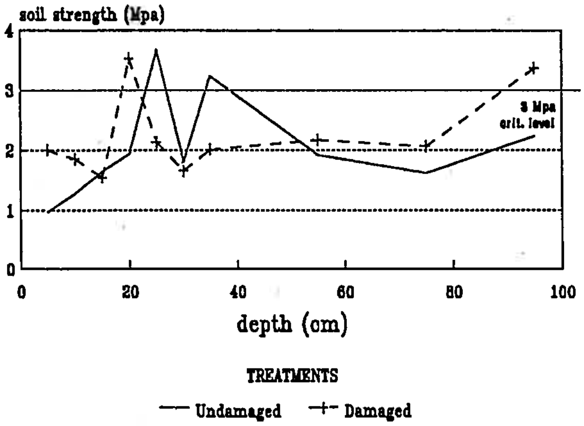
Yield

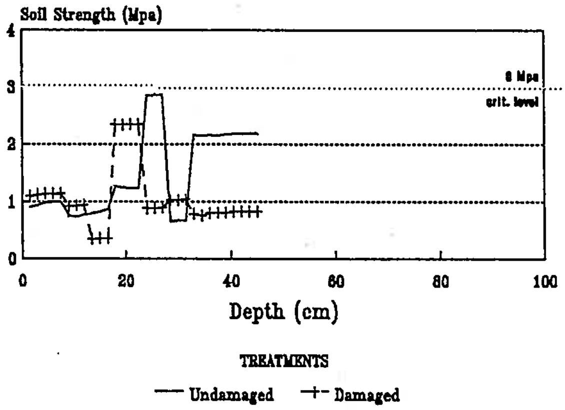
There was very little lint yield difference between the two sites (Fig 1). Hail badly affected this site in February 1990.

Soil Strength

Fig 17a Soil strength measurements using Handheld penetrometer at NARS.

Fig 17b Soil strength measurements using Rimik penetrometer at NARS.



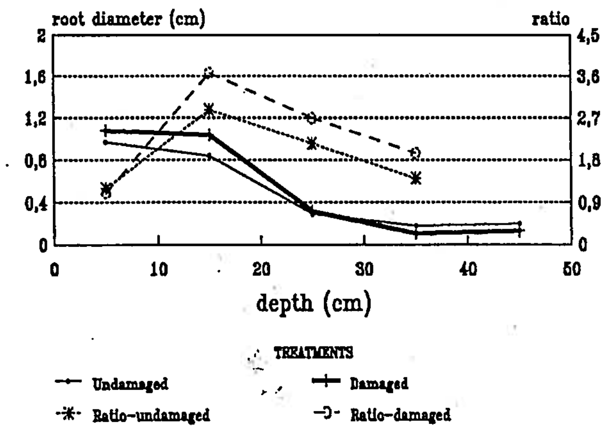


The Handheld penetrometer shows the soil strengths on both sites exceed the critical limit (Fig 17a). The Rimik penetrometer (Fig 17b) has the same pattern but the reading do not reach the critical limit. The differences in the two readings may be due to the inaccuracies of the calibration equation for this soil type.

Root distribution and root morphology

Fig 18a Root diameter changes with depth at NARS.

Fig 18b Root obliquity changes with depth at NARS.



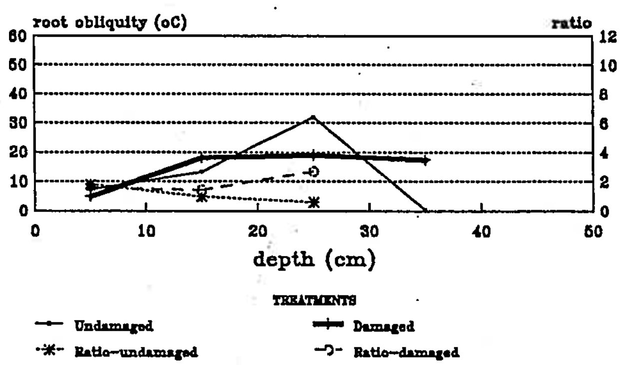
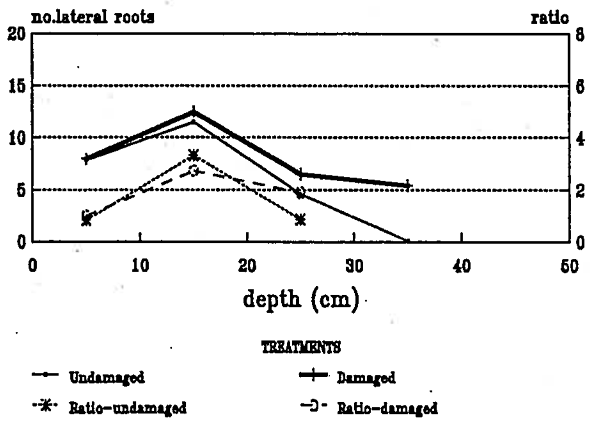
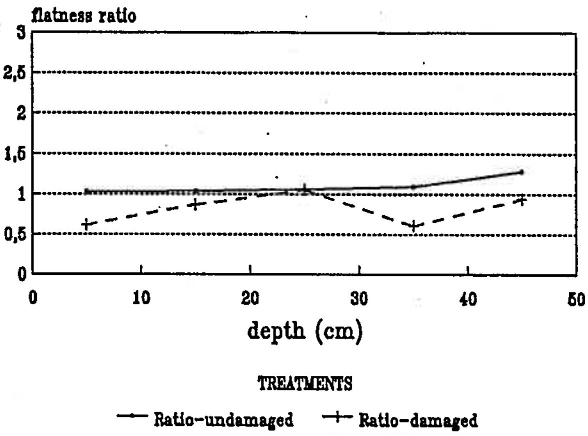


Fig 18c Changes in the number of lateral roots with depth at NARS.

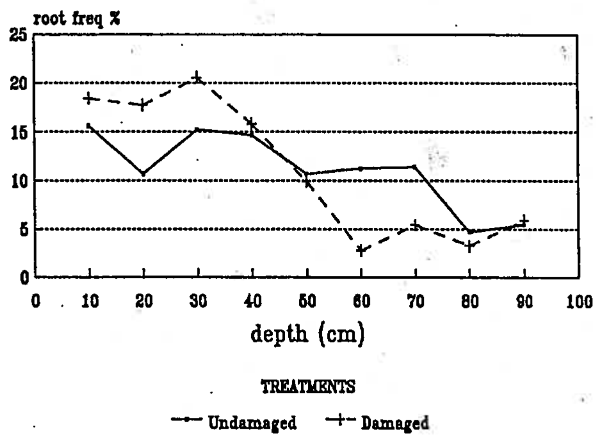
Fig 18d Root flatness at NARS.





The root morphological characteristics show little difference between the sites (Fig 18 a,b,c & d).

Fig 19 Distribution of roots under the hill down the profile at NARS.



The root distribution (Fig 19) is consistent with the soil strength measurements. The roots at the 'damaged' site encounter an unfavourable zone at approximately 20cm, and consequently there is a greater concentration above this depth. However, Figs 17a and 17b show that both 'damaged' and 'undamaged' sites had similar soil strength profiles ie. an 'unfavourable' zone at approximately 20-30 cm. The concentration of roots evens out with depth as the soil strength in the 'undamaged' site increases.

Summary

1. Yield data shows little difference between the 2 sites.

2. Soil Strength, root morphology and root distribution exhibit similar trends, which corresponds with the yields.

Table 12. Chemical properties relevant to soil structural stability at NARS.

Depth	Treatment	5cm	15cm	25cm	35cm	55cm	75cm	95cm
pH	undamaged	7.6	7.5	7.4	7.5	7.6	7.7	7.8
	damaged	7.6	7.6	7.6	7.7	7.7	7.8	7.6
ECe	undamaged	0.9	0.98	0.83	0.83	0.98	1.58	1.95
	damaged	0.98	1.05	0.98	1.2	1.35	1.5	1.73
ESP	undamaged	0.87	1.97	2.08	3.17	3.59	4.55	6.14
	damaged	1.76	1.88	2.04	2.20	2.58	3.57	4.66
Ca/Mg ratio	undamaged	2.64	3.12	2.61	2.64	1.82	1.63	1.48
	damaged	3.22	3.22	2.57	2.86	2.51	1.72	1.44
CEC	undamaged	28.8	24.8	24.6	25.7	24.8	25.1	24.7
	damaged	28.4	29.0	28.7	30.3	29.4	28.0	26.1
OM%	undamaged	1.62	1.46	1.61	1.22	1.29	0.99	0.93
	damaged	1.57	1.66	1.54	1.29	1.28	0.91	0.68
P	undamaged	49.0	44.8	30.1	47.2	75.4	5.7	7.2
	damaged	12.5	18.2	2.0	<0.2	2.1	1.8	1.9
N%	undamaged	0.77	0.7	0.55	0.45	0.4	0.35	0.27
	damaged	0.45	0.43	0.34	0.28	0.48	0.39	0.33

* shaded areas indicate problem areas.

OTHER STRUCTURE ASSESSMENT METHODS USED AT EACH OF THE 6 PROPERTIES

Soil Assessment Schemes Based on Visual Appraisal

During the 1989 pre-season soil sampling of sites, three soil survey descriptions were tested. These were Mckeague (Canada), Hodgson *et al.* (United Kingdom) and McDonald *et al.* (Australia). While the Hodgson and McDonald schemes were able to identify structural differences between soil types, they do not identify differences within soil types. McKeague's scheme is based predominantly on pore and crack description. This system works well on non-cracking soils, but has a number of limitations for cracking soils. For this to be used successfully many modifications would need to be made. To compound these problems there is also a large degree of operator error due to the difficulty in identifying pore and crack size, number and shape. For these reasons all three survey descriptions have been rejected as possible ways of assessing the soil structural condition within cotton fields on cracking grey clays.

In May-June 1990, after a visit by Dr Tom Batey (soil science lecturer and consultant, Aberdeen, Scotland), another scheme was identified for possible use. During his visit Dr Batey modified the Peerlkamp (The Netherlands) description to suit the soils of the Macquarie and Namoi Valleys, NSW. This system was tested during the wet winter of 1990, but further modifications are required for the assessment of dry soil.

From the assessment of these systems it was possible to devise an interim morphological description for incorporation into the current **SOILpak** manual.

Macroporosity

The Rhodamine dye technique gives a measure of the number of continuous macropores that connect the soil surface and subsoil; smeared layers are highlighted. The procedure indicted the extent to which roots can bypass zones with high strength and/or poor aeration. However, it is a messy and time consuming technique that, without major modifications, does not fit the criteria that we require for advisory staff. It is good for research purposes but is not suitable for rapid 'on the spot' field evaluations in its present form.

Water Usage

At this stage the results have not been analysed for this technique. However, Peter Cull (Neutron Probe Services, Narrabri) has found that there are good relationships between soil compaction and water use (Thomson & Cull, 1989; Roth & Cull, 1991)

Clod Shrinkage and Oxygen Diffusion

Clod shrinkage parameters and oxygen diffusion rate are accurate measures of soil condition, but are very time consuming laboratory techniques. Clod shrinkage is being used as the standard technique for identifying the degree of soil degradation. Data are still being processed at Rydalmere.

CONCLUSIONS

Of all the techniques tested, soil strength and root morphological measurements appear to be the best indicators of soil structural condition. They relate well to lint yield at Buttabone; the soil was poorly drained, due to sodic conditions and therefore was prone to compaction and smearing. These techniques are rapid, simple to use and can easily be repeated at different points within a field to assess the extent of compaction across the field. Other techniques appear to be able to identify the degree of soil compaction but are too time consuming, and therefore cannot be used for regular assessment across a field.

Soil strength measurements have to be interpreted carefully as corrections must be made for soil moisture content. The penetrometer still needs to be calibrated for each soil type before accurate conclusions can be obtained from the readings. This technique can be used at any time of the year. However, automated soil strength measurement from the soil surface requires expensive equipment which is prone to breakdown.

Root morphology measurements do not require any complicated equipment and can be carried out rapidly in the field. The technique is dependent upon the presence of cotton roots. It should be used after picking, and will ascertain if the roots encountered any compaction problems during the season. However, if there was any rain with subsequent soil damage during picking, the root morphological measurements would not identify it.

Our results show that it is possible to successfully manage cotton crops so that the adverse effects of soil compaction are minimized. This can be done in two ways; increased nitrogen fertiliser and shorter irrigation intervals. This was evident at Elengerah where the yields were high even though there was evidence of structural damage. In this case, extra irrigations were applied to ensure that the crop did not suffer the effects of high soil strength.

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PART II ASSESSMENT OF COMPACTION IN A VERTISOL USING TWO TYPES OF PENETROMETER AND A SHEAR VANE

D.C. McKenzie and D.J.M.Hall

Experimental design

The experiment was carried out on fields 23, 25 & 35, Auscott Warren, Macquarie Valley, NSW.

Measurements were taken two days after the final irrigation in late February 1990, and were repeated at 3 day intervals. Soil moisture ranged from 'very moist' to 'very dry'.

All measurements were taken under both the ridges and the furrows, at a depth of 20 cm below the ridges.

Measurements

1. Gravimetric water content, bulk density and air-filled porosity were measured in triplicate using thin-walled cores (50 mm long; 75 mm diameter).

2. Soil strength (kPa) was measured in triplicate with 3 devices:
   * 'Rimik' recording penetrometer (30° cone; 13 mm diameter, 25 mm long; rate of insertion = 15 mm/sec; recessed shaft)(ASAE standard).
   * 'Chatillon DPP-5 kg' hand-held penetrometer (60° cone; 6 mm diameter; rate of insertion = 15 mm/sec).
   * 'Geonor' hand-held shear-vane (with 2 right-angled vanes 15 mm across, 31.5 mm high; rate of rotation = 45 degrees/sec).

Statistical Analysis

Standard regression procedures were applied to the data using the 'JMP' statistical package. The 3 replicates of shear strength, and penetration resistance using 2 devices, taken under each of the furrows and ridges were meaned to allow comparisons with the bulk density, water content and air-filled porosity data.

Reliability of the derived equations for the prediction of bulk density and air-filled porosity using the shear vane was tested with an independent data set from previous Field 24 experiments. Sampling procedures for the independent data were the same, except that they were taken horizontally from the sides of backhoe pits rather than vertically from the soil surface.

Results

Bulk density and air-filled porosity changes as a function of water content

The ridges (equation 1) had a lower bulk density (BD) than the furrows (equation 2) which increased less rapidly as the water content ($Ø_g$) decreased.

$$BD(Mg\ m^{-3}) = 1.68 - 0.0134\ (Ø_g;\%) \ \ldots\ldots\ldots\ldots (1)$$
$$n = 44;\ r^2 = 0.47$$

$$BD(Mg\ m^{-3}) = 1.92 - 0.0180\ (Ø_g;\%) \ \ldots\ldots\ldots\ldots (2)$$
$$n = 45;\ r^2 = 0.43$$

Because residual shrinkage occurs at water contents below the range tested in this experiment, and structural shrinkage often is observed at high water contents, equations 1 and 2 should not be used beyond the Øg range 17-36 %.

The associated air-filled porosity changes with water content are described in equations 3 (ridge) and 4 (furrow).

$$AFP(\%) = 29.40 - 0.49(Øg;\%) \ \ldots\ldots\ldots\ldots (3)$$
$$n = 44;\ r^2 = 0.25$$

$$AFP(\%) = 17.30 - 0.33(Øg;\%) \ \ldots\ldots\ldots\ldots (4)$$
$$n = 45;\ r^2 = 0.07$$

Influence of water content and bulk density on shear strength and penetration resistance

The effects of $Ø_g$ and BD on shear strength (SV), 'Rimik' penetration resistance (RI) and 'Chatillon' penetration resistance (HH) are shown, respectively, in equations 5, 6 and 7.

$$SV(kPa) = -\ 4.4068 + 156.5778\ (BD;Mg\ m^{-3}) - 4.2735\ (Øg;\%) \ \ldots\ (5)$$
$$n = 77;\ r^2 = 0.65$$
Prob > F (Whole model) = 0.0000
Prob > F (BD) = 0.0000
Prob > F (Øg) = 0.0000

$$RI(kPa) = 2767.8440 + 983.2866\ (BD;Mg\ m^{-3}) - 108.0050\ (Øg;\%)\ .\ (6)$$
$$n = 88;\ r^2 = 0.53$$
Prob > F (Whole model) = 0.0000
Prob > F (BD) = 0.0937
Prob > F (Øg) = 0.0000

$$HH(kPa) = 4989.1485 + 317.2553\ (BD;Mg\ m^{-3}) - 152.7101\ (Øg;\%)\ ..\ (7)$$

$n = 89$; $r^2 = 0.35$
Prob > F (Whole model) = 0.0000
Prob > F (BD) = 0.7648
Prob > F ($Ø_g$) = 0.0000

The use of polynomial rather than linear models improved the r^2 values of equations 5, 6 and 7, respectively, to 0.72, 0.65 and 0.59 but did not greatly alter the probabilities, or the accuracy ranking, for the 3 instruments.

Both $Ø_g$ and BD have a significant effect upon the shear vane. When the results are plotted 2-dimensionally, the slopes of the lines relating $Ø_g$ and SV for the 2 levels of density (ridges and furrows) are clearly separated and parallel (Figure 1). These lines are described by equations 8 and 9.

$$SV\ (Furrow) = 299.1631 - 7.0294\ (Ø_g)\ ....\ (8)$$

$n = 35$; $r^2 = 0.56$

$$SV\ (Ridge) = 258.3105 - 6.5206\ (Ø_g)\ ....\ (9)$$

$n = 42$; $r^2 = 0.62$

In contrast, RI and HH are strongly influenced only by water content; bulk density does not have a strong effect in the multiple regression analyses. The slopes of the lines relating $Ø_g$ and RI for the 2 levels of density are very different, causing them to intersect (Figure 2). They are described by equations 9 and 10; a log scale has been used on the x axis to remove curvilinearity.

$$RI\ (Furrow) = 14494.698 - 4032.764\ (\ln Ø_g)\ ....\ (10)$$

$n = 44$; $r^2 = 0.51$

$$RI\ (Ridge) = 9466.5276 - 2540.784\ (\ln Ø_g)\ ....\ (11)$$

$n = 44$; $r^2 = 0.61$

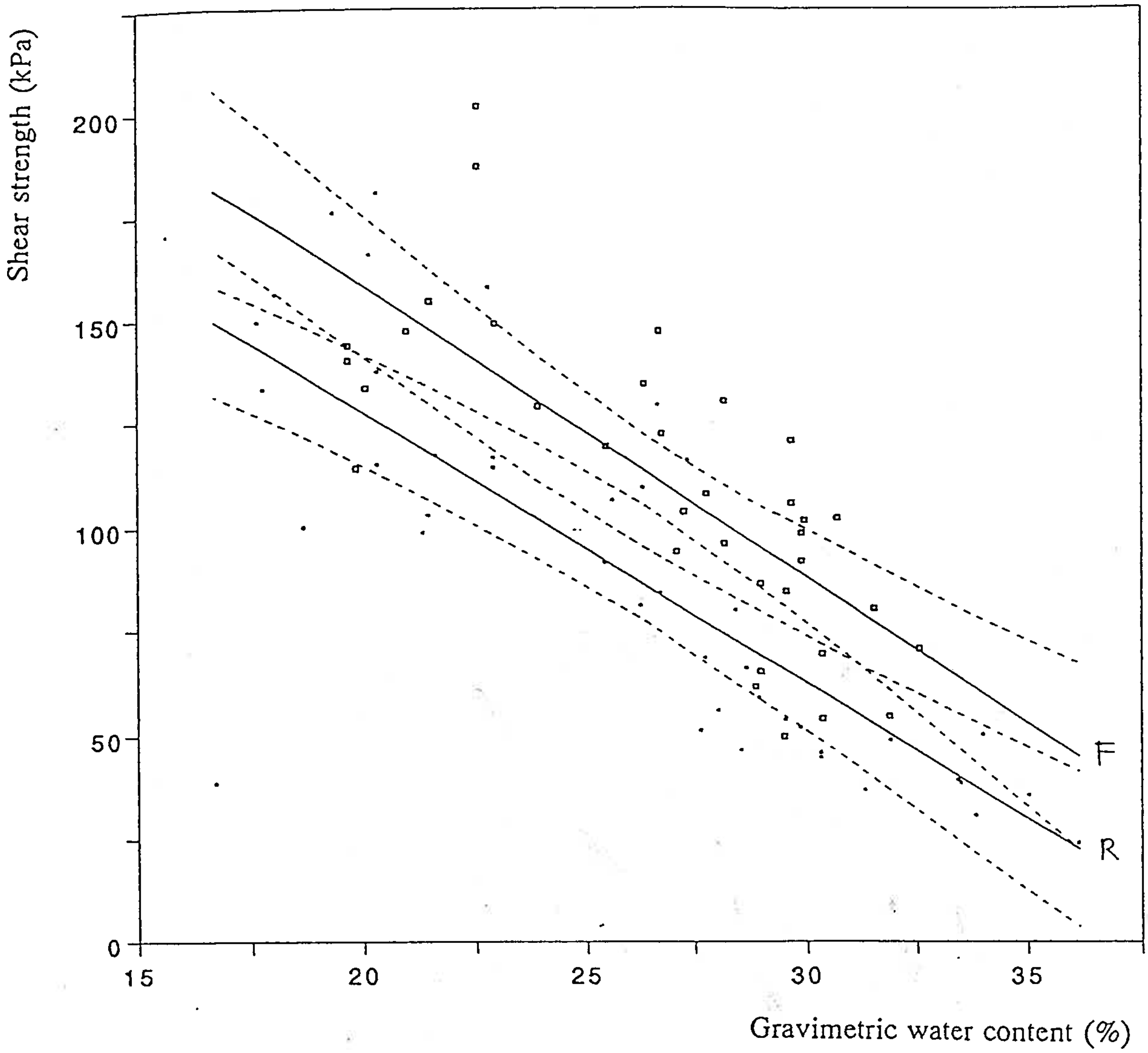

Figure 1. Shear strength as a function of gravimetric water content for the furrow (F; □) and ridge (R; ○). Dashed lines indicate the 95% confidence interval for each position.

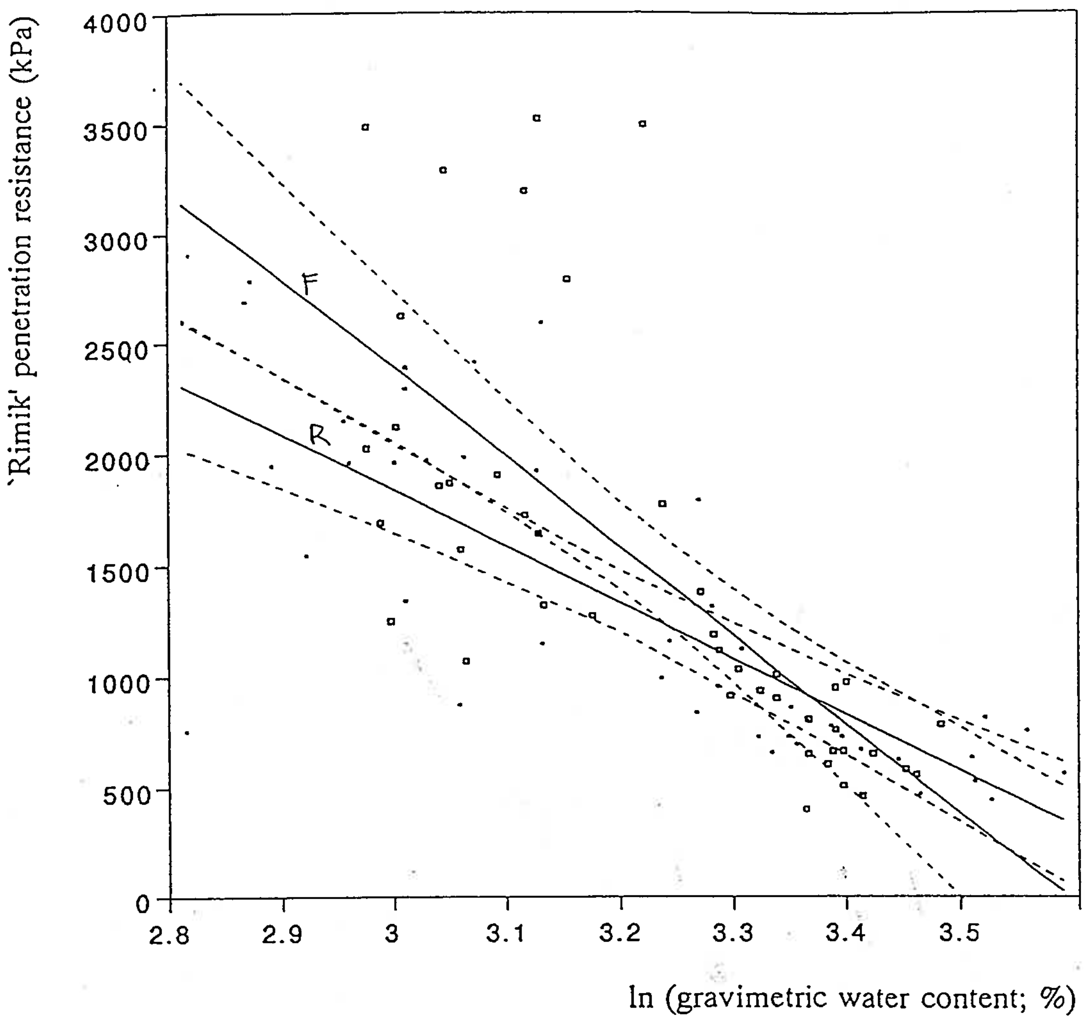

Figure 2. Cone index, measured with the 'Rimik' penetrometer, as a function of gravimetric water content for the furrow (F; □) and ridge (R; ○). Dashed lines indicate the 95% confidence interval for each position.

Relationship between the strength measuring devices

The slope of the relationship between SV and RI depends on the soil water content, as shown by the spline fit in Figure 3. Another way of describing this relationship is to use a second degree polynomial (see equation 12 and Figure 3).

$$SV = -5.8370 + 0.1263\,(RI) - 0.000024\,(RI)^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

$n = 76$; $r^2 = 0.66$

RI < 2500 kPa (inflection point)

The SV is more sensitive than the RI at low water contents. To allow a description of this correlation, straight lines have been fitted to each of the three segments (Figure 4); sections A, B and C are described, respectively, by equations 13, 14 and 15.

A: $$SV = 114.9687 + .0130\,(RI) \quad \ldots\ldots\ldots\ldots\ldots (13)$$

$n = 23$; $r^2 = 0.07$

Prob > F = 0.2247

B: $$SV = -38.1807 + 0.1390\,(RI) \quad \ldots\ldots\ldots\ldots (14)$$

$n = 28$; $r^2 = 0.53$

Prob > F = 0.0000

C: $$SV = 35.8386 + 0.0400\,(RI) \quad \ldots\ldots\ldots\ldots\ldots (15)$$

$n = 28$; $r^2 = 0.04$

Prob > F = 0.2961

The critical strength limits for cotton root growth according to the studies of Taylor et al. (1966) and Taylor and Ratliff (1969), standardized to a cone angle of 30° and a rate of insertion of 15 mm sec^{-1} using the procedures of Fritton (1990), are 1672 and 680 kPa (c.f. uncorrected values of 2500 and 700 kPa), respectively, for cessation of growth and 50 % reduction (Figure 4). The corresponding shear vane readings are 135 and 62 kPa.

Equation 16 describes the relationship between the two penetrometers, RI and HH. Because of their large scatter, the 'very dry' data were excluded from the analysis. It is shown diagrammatically in Figure 5.

$$RI = 214.3392 + 0.8448\,(HH) \quad \ldots\ldots\ldots\ldots (16)$$

$n = 71$; $r^2 = 0.70$

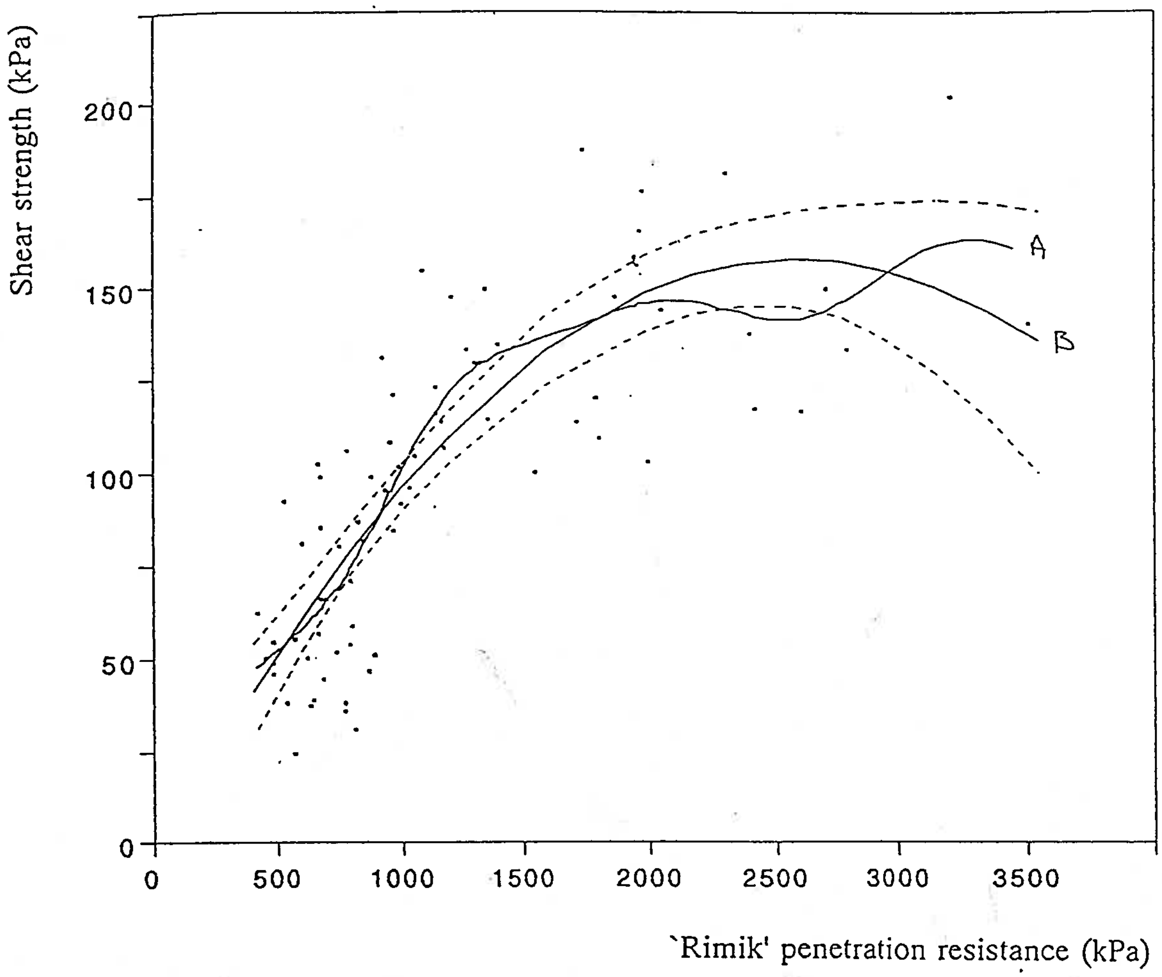

Figure 3. Smoothing spline fit (A) ($X=5x10^7$) ($r^2= 0.72$) and polynomial fit (B) ($r^2=0.67$) for the relationship between the `Rimik' penetrometer and the shear vane.

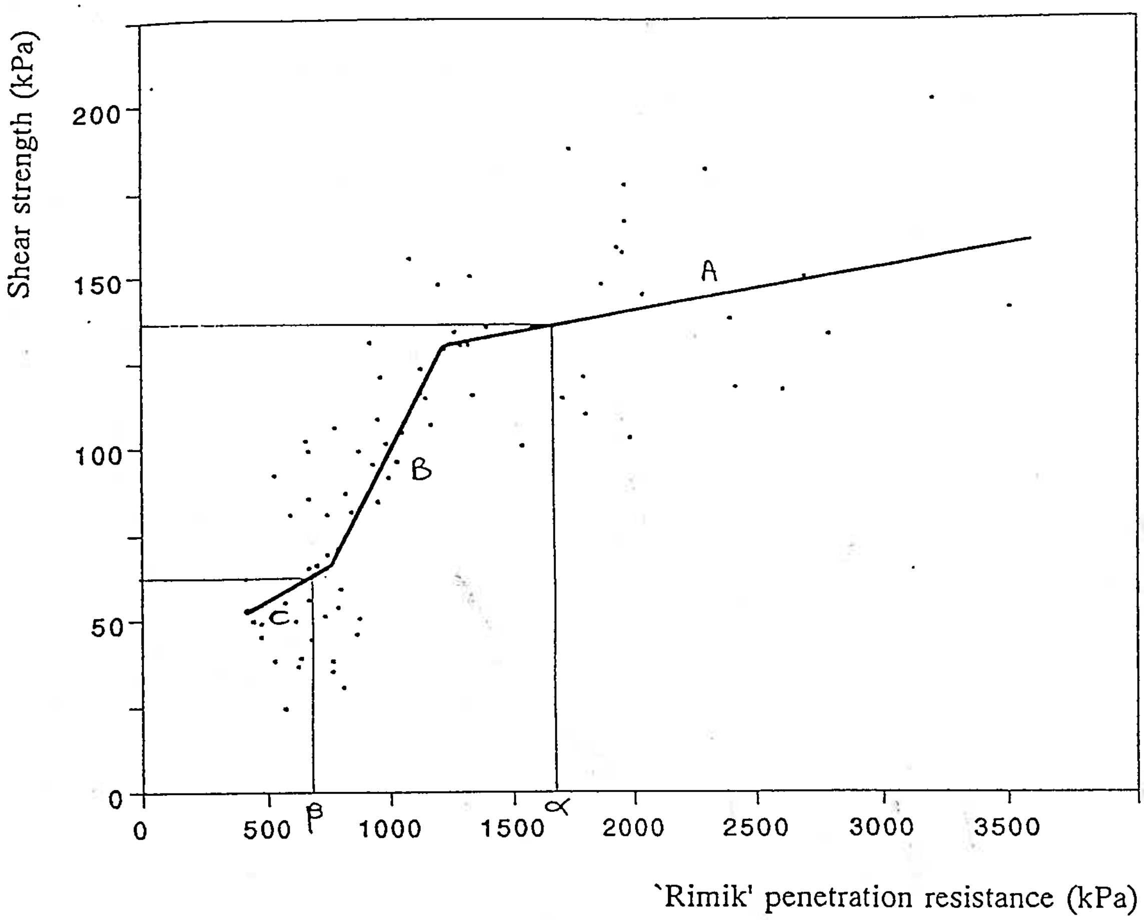

Figure 4. Linear segments (A,B and C) describing the relationship between the`Rimik' penetrometer and the shear vane. the critical strength limits for cotton roots, adjusted using the procedures of Fritton (1990), are shown for cessation of growth (Taylor *et al.*, 1966; α) and 50% reduction (Taylor and Ratliff, 1969; β).

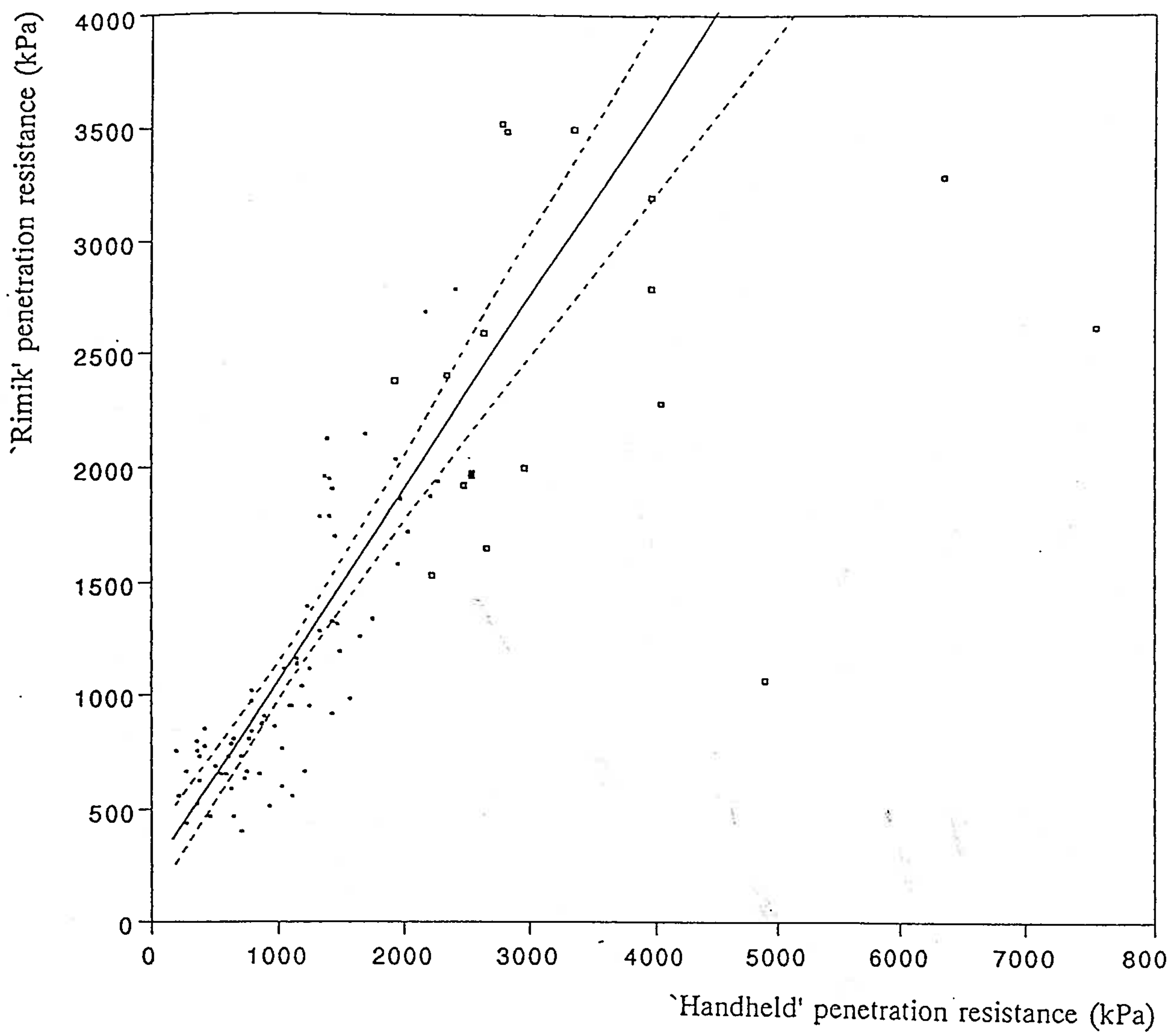

Figure 5. Relationship between the `Rimik' (RI) and Handheld (HH) penetrometers. Data collected under very dry conditions (□) have been excluded from the analysis.

Prediction of air-filled porosity using soil strength and volumetric water content data

A strong relationship exists between air-filled porosity (AFP), and shear strength and volumetric water content, of the soil, as shown by equation 17. All of the effects are strongly significant.

$$AFP(\%) = 64.5421 - 1.2027\ (Øv;\%) - 0.0834\ (SV;kPa) \text{ .... } (17)$$
$$n = 77;\ r^2 = 0.79$$

When Øg is used rather than Øv, the equation is:

$$AFP(\%) = 53.3358 - 1.1524\ (Øg;\%) - 0.1012\ (SV;kPa) \text{ .... } (18)$$
$$n = 77;\ r^2 = 0.36$$

Confidence intervals for the 3 strength measuring devices under a broad range of soil water contents

The coefficients of variation, and confidence intervals for a range of sample sizes, of the shear vane, 'Rimik' penetrometer and Hand-held penetrometer, used under the ridges and furrows when the soil was 'very wet', 'moist', and 'very dry', are shown in Table 1. The shear vane has higher coefficients of variation than the other instruments at all water contents; the two penetrometers had similar precision. Precision generally was slightly lower under the ridges than under the furrows, and increased as the soil became drier. The extent to which precision can be improved by increasing the degree of replication is shown in Table 1; for the shear vane, approximately 50 replicates are required to reduce confidence intervals to about 10 % of the mean values - i.e. about two hours work per site.

Validation using an independent data set

A plot of the relationship between shear vane values, corrected to a water content of 0.25 g/g using the average slope of equations 8 and 9, and degree of compaction (bulk density) for the Field 24 data is shown in Figure 6. Despite the large scatter of points, a significant relationship exists (Prob. > F = 0.0148), and the bulk density confidence intervals are low - confidence interval = 0.02 g cm^{-3}, when SV_{corr} = 100 kPa - when a large number of replicates - 101 - is available. A stronger relationship occurs between corrected shear strength and air-filled porosity (Figure 7); the confidence interval = 0.8 %, with 101 replicates for SV_{corr} = 100 kPa.

Table 1: Coefficients of variation (CV), and confidence intervals (CI) for a range of sample sizes, of the shear vane (SV), Rimik penetrometer (RI), Chattilon hand held penetrometer (HH), and gravimetric water content (Θg) NB: Measurements on the RI were always taken in multiples of 3 (the electronic recording is set up this way), so all strength data have been considered in sets of 3.

		SV						RI						HH						Θg					
		Mean (kPa)	N	CV (%)	CI (kPa)			Mean (kPa)	N	CV (%)	CI (kPa)			Mean (kPa)	N	CV (%)	CI (kPa)			Mean (kPa)	N	CV (%)	CI (kPa)		
					n=3	n=15	n=30				n-3	n=15	n=30				n-3	n=15	n=30				n=1	n=5	n=10
T1 (very wet)	Furrow	102	9	4.8	47.2	21.1	14.9	844	9	1.7	430.6	192.2	136.3	948	9	1.7	540.6	241.3	171.1	29.0	9	4.5	3.42	1.53	1.08
	Ridge	64	9	7.7	48.6	21.7	15.3	846	9	1.5	338.4	151.1	107.1	662	9	3.3	939.2	419.3	297.2	28.4	9	5.1	4.20	1.88	1.33
T3 (moist)	Furrow	120	9	4.0	45.0	20.1	14.2	1185	9	1.5	627.6	280.2	198.6	1173	9	1.4	549.4	245.3	173.9	26.5	9	5.6	4.40	1.98	1.41
	Ridge	85	9	6.2	55.6	24.8	17.6	979	9	2.0	748.4	334.1	236.8	883	9	2.2	728.0	325.0	230.4	27.4	9	3.4	1.76	0.79	0.56
T5 (very dry)	Furrow	166	3	3.4	64.8	28.9	20.5	2804	9	1.1	1768.8	789.6	559.8	4242	9	1.0	3420.6	1527.1	1082.5	22.1	9	5.9	3.38	1.51	1.07
	Ridge	131	7	4.2	60.0	26.8	19.0	2130	9	0.9	652.0	291.1	206.3	2616	9	0.9	1202.6	536.9	380.6	21.1	8	5.7	2.84	1.27	0.90

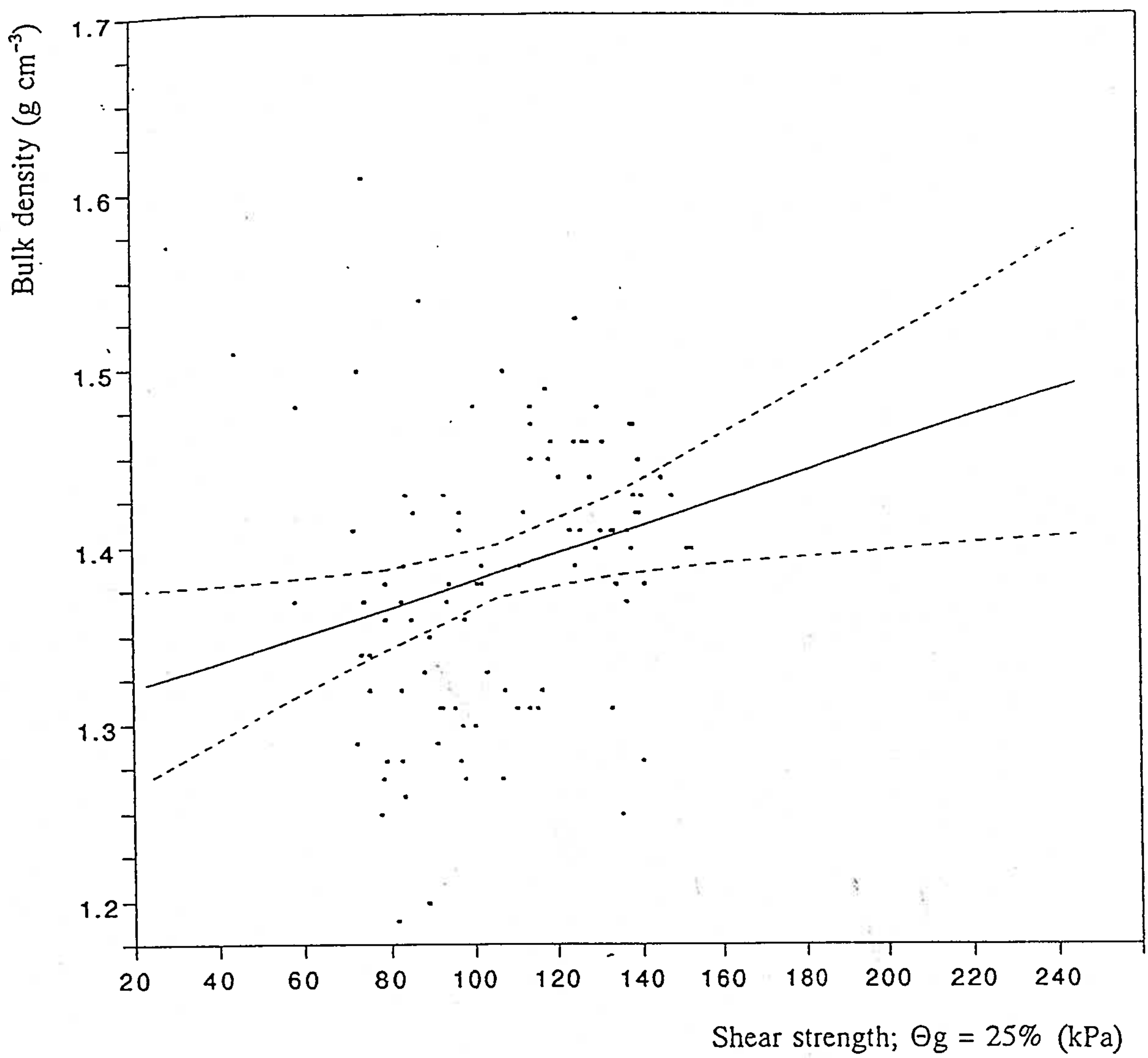

Figure 6. Relationship between corrected shear strength and bulk density for the independant data set (n=101, r^2=0.06).

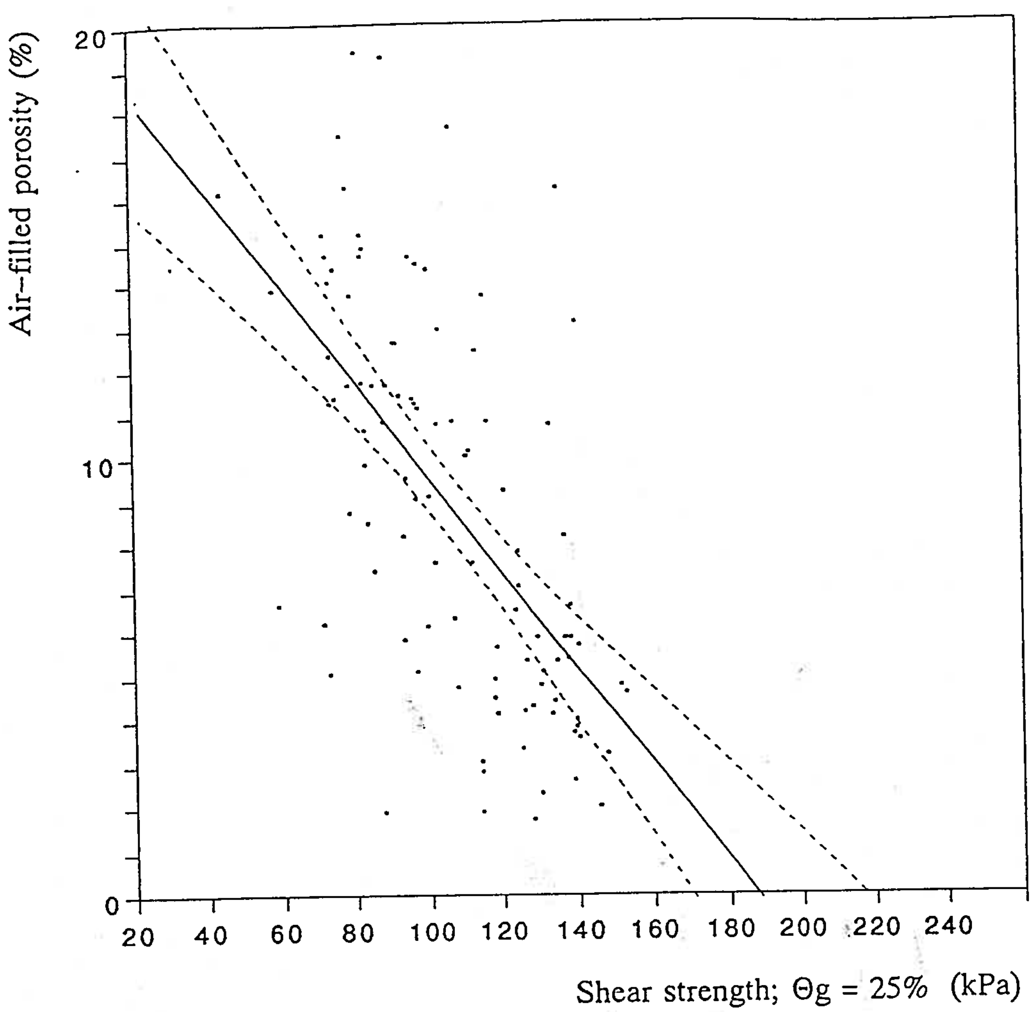

Figure 7. Relationship between corrected shear strength and air-filled porosity for the independant data set (n=101, r^2=0.37).

Discussion

Analyses of the relationship between soil strength, bulk density and water content show that with the shear vane, any of these properties can be predicted with confidence where 2 of the 3 are known. Also, measurements of shear strength and volumetric water content can be used to predict air-filled porosity of this soil. Practical applications of these measurements are as follows:

* the critical water contents at which soil strength and aeration become limiting can be estimated using the derived relationships, thus indicating to farm managers the optimal range of water contents that should be maintained in their soil. Figure 8 illustrates this procedure. The water contents corresponding to the critical strengths for root growth (ϕg-critical) for a range of compaction indices (SV_{corr}; ϕ_g = 25%) are derived from Figure 9, and used to produce the strength limitation line. The critical aeration line was produced by correcting the SV readings for a range of water contents, including 25 % (Figure 7), which provides SV values that correspond to an AFP of 14 %; this is the point at which oxygen diffusion becomes non-limiting in grey clays. The example in Figure 8 indicates the range of water contents (NLWR) that needs to be maintained for optimal crop growth for a given value of SV_{corr}. It also shows that the NLWR can be broadened by reducing the SV_{corr} values - e.g. by deep tillage, organic matter addition.

* in experimental situations the raw strength data, and response of a growing crop, can be plotted as a function of time to validate the critical limits; macroporosity can strongly influence these limits, so it should also be monitored. The raw strength values can also be used to estimate the degree of trafficability of the soil at a given time.

* research staff can use the equations to correct their data for both water content and bulk density which allows, for example, the degree of cementation for a range of soils to be compared.

Only under very dry conditions are there problems with the shear vane; off-scale readings with the smallest available vane can occur, and shattering of the soil during vane insertion may introduce bias. Therefore, compaction assessment with the shear vane should be carried out under moist conditions, although it should be possible to make smaller and sharper vanes.

The two penetrometers do not show a strong relationship between cone index and bulk density when the soil is very wet. Therefore, they should not be used to predict the degree of soil compaction on this soil type where a broad range of water contents, in particular high moisture contents, exist. This insensitivity to bulk density, particularly under moist conditions may be caused by:

- a layer of sticky clay that builds up around the tip under wet conditions.
- wet soil is less compressible than dry soil.

However, Hulme et al. (1991) showed that the Rimik penetrometer can provide valuable experimental data about changes in soil strength with depth under relatively dry conditions. It has excellent data capture facilities, and a depth resolution of 15 mm, but lacks versatility under commercial conditions because compaction assessment often occurs when the soil is wet.

The model choice for relating RI to SV is a crucial one. All experiments relating soil strength to root growth (e.g. Taylor et al. 1966) involve the use of penetrometers, whilst this study has concluded that shear vanes should be used to routinely assess soil compaction in the field - a conversion factor is required. The relationship is best described by a smoothing spline fit, which can be approximated mathematically by the 3 linear segments shown in Figure 5 (equations 13,14 and 15).

The critical root growth limits quoted in this study are rather tenuous because of the multi-stepped conversion procedure which is likely to have introduced large errors. Taylor's studies should therefore be repeated with direct measurement of shear strength, and with the use of modern cotton varieties. The effects of macropore density and degree of remoulding should also be evaluated.

Despite these inadequacies, shear strength data can be used commercially with existing knowledge. For example, a pre-planting compaction index survey of all fields on a cotton farm, at a depth of 20 cm under the ridges, will allow the fields to be ordered from best to worst in terms of their physical condition. This will provide objective data about watering sequences, and about the need for supplementary nitrogen application. Compacted soil needs to be watered earlier, and requires more nitrogen. At present, most growers rely upon frequent neutron probe measurements and petiole analysis after planting to make these decisions.

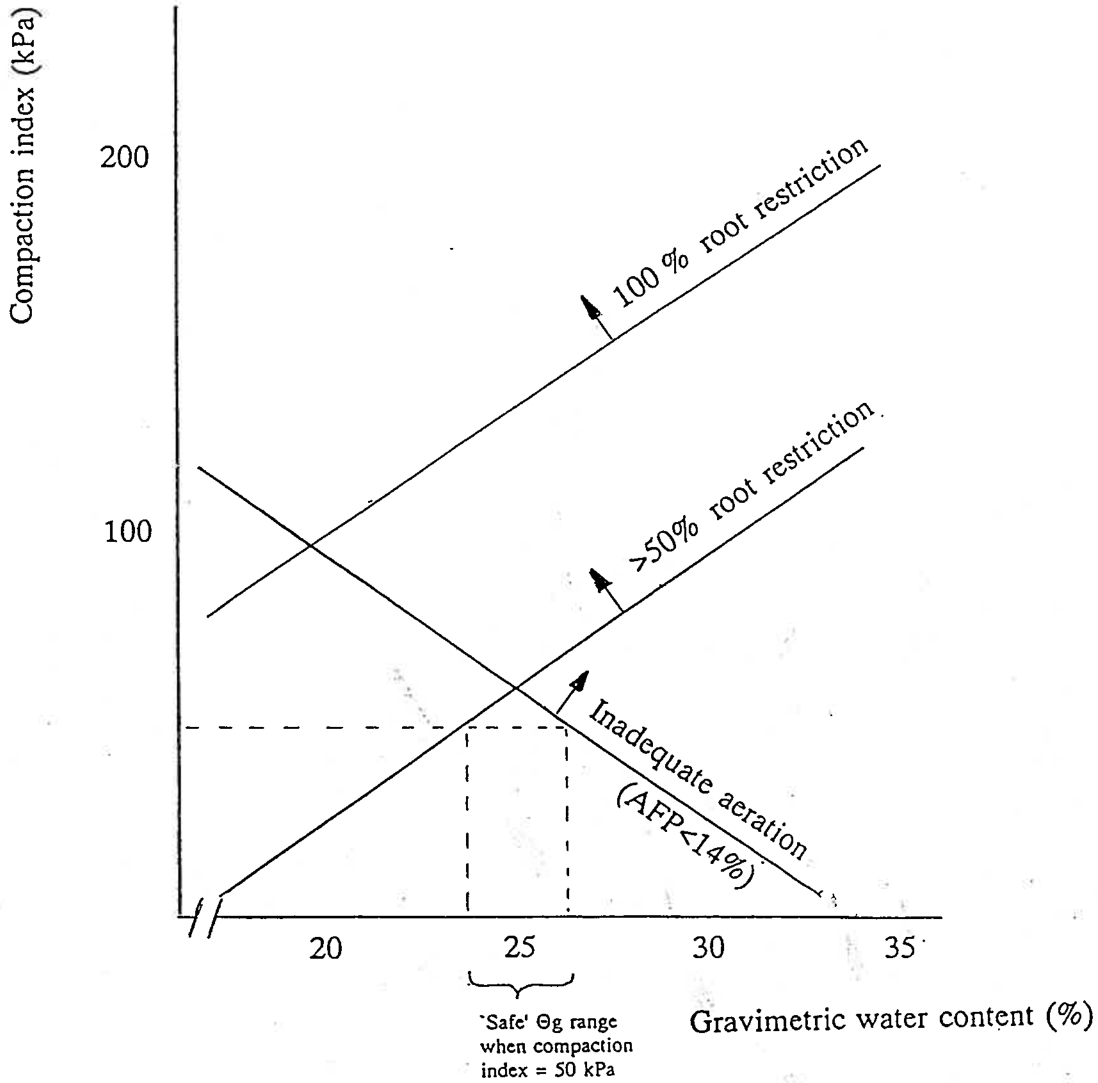

Figure 8. Compaction index (SV_{corr}; Θg=25%) in relation to critical strength and aeration limits for cotton, as influenced by gravimetric water content, for an Auscott Warren grey clay.

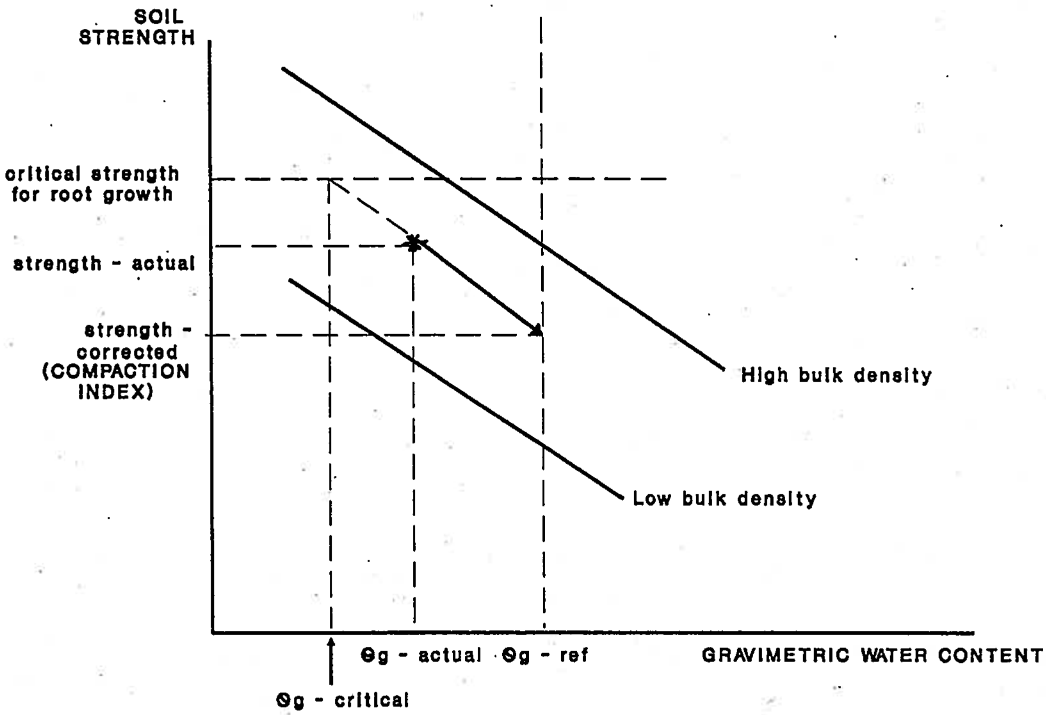

Fig 9. Scheme for the standardisation of soil strength data at a reference water content to provide a compaction index.

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