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Project Title:

“Structure regeneration of compacted cracking clays using wet/dry cycles and rotation crops”.

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A final report prepared for the Cotton Research and Development Corporation

Project:

Structure regeneration of compacted cracking clays using wet/dry cycles and rotation crops.

Executive Summary:

The Australian cotton industry has implemented the "retained bed" system of cotton growing in the majority of the irrigated areas. The system works well for cotton-beds on 1m or 2m spacing, tractors most commonly with 2m axles and all equipment conforming to 6, 8 or 12m widths. The system is one form of controlled traffic, where all wheels are restricted to specific furrows and the beds are only lightly cultivated when the soil is dry.

The system has been in use for approximately ten years, and some beds have been known to last for seven seasons. This poses the problem of periodic restoration of soil structure. Restricting all wheels to specific areas, results in extreme high density "lines" in the cotton paddock. Repair is required either where compaction in the furrow begins to invade the cotton hill, or where hills become mis-aligned so that guess rows widen and become unmanageable. In these situations it is vital that structure restoration of the furrows commences before the hills and furrows are removed. Once removed, the unique marker system that demarcated good and bad structure is lost and there is strong potential of placing new hills over old furrows; an error that led to a 50% reduction in cotton lint yield on a commercial cotton farm.

Results from previous studies have shown that soil structure, in the majority of irrigated cotton soils, responds positively to wet/dry cycles.

The main objective of this current work was to extend previous studies in terms of both assessing the effect of wet/dry cycles in different soils, and the use of selected break crops with wet/dry cycles to enhance and accelerate soil structure repair.

Studies were carried out on two irrigated cotton soils - one a soil capable of strong swelling/shrinking with wet/dry cycles, the other with only moderate potential. The wet/dry cycles were implemented on large (0.5m depth x 0.3m diam.) intact soil cores collected from the compacted wheel furrows at each site. For all cores wetting was by flooding to mimic field conditions. Drying for both sites was by evaporation, and also with break crops for the strong swell/shrink soil. The crops were: wheat, sorghum, lab lab and mung bean. Soil samples were collected after each of 3, 6 and 9 wet/dry cycles for all cores. Soil strength, soil clods for bulk density and image analysis were sampled down each profile. Carefully split cores were photographed for soil structure and root growth, and soil water use/infiltration were calculated for all cores.

Results from the site with moderate potential for swell/shrink repair with repeated wet/dry cycles showed that more than one wet/dry cycle was necessary to significantly improve structure. Flood wetting was more effective than rain wetting, giving deeper repair. Water infiltration (water intake at irrigation) increase x2 after five wet/dry cycles, and this was associated with a marked reduction in soil strength, demonstrating the development of a better plant root environment. Increasing the number of wet/dry cycles produced finer soil structure, important for seed placement and germination.

Results from the site with strong potential for swell/shrink repair with repeated wet/dry cycles gave strong treatment effects. Clod data showed that wetting and drying both with and without crops did improve structure condition, but to greater depths (up to 0.4m) and more rapidly with crops, particularly mung bean and lab lab. Image analysis results corresponded reasonably well with the clod data. Wheat and sorghum gave deep cracking of the soil (to 0.45m), at nine wet/dry cycles, but mung bean and lab lab gave finer structure (better aggregation) to depth by six wet/dry cycles. These results matched well the visible soil structure in the split soil cores, that also showed the legumes gave deep rooting patterns of many fine roots. The shear vane proved better at measuring strength differences between treatments. One season of wheat in the field significantly decreased strength to 0.3m in both the hills and furrow. Strength, with wet/dry cycles alone (no crops), did not decrease significantly. Soil water use was greater beneath the legumes, that matches well with greater and more rapid structure development under these crops. Greater drying gives greater shrinkage, so more potential for re-fill at irrigation; i.e. a greater cycle of wetting and drying, leading to rapid compaction repair.

In conclusion, the lab lab and mung bean crops improved soil structure to greater depths and more rapidly than the wheat and sorghum. This was evident in the visible soil structure, greater evapotranspiration, finer porosity in the images, reduced soil strength and greater porosity in the soil clods. The structure repair would have been greater if these experiments had been conducted on hill material - the plants would have developed better root systems, more rapidly in the loose surface mulch. The structure repair would then have probably encompassed the whole hill, including hard shoulders on the sides of the hills. Wet/dry cycles have again been shown to be a critical method of repairing compaction in these soils. Even the moderate swell/shrink soil showed good potential for repair (with evaporation the only drying medium). Generally, the greatest improvements occurred after six wet/dry cycles, particularly in terms of deep fracturing and small aggregate formation below 0.2m, as seen in the soil images and soil profile photographs. Shear strength was a more sensitive method of demonstrating treatment effects and to greater depth than the penetrometer. The clod data showed that one season of a wheat "break crop" in the field significantly increased porosity to 0.2m. The benefit of this is that shallow ripping of furrows after the wheat crop (if the soil was at or below the plastic limit) would break-out this better structured soil and assist aggregate formation. These finer aggregates may then be incorporated into the hill, giving better hill/furrow demarcation.

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1 INTRODUCTION

The periodic restoration of soil structure is of paramount importance in "controlled traffic" cropping systems. In such systems tractor and equipment wheels are restricted to specific wheel track areas (furrows or inter-rows) and the beds (rows or plant lines) are only cultivated lightly when below the plastic limit (Pillai-McGarry and McGarry, 1992 and Sarmah *et al.*, in press). In the Australian cotton industry such a system has developed over the past 10 years principally to control the location of soil compaction through concentrating it in the wheel furrows (McGarry, 1996). This practice differs dramatically from those of the 1960's and 1970's where, annually, beds were removed after harvest and reformed before sowing; a practice shown to have the potential of producing soil compaction over 100% of a field when done in wet soil (McGarry, 1989a). In practice periodic cultivation of beds is required due to such factors as cumulative tractor driver error giving misaligned beds, and cultivation of beds above the plastic limit with consequent structure degradation (McGarry, 1989b). When beds are removed the unique marker system that demarcated good and highly compacted soil structure is lost and there is strong potential of inadvertently placing new hills over old furrows; an error that gave a 50% decrease in cotton lint yield on a commercial cotton farm (McGarry, 1990).

Results from recent studies (Pillai-McGarry, 1991; Sarmah *et al.*, in press) suggest that the repetition of wet/dry cycles is a key process in regenerating degraded structure in Vertisols. Both studies used soil drying solely by evaporation, not common practice in irrigated Vertisols where there is potential to grow "break crops" to repair soil structure (McGarry, 1996).

Pillai-McGarry and Collis-George (1990a) conducted a laboratory study on puddled and non-puddled soils and found that a minimum of three wet/dry cycles was required to begin to regain features of the field structure. In other work (Pillai-McGarry, 1991) using soil blocks from wheel track areas of a self-mulching Vertisol, it was found that three wet/dry cycles did not regenerate the original loose crumb structure of the topsoil. Sarmah *et al.*, (in press) found that one wet/dry cycle gave a marked decrease in strength of the immediate soil surface, and five wet/dry cycles resulted in marked increases in water infiltration.

The structure of Vertisols, because it changes with water content, poses difficulties with measurement and characterisation. A range of methods have been used to assess changes in soil structure such as bulk density, drainable porosity and penetration resistance (Coughlan *et al.*, 1991). The SARAN resin technique for the determination of soil clod density has been found to be one of the better methods to characterise changes in soil structure of Vertisols (Daniells, 1989; McGarry and Malafant, 1987; McGarry, 1989a; Coughlan *et al.*, 1991; McGarry, 1993).

Soil image analysis is gaining considerable use as both a pictorial and quantitative assessor of soil management effects, particularly in Australia. Moran *et al.*, (1988) compared the effect of direct drilling and conventional cultivation for wheat in NSW, Australia. Cavanagh *et al.*, (1991) compared the differences in pore structure attributes in a minimum till trial on a red-brown earth in NSW, Australia. Wild *et al.*, (1991) assessed the long term effects of growing

irrigated cotton on a Vertisol, with contrasting treatments of deep and shallow ripping and gypsum application. Douglas *et al.*, (1992a and b) assessed the effects of wheel traffic on the growth of perennial grass in Scotland. Lytton-Hitchins *et al.*, (1994) compared binary images and derived structure attributes of adjacent bio-dynamic and conventionally managed dairy pastures in Victoria, Australia.

This report is presented in two parts.

Part A provides the Summary of a Masters Thesis entitled "Structure repair of compacted cracking clays using wet/dry cycles" by Mr A.K. Sarmah. The degree was awarded to Mr Sarmah in 1995 and a copy of the final thesis was sent to the CRDC in June 1995. A journal publication of this work is in press with *Soil and Tillage Research*.

Part B provides details of the work carried out by Dr U. Pillai-McGarry and Dr D. McGarry, where the structure repair of a second compacted Vertisol using wet/dry cycles with drying by crops and by evaporation alone was assessed. The main component of this study was undertaken in a controlled environment glasshouse at the University of Queensland. Two journal publications are being prepared from this study.

A summary of the whole project will be presented in the Australian Cottongrower this year.

Project Objectives:

- Part A:**
- (i) To study the effect of wet/dry cycles with drying by evaporation alone in ameliorating degraded furrows in retained hill cotton (at the Fressor site).
 - (ii) To quantify the soil structure changes in (i) and relate them to soil physical properties.
- Part B:**
- (i) To study the relative effect of rotation crops (evaporation alone and no crops) in ameliorating degraded furrows in retained hill cotton (at the Leadbetter site).
 - (ii) To quantify the structure changes in (i) and relate them to growing rotation crops.

Part A: Structure repair of a compacted clay using wet/dry cycles.

Summary of a Master's Thesis, submitted by Mr A. K. Sarmah, Agriculture Department, the University of Queensland.

The effect of wet/dry cycles on repairing a compacted Vertisol was studied. The change in soil structure when intact soil cores from the field were subject to wet/dry cycles, was assessed by infiltration, clod bulk density, shear strength and image analysis of surface morphology. Wetting was done by flooding and by simulated rainfall. Drying was done by surface evaporation.

The study site was located on a farm 12 kilometres south-west of Dalby on the Darling Downs of Queensland. The soil, a typical irrigated soil in that area, had been cultivated for

30 years and furrow-irrigated for the last 20 years. The soil had moderate shrink/swell properties compared to other Vertisols. The detailed methodology and results have been presented in Mr Sarmah's thesis.

The major findings were:

1. Wet/dry cycles repaired soil structure but more than one cycle was necessary for significant repair to occur.
2. Flood wetting was more effective than rain-wetting in producing deeper repair of soil structure. Rain-wetting, being a slower form of wetting than flooding, sealed the soil surface producing an infiltration throttle. Hence the soil wet to shallower depths than in the flood wetting.
3. There was a two-fold increase in infiltration rate after five flood-wet cycles which was also associated with a marked reduction in shear strength. This indicated that wet/dry cycles were effective in repairing soil structure.
4. Increased number of wet/dry cycles decreased the crack sizes and the shrinkage block sizes. This indicated that as the structure improved the soil became less aggregated in large cohesive blocks with large cracks separating the blocks.
5. There was insufficient data available to draw conclusions about a direct correlation between surface morphology parameters and infiltration rates measured by the disc permeameter.

Problems encountered

A part of the project was to produce an image analysis software to quantify the surface morphological features of the soil's surface i.e. size and quantity of cracks and size and quantity of soil blocks. This was not completely achieved as algorithms necessary to define the complexities of naturally cracking soil was a challenge to write in the time allocated and no commercial software was available even for modification. Hence, the surface morphology was characterised manually using a digitiser and software written to specifically characterise the required features.

Part B: Structure repair of a compacted Vertisol, comparing the effect of selected rotation crops with no crops (evaporation alone).

2 MATERIALS AND METHODS

2.1 Site selection

The study site was located at one end of a field (15m from the tail-ditch) on a commercial cotton farm, 10km north-west of Pampas on the Darling Downs of Queensland, Australia. The field has been cultivated for 20 years and furrow irrigated for all of that time. The soil is a Vertisol (Soil Survey Staff, 1975) and is regarded as a high quality, irrigated soil in the area.

The field was selected as McGarry (1992) identified severe soil compaction to 0.35m in the beds and furrows of this field, associated with wet cultivation and traffic.

2.2 Soil physical and chemical properties

The site has been described and chemical analysis (to 0.5m) presented by McGarry (1992). Additionally, a soil sample of the top 0.2m was collected to determine the plastic and liquid limits with the rolling bead (Sowers, 1965) and the drop cone method (Vickers, 1983), respectively, and grain size distribution, and organic carbon content (Heanes, 1984).

2.3 Sampling times

There were three sampling scenarios.

2.3.1 Field

The field site was sampled on each of two dates: mid-May 1993 and early-December 1993. The aim was to assess the effect of wetting and drying by crops in the field. The first sampling date is termed "time zero" in the overall experiment, as this was the time when the soil cores for glasshouse w/d events (specified below) were collected. At that time the field had standing, almost mature sorghum, planted in 3 m beds. At the second sampling date, a mature wheat crop was standing in the field. The crop had been broad-acre sown so both hills and furrows were sown, following soil ripping (to 0.15m) of the hills only, soon after harvesting of the sorghum crop.

It had been proposed to repeat the field sampling exercise after another two or three crops in this same field. However, zero water availability prevented further sowings. The next crop in this field was sown in 1995, after this project terminated.

Soil sampling

On each sampling occasion, four locations were sampled in each of the bed and furrow. Soil strength was recorded using both a pocket penetrometer and a handheld torvane at 0, 0.02, 0.05, 0.1, 0.15, 0.2, 0.3 and 0.4m. As soil strength varies with water content, a soil sample was taken at the same depths for determination of gravimetric soil water content and soil matric potential using the filter paper method (Fawcett and Collis-George, 1967). Soil clods were collected for six depths: 0-0.05, 0.05-0.1, 0.1-0.15, 0.15-0.2, 0.2-0.3 and 0.3-0.4m. Clods were placed in polythene bags and stored in a cold room ($\sim 4^{\circ}\text{C}$) until clod density was determined using the SARAN resin technique (McGarry and Daniells, 1987). All clods were SARAN-coated at the sampled water content.

Seven parameters were derived from lines fitted to the shrinkage data after Coughlan *et al.* (1991). Only five will be presented in this script; α and v_A will be excluded, recognising that the information they provide is repeated by P_e and P_A . The latter express the data in terms of 'porosity' and the former simply a transformation in terms of 'solids'.

These parameters are:

- r: the slope of the line in residual shrinkage
- n: the slope of the line in normal shrinkage
- θ_A : the soil water content at the onset of residual shrinkage (Mg Mg^{-1})
- P_a : the specific volume of air-filled pores at zero water content (m^3Mg^{-1})
- P_A : the specific volume of air-filled pores at the onset of residual shrinkage (m^3Mg^{-1})

Immediately beside the bed and furrow locations, three metal sampling sleeves (120 x 120 x 240 mm length) were hydraulically pushed into the soil. They were then dug out, transported to the laboratory for resin impregnation (McBratney and Moran 1990), sectioned with a diamond saw after curing and subjected to image analysis (Moran *et al.*, 1990). The binary soil pore image for each cube was 512 x 512 pixels over a 120 x 120mm area; giving a resolution of 234 microns per pixel.

Core collection

An hydraulically operated metal push-tube (0.3 m internal diameter and 0.5 m long) was used to collect the intact soil cores. After collection the cores were wrapped with polythene sheet to avoid moisture loss and gently placed in casings of PVC pipe (previously split in two) and bound with strong adhesive tape. Circular PVC discs with drainage holes, held inside the bottom of the casings on a pop-riveted ring, were used as the base for the cores. A total of 97 cores were collected from the site, all from wheel track areas. At this site, the combination of 3 m wide beds, tractors on 3 m centres and 6 m wide cultivating equipment caused all furrows to be wheel track areas, where each of these furrows had been wheeled at every tractor pass.

2.4 Wet/dry experiment

All cores were transported to a glasshouse where, before the start of the wet/dry experiment the PVC casings on each core were temporarily removed and the sides of the soil core coated with latex (MR Rebutex, Thomson Rubber, Brisbane). The soil surface and the base were left uncoated to permit surface evaporation and through-drainage. The casings were then re-assembled and strapped together with heavy duty tape. The purpose of the latex coating was to contain the soil during repeated wetting and drying while permitting soil swelling, and minimising evaporation from the sides.

Design of the wet/dry strategy on the cores was based on five factors:

- (1) The cotton industry recognises that the majority of its soils (cracking clays) respond to wet/dry cycles, to repair structure.
- (2) Past studies succeeded in showing soil structure repair of the topsoil by repeated wetting/drying where the drying was solely by evaporation (Pillai-McGarry and McGarry 1992; Sarmah *et al.* in press). Other field studies have examined the role of rotation crops in drying the soil profile to prevent compaction in subsequent cultivation (Hodgson and Chan 1984; Hulme *et al.* 1991).

- (3) Cotton growers have grown a range of rotation crops (i.e. break crops for cotton) with wheat, sorghum, lab lab and mungbean being popular choices.
- (4) Previous studies by Pillai-McGarry and Collis-George (1990a) and by Pillai-McGarry (1991) showed that it required more than three wet/dry cycles to produce treatment effects on puddled and non-puddled soils.
- (5) These authors along with Sarmah *et al.*, (in press) found that wetting by simulated flood irrigation had a more rapid and pronounced effect on structure regeneration of compacted soil than wetting by simulated rainfall.

The design of the current experiment is, therefore:

- 4 crops: wheat, sorghum, lab lab, mungbean
- no crops: drying solely by evaporation
- up to nine wet/dry (w/d) cycles
- wetting to simulate flood irrigation

For all cores in the crop experiment the soil surface was flood wetted for 30 minutes, drained and then sown. Subsequent flood wetting (to field capacity) occurred when the crop wilted (determined as 30 bars leaf water potential at 12 noon). After each of 3, 6 and 9 w/d cycles the crops were harvested, when they had just commenced flowering (indicating a physiological stage beyond which root growth ceases). In the no crop experiment water was ponded on the surface of each core for 30 minutes under a constant head of water (15-20 mm). The core was then allowed to dry until the core weight was constant over a 48 hour period. Cores were sampled after each of 3, 6 and 9 w/d cycles. The wetting procedure in each experiment simulated furrow irrigation in the field, the common irrigation practice used in Australia for cotton.

Two measures were taken of the "dynamics" of the water added and used during the w/d cycles. In the no crop experiment the cores were weighed before and after wetting and re-weighed periodically to check the weight loss (i.e. water loss). In the crop experiment each core was weighed after wetting and again at harvest - giving the **total evapotranspiration** at each of 3, 6 and 9 w/d cycles. In this study on a clay soil where through drainage is recognised as negligible, the major mechanisms of water loss in the no-crop experiment were evaporation from the soil surface, and in the crop experiment a combination of evaporation and crop transpiration. Through the experiment, the average minimum and maximum temperature range was 25°-30°C, while humidity was 40-50%.

In the crop experiment, three cores were sampled at each sampling event. The cores were prised open, making every effort to break the cores open along natural cleavage planes. In this way, the natural soil structure units down the soil profile, and the root proliferation/density, were exposed. The profiles of the crop experiment were photographed.

In the no crop experiment, 6 cores were sampled at each sampling event, three for strength and clods and three for image analysis. Soil strength and water content measures were taken on one half of the core at the same depths (omitting 0.02m) as in the field. Both a pocket penetrometer and a handheld torvane were used; 10 and 5 measures, respectively taken per

depth. Once the measures were done, that half of the core was carefully excavated down to the next sampling level. Soil clods were sampled from the remaining half for the same depth increments as in the field location, and treated in the same way. Another three cores were carefully split lengthwise and one half laid horizontally on a concrete floor. A metal sampling sleeve (120mm x 120mm x 120mm) was hydraulically pushed into the soil profile. Four sleeves were pushed into each core: 0-120mm, 120-240mm, 240-360mm and 360-480mm. They were then dug out, transported to the laboratory for resin impregnation and image analysis, as with the field samples.

Statistical analysis

Univariate analysis of variance was performed on the clod shrinkage and image analysis data. For each of the crop and no crop experiments, the "time zero" samples were the May 1993 field samples, and subsequent changes in soil structure for each of clod shrinkage data and image analysis were related to them. Means and standard errors were calculated for the soil strength, and the soil water and matric potential data.

3. RESULTS AND DISCUSSION

3.1 Site characterisation

Tables 1 and 2 characterise the soil in terms of its chemical composition, grain size distribution, and plastic and liquid limits. The soil at this site has a high CEC (61-66), low ESP (2.6-5.2) and a poor Ca/Mg ratio (1.3-1.5). Probert *et al.*, (1987) give a CEC range for Vertisols of 20-80 cmol(+)/kg, so this site is at the upper end of the range. Values of ESP >8 have been associated with clay dispersion (Loveday and Pyle, 1973), so surface soil values of 2 and 3 at this site are very low. Cockroft and Tisdall (1978) have related Ca/Mg ratio >2 with good structure, so values of 1.3-1.5 are relatively low. Clay activity (the charge per kg of clay, calculated as CEC/clay.100 in the 0-0.1m layer of this site = 77.5 cmol(+)/kg⁻¹, indicating the clay fraction is dominated by smectite. The sum of these analyses shows the potential for self-repair at the study site is moderate to high.

3.2 SARAN coated clod data

Table 3 summarises the results of the analysis of variance for each of the three experiments. Emphasis here will be given to each of the significant, highest level interactions presented in this table, and only for five parameters: r , n , θ_A , P_α and P_A . The emphasis on the highest level interaction permits investigation of the means (with respective standard errors) of most relevance to resolving the interaction of the treatments with depth.

The field data

Each of n , P_α and P_A gave highly significant interactions for depth x position x crop (Table 3a).

An increase in the value of n shows that for the same change in water content the soil with the greater value of n has a greater decrease in volume, i.e. greater shrinkage (McGarry and Daniells, 1987). This can be seen as a positive effect in terms of this experiment, as more

Table 1 Chemical properties of the soil at the field site (part from McGarry, 1992).

Depth (m)	pH	EC (dS/m)	Cl (mg/kg)	(cmol(+)/kg)				CEC	ESP (%)	Ca/Mg
				Ca	Mg	Na	K			
0 - 0.1	7.8	0.09	29	35	24	1.6	1.60	62	2.6	1.5
0.1- 0.2	8.1	0.11	49	34	25	2.0	1.50	62	3.2	1.4
0.2 - 0.3	8.5	0.11	38	37	26	2.5	0.98	66	3.8	1.4
0.3 - 0.4	8.6	0.13	36	34	26	2.8	0.76	63	4.4	1.3
0.4 - 0.5	8.8	0.12	41	33	25	3.2	0.74	61	5.2	1.3

pH, EC and Cl were determined using a ratio of 1:5 soil : water. Ca⁺⁺,Mg⁺⁺,Na⁺⁺,K⁺ exchangeable cations were extracted using alcoholic 1M NH₄Cl @ pH 8.5 with a pre-wash to remove soluble salts. CEC = the sum of the exchangeable cations (Ca+Mg+Na+K) and ESP = (Na/CEC)%.

Table 2 Particle size analysis, organic carbon content and the water contents at the liquid and plastic limits of the 0-0.1m layer at the field site.

	(mm)	%
Coarse sand	(0.2 - 2)	1
Fine sand	(0.02 - 0.2)	3
Silt	(0.002-0.02)	13
Clay	(<0.002)	80
Organic C		1.3
Plastic limit		
Liquid limit		

Table 3 Results of analysis of variance for seven model parameters expressed as probability levels of the F (variance ratio) value for (a) the field data, (b) the glasshouse no crop and (c) the glasshouse crop experiments, where the probability levels are: $P \leq 0.05 = *$, $P \leq 0.01 = **$, $P \leq 0.001 = ***$, ns = non significant.

(a)	position (p)	crop (c)	p x c	depth (d)	d x p	d x c	d x p x c
r	ns	*	ns	*	ns	ns	ns
n	ns	ns	**	ns	ns	ns	***
θ_A	ns	**	ns	***	ns	ns	ns
P_α	ns	ns	ns	***	***	**	***
P_A	ns	ns	**	***	***	**	***

(b)	wettings (w)	depth (d)	w x d
r	**	**	ns
n	*	***	ns
θ_A	ns	**	***
P_α	***	***	**
P_A	*	***	***

(c)	wettings (w)	crop (c)	w x c	depth (d)	d x w	d x c	d x w x c
r	**	ns	**	***	ns	***	ns
n	ns	***	**	ns	ns	*	***
θ_A	***	ns	**	**	ns	*	*
P_α	ns	***	***	***	*	***	**
P_A	***	***	*	***	**	**	*

shrinkage will lead to greater fracturing and smaller aggregate size. At "time zero" n was significantly less in the furrow than in the hill to 0.15m, showing poorer structure in the furrow (Table 4(i)a). Also evident, n at "time zero" in the furrow to 0.3 gave the lowest values of any field sampling occasion, showing that the cores collected for the glasshouse wet/dry experiments were truly degraded. Comparing means for individual depths for each sampling occasion and sampling location (hill and furrow) shows where there was a significant increase in n between May and December for each of the 0-0.05 and 0.1-0.15m depths in the furrow (Table 4(i)b) and a significant decrease at 0-0.05 in the hill (Table 4(i)c). So, the wetting/drying effect of the wheat crop had improved structure in the furrow, but it was not evident in the hill. Wet soil conditions during ripping, prior to sowing the wheat crop, gave visible slicking and degraded surface soil structure in the hills. This is supported by the comparison of the furrow and hill locations under wheat where the hill had lower n values to 0.4m, significantly less only at 0-0.05m (Table 4(i)d).

Table 4: The means for each of (i) n, (ii) P_{α} and (iii) P_{A} . Following each table of means are the calculated differences for individual depths: (a) hill-furrow, May '93, (b) furrow-furrow, December and May '93, (c) hill-hill, December and May '93, and (d) hill-furrow, December '93.

(i) n	Depth	Furrow		Hill	
		May 1993	December 1993	May 1993	December 1993
		0 - 0.05	0.8939	1.0686	1.1144
0.05 - 0.1	0.9280	1.0010	1.0232	0.9740	
0.1 - 0.15	0.9362	1.0193	1.0170	1.0098	
0.15 - 0.2	0.9690	1.0002	1.0035	0.9921	
0.2 - 0.3	0.9839	0.9877	1.0215	1.0029	
0.3 - 0.4	1.0086	0.9701	1.0085	1.0048	

(a)	May hill	May furrow	(b)	Dec furrow	May furrow	(c)	Dec hill	May hill	(d)	Dec hill	Dec furrow
0 - 0.05	+0.2205 ***			+0.1747 ***			-0.2324 ***			-0.1866 ***	
0.05 - 0.1	+0.0952 *			+0.073			-0.0492			-0.027	
0.1 - 0.15	+0.0808 *			+0.0831 *			-0.0072			-0.0095	
0.15 - 0.2	+0.0345			+0.0312			-0.0114			-0.0081	
0.2 - 0.3	+0.0376			+0.0038			-0.0186			+0.0152	
0.3 - 0.4	-0.0001			-0.0385			-0.0037			+0.0347	

(ii) P_{α}	Depth	Furrow		Hill	
		May 1993	December 1993	May 1993	December 1993
		0 - 0.05	0.2300	0.2509	0.2621
0.05 - 0.1	0.1888	0.2001	0.1549	0.1617	
0.1 - 0.15	0.1366	0.1590	0.1347	0.1495	
0.15 - 0.2	0.1242	0.1400	0.1418	0.1463	
0.2 - 0.3	0.1448	0.1322	0.1410	0.1498	
0.3 - 0.4	0.1497	0.1261	0.1456	0.1531	

(b)	May hill	May furrow	(b)	Dec furrow	May furrow	(c)	Dec hill	May hill	(d)	Dec hill	Dec furrow
0 - 0.05	+0.0321 *			+0.0209			-0.0777 **			-0.0665 *	
0.05 - 0.1	-0.0339 *			+0.0113			+0.0068			-0.0384 *	
0.1 - 0.15	-0.0019			+0.0224			+0.0148			-0.0095	
0.15 - 0.2	+0.0176			+0.0158			+0.0045			+0.0063	
0.2 - 0.3	-0.0038			-0.0126			+0.0088			+0.0176	
0.3 - 0.4	-0.0041			-0.0236			+0.0075			+0.0270	

(iii) P_A

Depth	Furrow		Hill	
	May 1993	December 1993	May 1993	December 1993
0 - 0.05	0.1313	0.1656	0.1639	0.0919
0.05 - 0.1	0.0862	0.1031	0.0526	0.0561
0.1 - 0.15	0.0409	0.0632	0.0380	0.0406
0.15 - 0.2	0.0264	0.0445	0.0375	0.0349
0.2 - 0.3	0.0261	0.0342	0.0387	0.0347
0.3 - 0.4	0.0370	0.0270	0.0387	0.0362

(c)	May hill	May furrow	(b)	Dec furrow	May furrow	(c)	Dec hill	May hill	(d)	Dec hill	Dec furrow
0 - 0.05	+ 0.0326 **			+ 0.0343 **			- 0.0720 ***			- 0.0737 ***	
0.05 - 0.1	- 0.0336 **			+ 0.0169			+ 0.0035			- 0.047 ***	
0.1 - 0.15	- 0.0029			+ 0.0223 *			+ 0.0026			- 0.0226 *	
0.15 - 0.2	+ 0.0111			+ 0.0181 *			- 0.0026			- 0.0096	
0.2 - 0.3	+ 0.0126			+ 0.0081			- 0.0040			+ 0.0005	
0.3 - 0.4	+ 0.0017			- 0.0100			- 0.0025			+ 0.0092	

At "time zero" P_a was significantly greater in the 0-0.05m layer of the hill than in the furrow (Table 4(ii)a). This trend reversed in the 0.05-0.1m layer, showing the poor, initial state of the hill below 0.05m. The wheat crop did not increase porosity in the furrow or the hill (Table 4(ii)b and c). As with n the wet ripping of the hills degraded the immediate soil surface, significantly ($P \leq 0.01$) reducing porosity by almost 8% (Table 4(ii)c). Again, similar to n , structure in the furrow (0-0.1m layers) in December is significantly better in the furrow than in the hill (Table 4(ii)d).

The trends for P_A correspond with P_a , though for the latter significance levels are greater and there are more of them. Noticeable is the improvement in porosity from May to December in the furrow, significant at three depths to 0.2m (Table 4(iii)b). The better porosity in the furrow than in the hill in December is significant to 0.15m (Table 4(iii)d).

The no crop experiment

Each of θ_A , P_a and P_A gave highly significant interactions for wettings x depth (Table 3b).

The parameter θ_A gave a $P \leq 0.001$ level interaction. A lower value of θ_A has been related to poorly structured, massive soils that have increased parallel particle arrangement, hence less potential for water holding than a soil with a more edge-face arrangement (McGarry and Daniells, 1987). A general increase in θ_A , to increasingly greater depths, as number of w/d cycles increases is evident in Table 5(i). For any one depth (all but 2) all θ_A values, with wet dry cycles, are greater than the May 1993 values. The most significant increases are for 9 w/d cycles, highly significant to 0.15-0.2m (Table 5(i)).

Table 5 The means of (i) θ_A (ii) P_a and (iii) P_A for "time zero", i.e. the furrow in May 1993, and after 3, 6 and 9 wet/dry cycles for the no crop experiment. Following each table of means is the difference between the mean of each wet/dry cycle and the mean for "day zero", with the significance level. A + shows an increase and a - shows a decrease from "time zero".

(i) θ_A

Depth	Furrow May '93	wet/dry cycles		
		3	6	9
0 - 0.05	0.1168	0.1265	0.1381	0.1151
0.05 - 0.1	0.1211	0.1279	0.1348	0.1397
0.1 - 0.15	0.1229	0.1379	0.1385	0.1485
0.15 - 0.2	0.1295	0.1436	0.1318	0.1473
0.2 - 0.3	0.1326	0.1363	0.1377	0.1410
0.3 - 0.4	0.1335	0.1408	0.1299	0.1367

Depth	wet/dry cycles		
	3	6	9
0-0.05	+0.0096*	+0.0212***	-0.0017
0.05 - 0.1	+0.0068	+0.0137*	+0.0185**
0.1 - 0.15	+0.0149**	+0.0156**	+0.0255***
0.15 - 0.2	+0.0140*	+0.0023	+0.0177**
0.2 - 0.3	+0.0037	+0.0051	+0.0084
0.3 - 0.4	+0.0072	-0.0036	+0.0031

(ii) P_a

Depth	Furrow May '93	wet/dry cycles		
		3	6	9
0 - 0.05	0.2300	0.1884	0.1882	0.2551
0.05 - 0.1	0.1888	0.1643	0.1699	0.1740
0.1 - 0.15	0.1366	0.1601	0.1490	0.1639
0.15 - 0.2	0.1242	0.1604	0.1502	0.1640
0.2 - 0.3	0.1448	0.1501	0.1590	0.1614
0.3 - 0.4	0.1497	0.1571	0.1680	0.1683

Depth	wet/dry cycles		
	3	6	9
0-0.05	-0.0415***	-0.0418***	+0.0251*
0.05 - 0.1	-0.0244*	-0.0188	-0.0147
0.1 - 0.15	+0.0235*	+0.0124	+0.0273*
0.15 - 0.2	+0.0362**	+0.0260*	+0.0398***
0.2 - 0.3	+0.0053	+0.0142	+0.0166
0.3 - 0.4	+0.0074	+0.0183	+0.0184

(iii) P_A

Depth	Furrow	wet/dry cycles		
	May '93	3	6	9
0 - 0.05	0.1313	0.1043	0.0818	0.1680
0.05 - 0.1	0.0862	0.0714	0.0534	0.0651
0.1 - 0.15	0.0409	0.0534	0.0412	0.0465
0.15 - 0.2	0.0264	0.0377	0.0374	0.0407
0.2 - 0.3	0.0261	0.0469	0.0500	0.0416
0.3 - 0.4	0.0370	0.0509	0.0584	0.0486

Depth	wet/dry cycles		
	3	6	9
0-0.05	-0.0269*	-0.0495***	+0.0367**
0.05 - 0.1	-0.0147	-0.0327**	-0.0210
0.1 - 0.15	+0.0125	+0.0003	+0.0096
0.15 - 0.2	+0.0113	+0.0110	+0.0143
0.2 - 0.3	+0.0208	+0.0239	+0.0155
0.3 - 0.4	+0.0139	+0.0214	+0.0116

Nine w/d cycles were required to significantly increase P_a in the 0-0.05m layer, relative to "time zero" in May 1993 (Table 5(ii)). At 3 w/d P_a significantly decreased from "time zero" to 0.1m. Only from 3 w/d did the deeper soil layers (0.1-0.2m) increase in P_a with the greatest increase ($P \leq 0.001$) at 9 w/d. Slaking of the top soil under flood wetting may explain the reduced porosity in surface layers, showing light cultivation is required to break-up surface crusting and stimulate aggregate formation even in this highly resilient soil. P_a continues to improve up to 9 w/d in the deeper soil layers (0.2-0.4m), showing that without crops, many repeated w/d cycles are required to improve structure status. The trends for P_A correspond with P_a though comparable to the field situation P_a gives greater significance levels to greater depth (Table 5(iii)).

The crop experiment

Each of n , θ_A , P_a and P_A gave significant interactions for depth x wettings x crop (Table 3c).

The parameter n gave the most significant ($P \leq 0.001$) interaction. All significant changes in n relative to "time zero" were positive (Table 6(i)). Lab lab and mung bean gave a greater number of and more significant increases in n than wheat and sorghum. At 6 w/d cycles, mung bean gave significant increases in n to 0.3m. Lab lab achieved this same effect at 9 w/d. Sorghum only gave a significant increase to 0.1m (at 3 w/d) and this did not improve up to 9 w/d. Wheat gave a significant increase in n to 0.15m at 3 w/d but this effect lessened, so that at 9 w/d the only significant increase was in the top 0.05m.

The parameter θ_A gave the lowest level of significance ($P = 0.05$) for the depth x wettings x crop interaction and this is reflected in Table 6(ii). Where there are few significant changes with time over the "time zero" data. Significant, positive increases in n (seen as indicating better structured soil) occur only at 6 and 9 w/d cycles. Comparable to n , above, lab lab and

mung bean give more significant (up to $P \leq 0.001$) improvements to greater depth (to 0.15m) than sorghum or wheat, but they are achieved only at 9 w/d. At 6 w/d sorghum and wheat significantly improve θ_A at only one depth (0.05-0.1m), an effect carried through to 9 w/d only by wheat. Below the 0.1-0.2m depth, θ_A significantly decreases under sorghum and wheat at 3 w/d and for lab lab and mung bean at 6 w/d. These negative effects do not occur at 9 w/d, showing that 9 w/d cycles are required to improve soil structure (in terms of θ_A) deeper in the soil.

Both P_α and P_A gave significant interactions of depth x wettings x crop, being slightly better for P_α than P_A ; $P = 0.01$ and $P = 0.02$, respectively (Table 3c). There were high values of P_α at "time zero" for each of the 0-0.05 and 0.05-0.1m layers (Table 6(iii)), consequently there were no significant increases in P_α with w/d cycles under any crop. Significant increases occurred only for lab lab and mung bean in the 0.10-0.4m layers, especially at 3 w/d. There is a distinct trend for P_α to decrease with increased number of w/d cycles under all crops. One reason was observed during core sampling in the glasshouse. As w/d cycles increased it became most difficult to sample composite soil clods, i.e. clods composed of many aggregates. Fracturing was so great that clods tended to be individual peds, leading to decreased porosity with time.

The parameter P_A again gives significant decreases from "time zero" for the 0-0.1 layers, the difference increasing with number of w/d cycles (Table 6(iv)). Below 0.1m each of lab lab and mung bean gave strongly significant (up to $P \leq 0.001$) increases in P_A to 0.4m, particularly for 3 and 6 w/d cycles. As with P_α , differences from the "time zero" data are at a minimum at 9 w/d cycles, as a result of sampling individual soil peds.

Comparison of results of the no crop and crop experiments

The relative effects of the two experiments can be compared using the means of θ_A , P_α and P_A (Tables 5 and 6); the common parameters in each experiment (that gave a significant interaction at the highest level). For θ_A , the no crop means at 9 w/d cycles range from 0.1397 to 0.1485 for the 0.05-0.2m layers. Of the four crops, only lab lab and mung bean achieved these values (a range of 0.1364-0.1464 for the same depths) at 9 w/d. So in terms of θ_A the crops did not achieve a better structure state. For P_α , the no crop means at 9 w/d cycles ranged from 0.1614 to 0.1740 in the 0.05-0.4m layers. Of the four crops, only mung bean at 3 w/d cycles gave comparable values (0.1705-0.1872) but these values lessened by 9 w/d cycles. Sorghum and wheat did not achieve the no crop values even by 9 w/d cycles.

It may be unrealistic to compare results of the clod analysis between the two experiments, as each experiment produced different structure states with time, that may influence clod data. The intense soil fracturing beneath the crops would tend to provide individual soil aggregates as clods, so causing porosity to apparently decrease with time. If it had been possible to sample very large, composite-aggregate clods then porosity may have decreased with time.

Table 6 The means of (i) n , (ii) θ_A (iii) P_α and (iv) P_A for "time zero", i.e. the furrow in May 1993, and after 3, 6 and 9 wet/dry cycles under each of four crops: lab lab, mung bean, sorghum and wheat. All means have increased from "time-zero" (May '93), unless in italic where there has been a decrease. Significance of the difference is given as a probability level, where $P \leq 0.05 = *$, $P \leq 0.01 = **$, $P \leq 0.001 = ***$.

(i) n	Depth	"Time-zero"	3 wet/dry				6 wet/dry				9 wet/dry			
			Lab lab	Mungbean	Sorghum	Wheat	Lab lab	Mungbean	Sorghum	Wheat	Lab lab	Mungbean	Sorghum	Wheat
	0-0.05	0.8939	0.9835 ***	1.0116 ***	1.0169 ***	1.0402 ***	0.9180	0.9846 ***	1.0193 ***	1.0444 ***	1.0871 ***	1.0710 ***	0.9530 *	0.9494 *
	0.05-0.1	0.9280	1.0610 ***	0.9622	0.9904 *	1.0099 **	1.0027 **	1.0716 ***	0.9732	1.0042 **	1.0514 ***	1.0341 ***	0.9693	0.9702
	0.1-0.15	0.9362	1.0058 *	1.0083 **	0.9771	1.0000 *	1.0011 *	1.0194 **	0.9417	0.9773	1.0457 ***	1.0231 **	0.9742	0.9634
	0.15-0.2	0.9690	1.0340 *	1.0010	0.9695	0.9613	1.0158	1.0477 **	0.9556	0.9524	1.0516 **	1.0128	0.9997	0.9614
	0.2-0.3	0.9839	1.0255	1.0082	0.9722	0.9510	0.9999	1.0501 *	0.9393	0.9663	1.0416 *	1.0080	0.9832	0.9694
	0.3-0.4	1.0086	1.0483	1.0324	0.9629	0.9508	0.9915	1.0372	0.9402	0.9501	1.0348	1.0149	0.9757	0.9654
(ii) θ_A	Depth	"Time-zero"	Lab lab	Mungbean	Sorghum	Wheat	Lab lab	Mungbean	Sorghum	Wheat	Lab lab	Mungbean	Sorghum	Wheat
	0-0.05	0.1168	0.1108	0.1163	0.1129	0.1094	0.1116	0.1071	0.1249	0.1286	0.1365 **	0.1468 ***	0.1263	0.1234
	0.05-0.1	0.1211	0.1209	0.1252	0.1233	0.1166	0.1154	0.1213	0.1386 **	0.1366 *	0.138 **	0.1459 ***	0.1323	0.136 **
	0.1-0.15	0.1229	0.1244	0.1320	0.1166	0.1166	0.1225	0.1063 *	0.1256	0.1330	0.1464 ***	0.1390 *	0.1335	0.1329
	0.15-0.2	0.1295	0.1208	0.1217	0.1143 *	0.0904 *	0.1286	0.1143 *	0.1281	0.1294	0.1404	0.1364	0.1351	0.1292
	0.2-0.3	0.1326	0.1188 *	0.1255	0.1154 *	0.0902 *	0.1126 *	0.1199 *	0.1347	0.1285	0.1388	0.1383	0.1173 *	0.1286
	0.3-0.4	0.1335	0.1195 *	0.1318	0.1166 *	0.0917 *	0.1201 *	0.1120 *	0.1192 *	0.1318	0.1374	0.1405	0.1239	0.1314
(iii) P_α	Depth	"Time-zero"	Lab lab	Mungbean	Sorghum	Wheat	Lab lab	Mungbean	Sorghum	Wheat	Lab lab	Mungbean	Sorghum	Wheat
	0-0.05	0.2300	0.2022 ***	0.2127 *	0.1981 ***	0.1925 ***	0.1945 ***	0.1745 ***	0.2003 ***	0.2068 **	0.1946 ***	0.197 ***	0.173 ***	0.1890 ***
	0.05-0.1	0.1888	0.1794	0.1872	0.1467 *	0.1461 *	0.1639 *	0.1625 *	0.1674 *	0.1758	0.1674 *	0.1700 *	0.1518 *	0.1551 *
	0.1-0.15	0.1366	0.1642 ***	0.1725 ***	0.1302	0.1236	0.153 *	0.1529 *	0.1296	0.1267	0.1611 **	0.1600 **	0.1379	0.1390
	0.15-0.2	0.1242	0.1563 ***	0.1793 ***	0.1180	0.1102	0.1616 ***	0.1547 ***	0.1235	0.1299	0.1578 ***	0.1406 *	0.1348	0.1282
	0.2-0.3	0.1448	0.1520	0.1705 *	0.1143	0.1110 *	0.1558	0.1518	0.1372	0.1268 *	0.1501	0.1420	0.1279 *	0.1289 *
	0.3-0.4	0.1497	0.1550	0.1769 **	0.1293 *	0.1178 *	0.1547	0.1596	0.1276 *	0.1379	0.1528	0.1573	0.1472	0.1369
(iv) P_A	Depth	"Time-zero"	Lab lab	Mungbean	Sorghum	Wheat	Lab lab	Mungbean	Sorghum	Wheat	Lab lab	Mungbean	Sorghum	Wheat
	0-0.05	0.1313	0.1173	0.1225	0.1074 **	0.1042 ***	0.1128 *	0.1005 ***	0.1063 ***	0.1008 ***	0.0806 ***	0.0825 ***	0.0786 ***	0.0833 ***
	0.05-0.1	0.0862	0.0839	0.0839	0.0542 ***	0.0597 ***	0.0794	0.0828	0.0653 **	0.0733	0.0598 ***	0.0604 ***	0.0553 ***	0.0560 ***
	0.1-0.15	0.0409	0.0622 **	0.0650 **	0.0446	0.0443	0.0672 ***	0.0772 ***	0.0388	0.0320	0.0466	0.0542	0.0388	0.0391
	0.15-0.2	0.0264	0.0579 ***	0.0805 ***	0.0348	0.0450 *	0.0670 ***	0.0766 ***	0.0326	0.0295	0.0456 *	0.0386	0.0339	0.0326
	0.2-0.3	0.0261	0.0575 ***	0.0707 ***	0.0335	0.0423 *	0.0717 ***	0.0762 ***	0.0324	0.0329	0.0463 **	0.0385	0.0438 *	0.0383
	0.3-0.4	0.0370	0.0600 **	0.0709 ***	0.0483	0.0531 **	0.0697 ***	0.0841 ***	0.0414	0.0411	0.0503	0.0473	0.0576 **	0.0417

3.3 Image analysis

The field data

The binary images of the hill and furrow profiles in each of May and December 1993 are presented (Figs. 1 and 2). There are marked contrasts in pore (black) size, shape and location in the profiles both between locations and between times. Most apparent is the high density (white) nature of the material to 0.24m in the May '93 furrows. There are widely spaced, vertical cracks to 0.24m as commonly found in highly compacted furrows. The structural state of the furrows changes little from May to December '93. In May, there is good aggregation to approx. 0.07m, but by December fine aggregation is restricted to the top 0.01 or 0.02m with large (0.01-0.03m) angular blocky peds to 0.07m.

The no crop experiment

Generally, wet/dry cycles with no crop did not change soil structure even up to 9 w/d (Fig. 3). At 3 w/d cycles the fine surface aggregation in the furrow at "time zero" (May '93) has been lost, and the soil surface is massive with widely spaced cracks. Cracks in the 0.3-0.4m layer at 3 w/d cycles are below the compacted layer visible in the field and represent natural soil structure. At 6, then 9 w/d the surface soil becomes more crusted, and there are a few cracks to approx. 0.2m.

The crop experiment

With crops and wet/dry cycles structure - return activity and the depth to which it occurs is far greater than with no crop. Wheat and sorghum produce dense angular blocky peds to approx. 0.2m, 0.26m and 0.45m with 3, 6 and 9 w/d cycles (Fig. 4). The size of ped also decreases with time with sorghum in particular producing small aggregate sizes but only to 0.1m by 9 w/d cycles. Lab lab and mung bean produced better structure (smaller structured units with more interconnected cracks). At each of 6 and 9 w/d, the soil cores were quite moist, so cracking was not as evident. However, very fine pores are evident throughout the profiles (to 0.45m) for both crops, showing a high degree of structure repair to depth. This relates well to deeper rooting in lab lab and mung bean (Fig. 5). Generally, the structure at 9 w/d under sorghum and wheat was achieved at 6 w/d by mung bean and lab lab. The 9 w/d cycles with mung bean and lab lab gave a much finer structure with small peds and fine pores.

3.4 Strength

Field

After only one season of wheat there was a marked decrease (ranging from 23%-50%) in strength (both shear strength and penetration resistance) in the 0.1-0.2m depths of both furrow and hill (Figure 6b and d). This reduction was evident despite the soil being drier after wheat (Figure 6f) indicating that the reduction was due to the soil being less cohesive at these depths. A zone of high strength after wheat at 0.05m depth was beyond the measuring limit of the shear vane and hence could not be recorded. The low water content combined with the denseness of the structure would have contributed to high strength at this depth.

Figure 1: Binary images of soil structure for the field samples at "time zero", i.e. May 1993; three images for each of the (a) furrow and (b) hill. In all images, black = soil pore (air space) and white - soil solid.

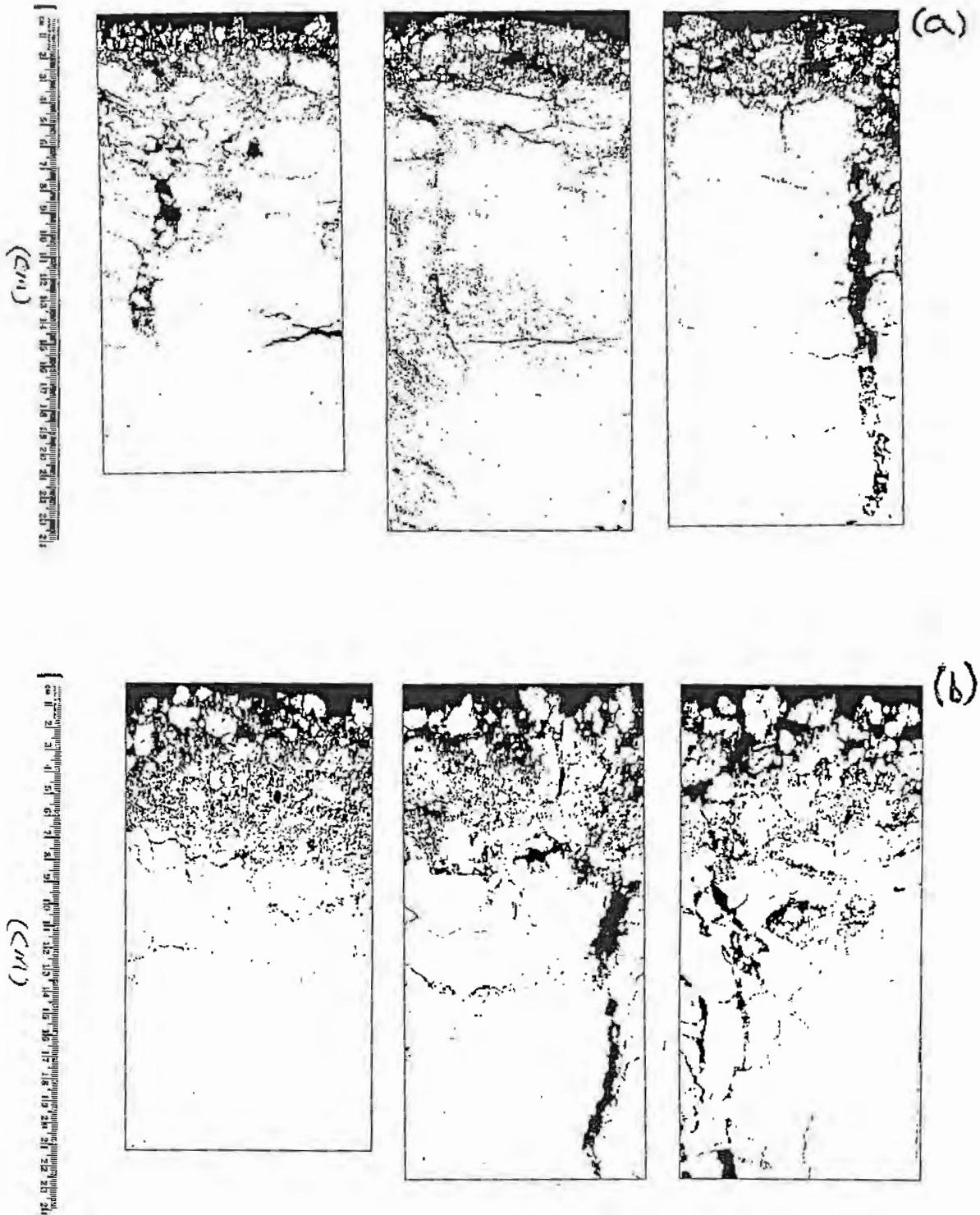


Figure 2: Binary images of soil structure for the field samples in December 1993, i.e. at maturity of the wheat crop for each of the (a) furrow and (b) hill.

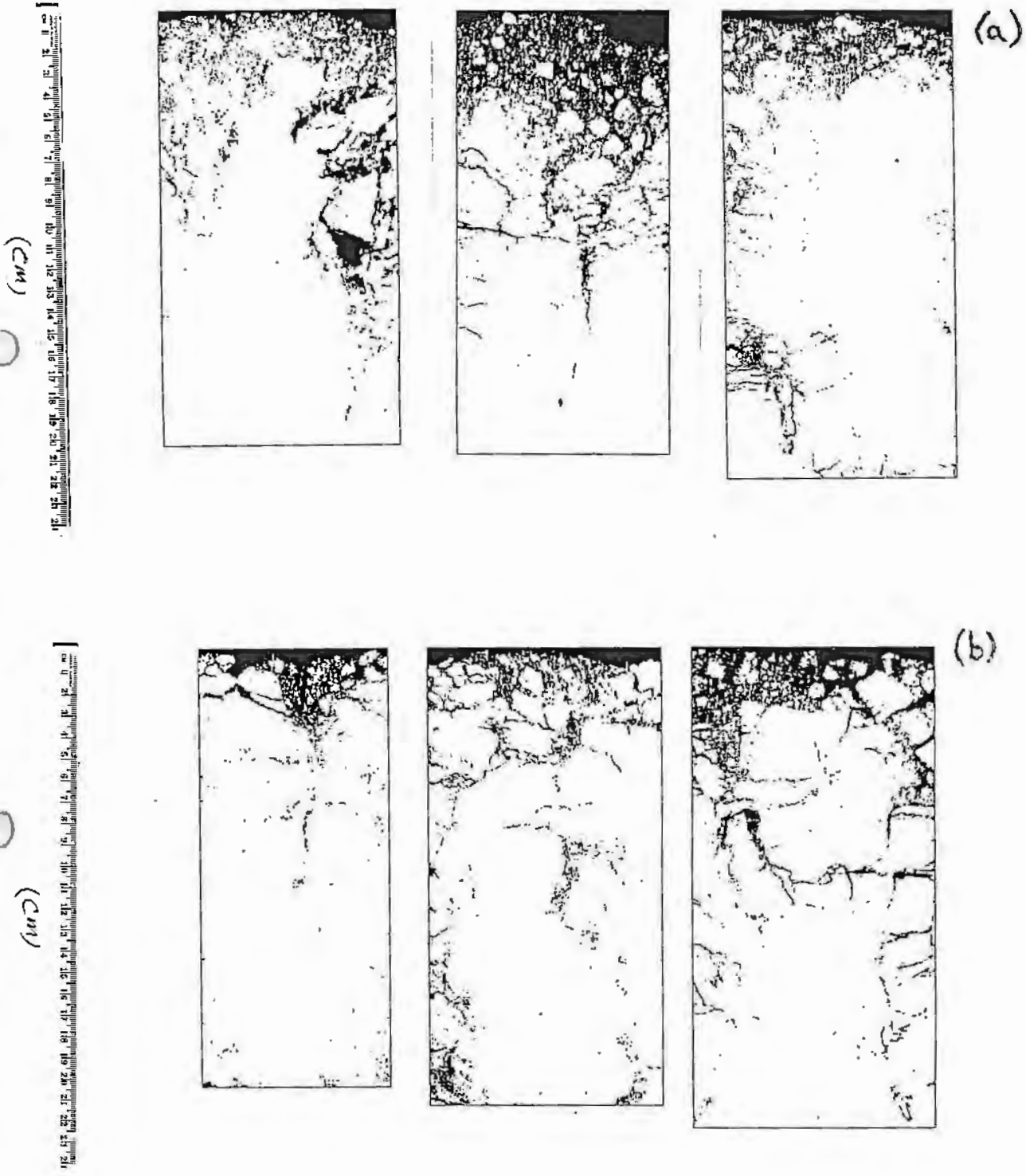


Figure 3: Binary images of one profile for each of 3, 6 and 9 wet/dry cycles of the no crop experiment.

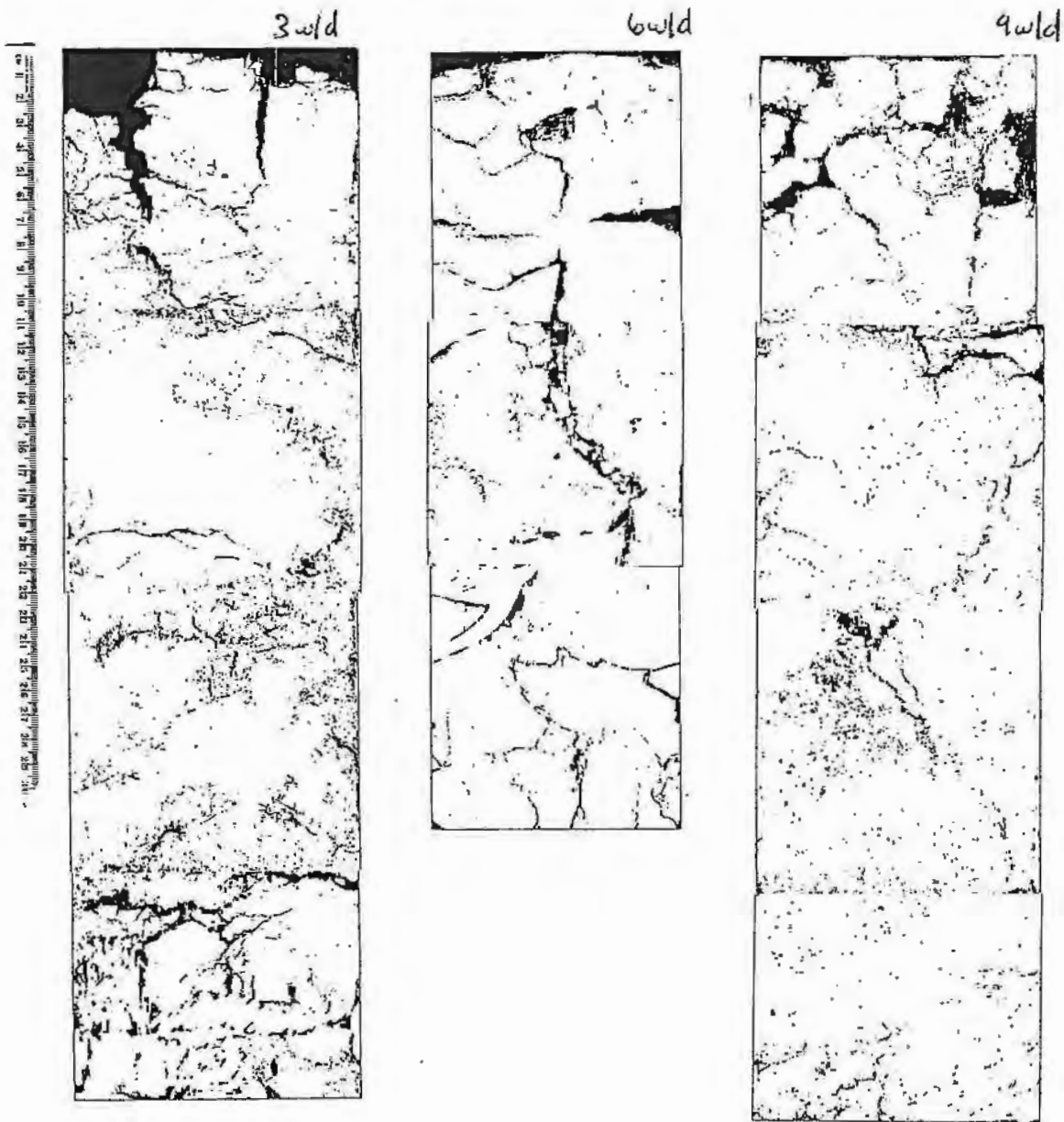
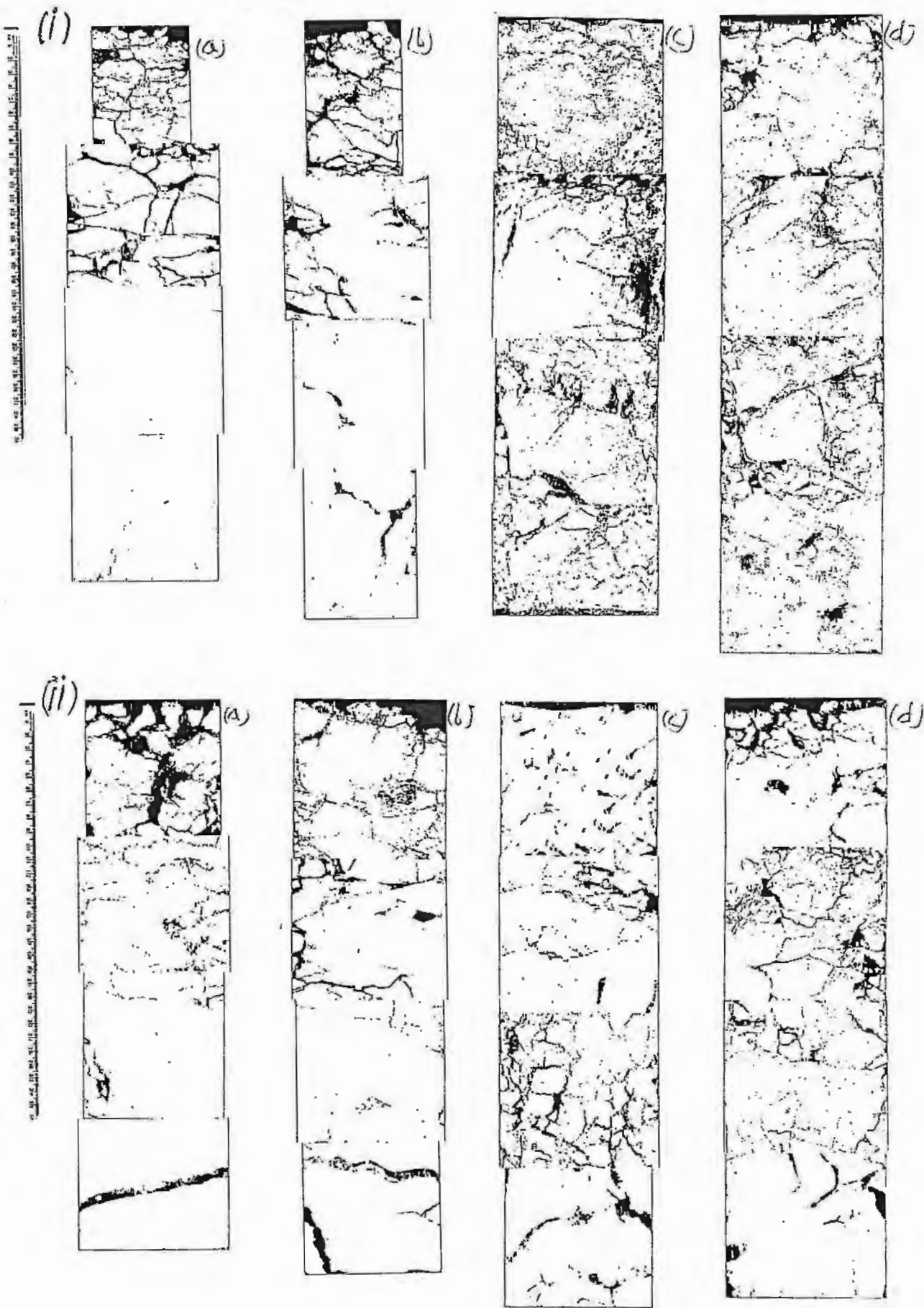
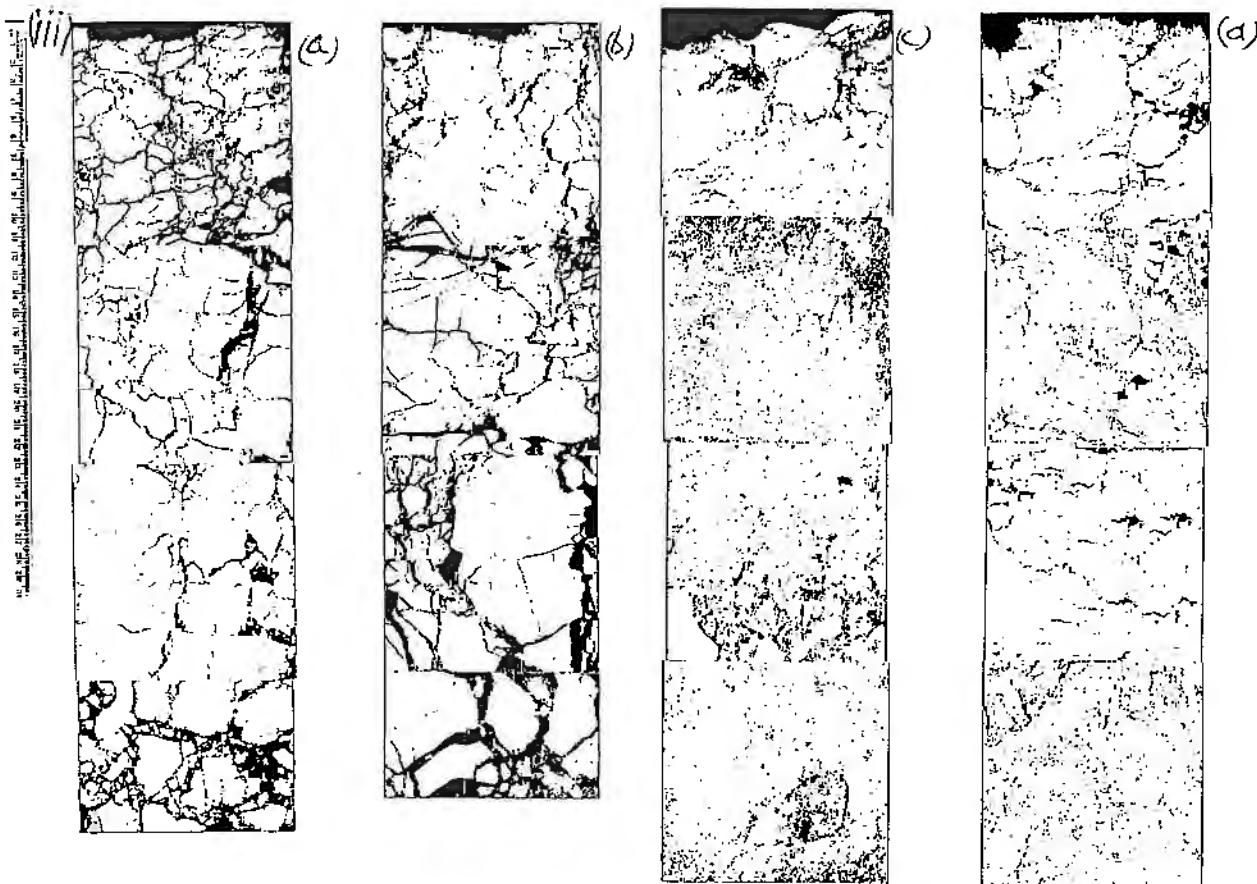


Figure 4: Binary images of one profile for each of (i) 3, (ii) 6 and (iii) 9 wet/dry cycles of each of (a) sorghum, (b) wheat, (c) mung bean and (d) lab lab for the crop experiment.





As would be expected the furrow had a greater decrease in strength compared to the hill after wheat though the values remained higher for the furrow than the hill. The dryness of the furrow compared to the hill indicates that the wheat extracted more water from the furrow thus causing greater shrinkage of the soil and hence producing greater potential for soil fragmentation. The shear vane was more sensitive to the change in strength with changes detected to a greater depth (0.3m) than the penetrometer.

The no crop experiment

Strength measurements were only taken for the no crop experiment. For these cores the soil was drier beyond 0.2m depths after 3 w/d compared to six and nine w/d (Figure 7c). Associated with this dryness were higher penetrometer strengths (Figure 7b). Hence even after 3 w/d the soil was structurally cohesive beyond 0.2m depth.

With further wet/dry cycles there was a slight decrease in the shear vane strength throughout the core which became significantly marked after nine wet/dry (Figure 7a). This trend was not so obvious in the penetrometer results, where the lower water contents after nine wet/dry, particularly in 0.05-0.1m gave higher strengths after nine w/d at these depths than for the six w/d.

In summary, one season of wheat reduced the strength by up to 50% of the soil to 0.3m depth in the field. In the core experiment 3 wet/dry cycles with surface evaporation was insufficient to cause structure repair. Even after nine wet/dry cycles the soils remained wet to depth causing insufficient shrinkage for rapid structural disaggregation.

The shear vane was more sensitive to structural changes than the penetrometer.

Figure 5: Photographs of soil profiles from the split cores of the glasshouse crop experiment. Each of (a) wheat, (b) sorghum, (c) lablab and (d) mungbean are presented after 6 wet/dry cycles. All photographs are at the same scale (the ruler visible in (d) is 0.3m long)

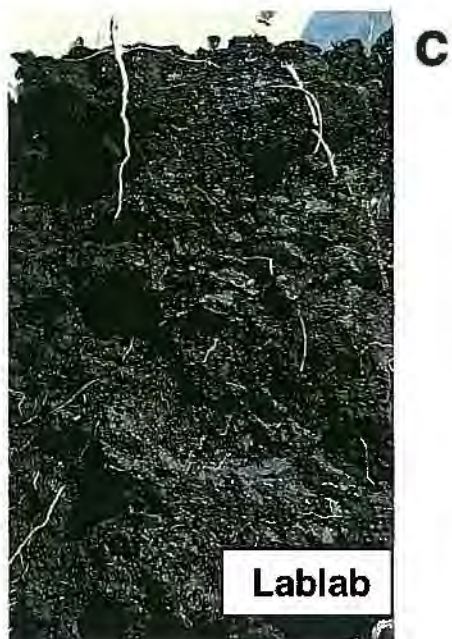
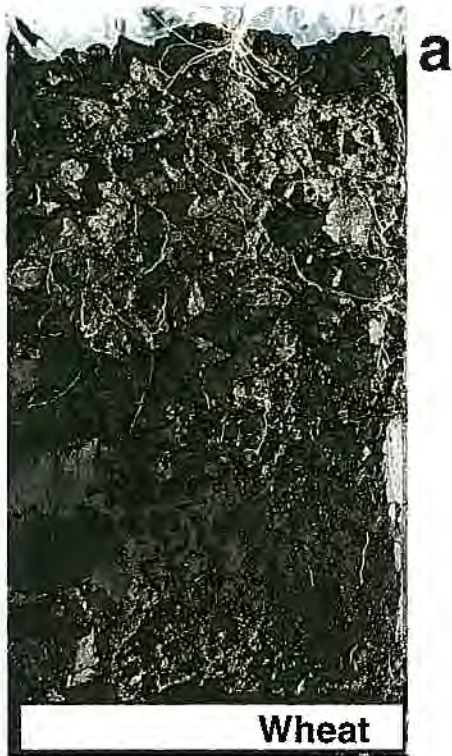


Figure 6: Means and standard errors of field data collected after sorghum (May '93): (a) shear strength, (b) penetration resistance and (c) water content; and after wheat (December '93): (b) shear strength, (d) penetration resistance and (e) water content.

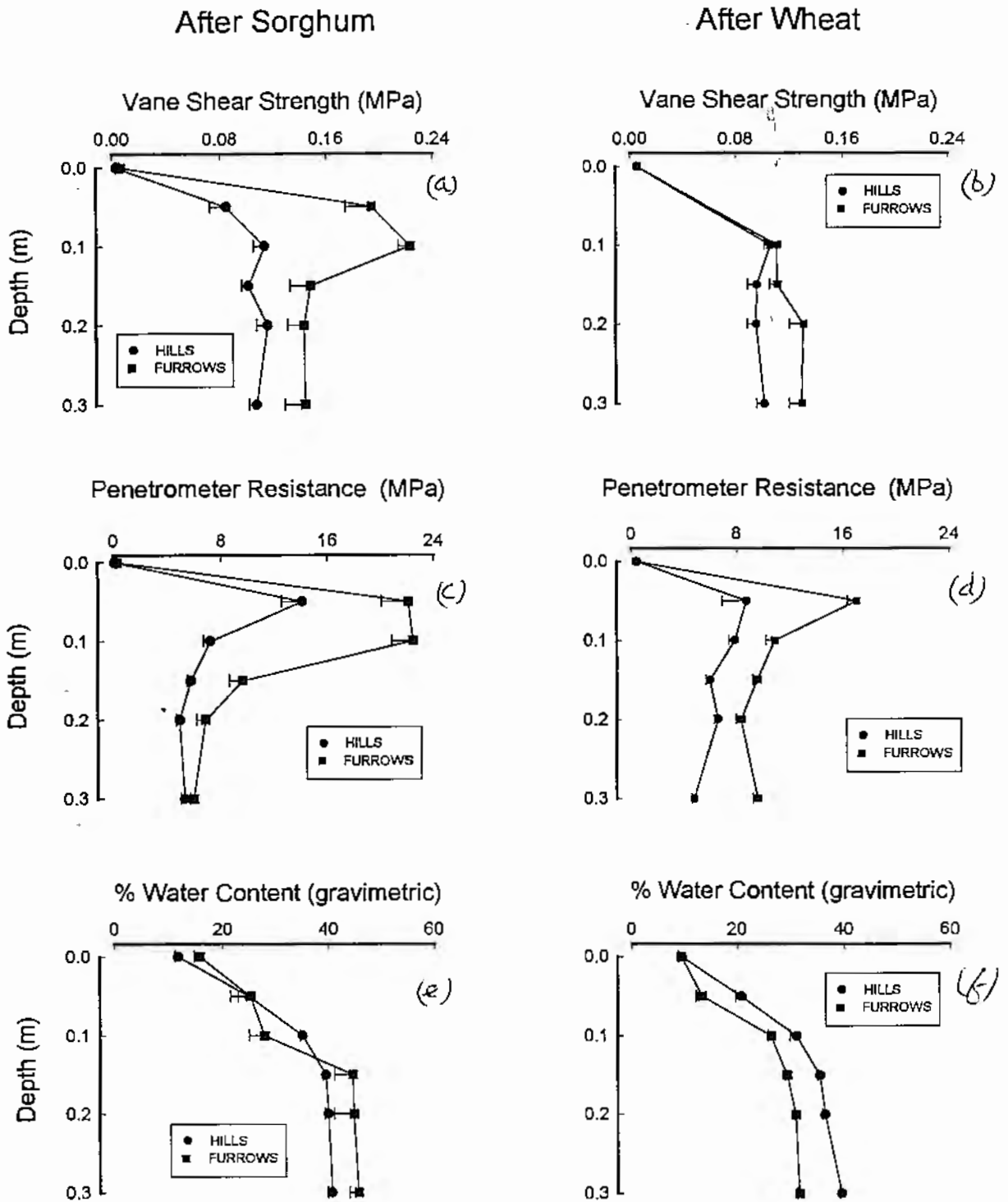
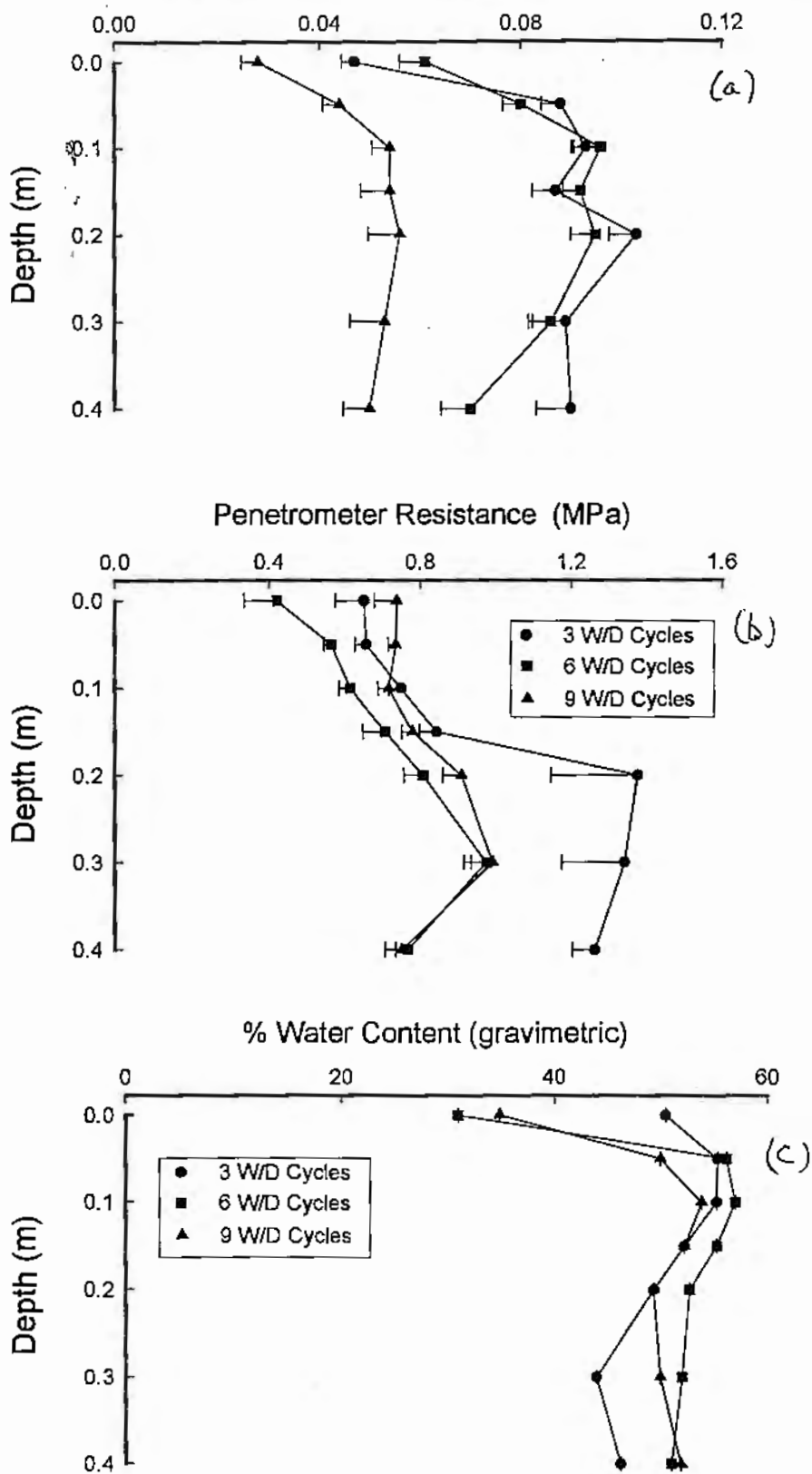


Figure 7: Means and standard errors of glasshouse data collected in the no crop experiment after 3, 6 and 9 wet/dry cycles: (a) shear strength, (b) penetration resistance and (c) water content.



3.5 Water use

Table 7 presents the total evapotranspiration that occurred prior to each sampling event. The legumes used more water during growth compared to wheat and sorghum. The greater drying potential of the legumes would indicate that the soil under the legumes would shrink to a greater extent than either wheat or sorghum. On subsequent wetting of the soil it would also swell to a greater extent, thus producing greater soil activity conducive to good structure formation. Evidence of this is seen in the clod shrinkage results and the soil binary images, where the legumes have much larger air filled pores and show much finer porosity to depth.

For all crops the water use after 9 w/d was reduced compared to 6 w/d. Though not evident from the dry matter yield data (Table 8), it was noted at harvest, after 9 w/d, that all plants began to senesce. Further study would be required to ascertain if 9 w/d produced soil porosity to such an extent that it became detrimental to crop growth. Reduction in soil-root contact would reduce water uptake as well as nutrient uptake necessary for plant growth.

It is interesting to note that except for the lab lab the greatest water use at 6 w/d did not relate to the greatest dry matter yield. However, this does not reflect on possible positive trends in grain yields in these crops.

Table 7: Evapotranspiration with standard derivation in parenthesis from the cores with crops after three, six and nine wet/dry (w/d) cycles.

Crop	Evapotranspiration (mm)		
	3 w/d	6 w/d	9 w/d
Sorghum	75 (14)	140 (7)	95 (4)
Wheat	78 (14)	145 (6)	100 (1)
Lab lab	178 (25)	207 (17)	189 (12)
Mung bean	154 (25)	178 (31)	149 (16)

Table 8: Crop dry weight (t/ha) at harvest after three, six and nine wet/dry cycles. Standard derivations are in parenthesis.

Crop	3 w/d	6 w/d	9 w/d
Sorghum	2.9 (0.7)	3.0 (0.3)	4.1 (0.2)
Wheat	1.4 (0.3)	1.4 (0.1)	1.7 (0.2)
Lab lab	3.6 (0.3)	5.8 (0.9)	4.7 (1.1)
Mung bean	3.6 (1.8)	3.5 (0.8)	3.5 (1.3)

4 CONCLUSIONS

In conclusion, the lab lab and mung bean crops improved soil structure to greater depths and more rapidly than the wheat and sorghum. This was evident in the visible soil structure, greater evapotranspiration, finer porosity in the images, reduced soil strength and greater porosity in the soil clods. The structure repair would have been greater if these experiments had been conducted on hill material - the plants would have developed better root systems, more rapidly in the loose surface mulch. The structure repair would then have probably encompassed the whole hill, including hard shoulders on the sides of the hills. Wet/dry cycles have again been shown to be a critical method of repairing compaction in these soils. Even the moderate swell/shrink soil showed good potential for repair (with evaporation the only drying medium). Generally, the greatest improvements occurred after six wet/dry cycles, particularly in terms of deep fracturing and small aggregate formation below 0.2m, as seen in the soil images and soil profile photographs. Shear strength was a more sensitive method of demonstrating treatment effects and to greater depth than the penetrometer. The clod data showed that one season of a wheat "break crop" in the field significantly increased porosity to 0.2m. The benefit of this is that shallow ripping of furrows after the wheat crop (if the soil was at or below the plastic limit) would break-out this better structured soil and assist aggregate formation. These finer aggregates may then be incorporated into the hill, giving better hill/furrow demarcation.

APPENDIX 1: BUDGET

	Salary*	Travel	Operating	Capital	Total
	\$	\$	\$	\$	\$
1991/1992	26,601	2,280	11,120	12,580	52,581
1992/1993	36,601	2,836	9,905	-	49,342
1993/1994	24,083	2,726	7,757	-	14,580
1994/1995	12,949	-	3,947	-	16,896

* Used mainly for Mr Sarmah's student stipend, and the employment of a research assistant for 12 months.

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