CHAPTER 5

SOIL SWELLING, AND NEUTRON MOISTURE METER AND GAMMA DENSITY METER CALIBRATIONS

5.1 INTRODUCTION

The importance of swelling to the physical behaviour of vertisols, together with weaknesses in current methods of accounting for swelling, was described in Section 3.2. An experiment was undertaken to examine the nature of swelling in the field, and its relationship to swelling measured in the laboratory. This experiment is described in Section 5.2. Because of the wide use of the neutron moisture meter in measurement of soil water in the current study, a procedure for neutron moisture meter and gamma density meter calibration, in which the findings of Section 5.2 are taken into account, is described in Section 5.3.

5.2 FIELD MEASUREMENT OF SOIL SWELLING

5.2.1 Introduction

Current theories to account for soil swelling in field measurements assume that swelling is normal (changes in water content equal changes in specific volume (v)), and equidimensional (equal in horizontal and vertical planes). Data on which these theories are based come from either sequential sampling using small diameter undisturbed cores (e.g. Berndt and Coughlan, 1977), or from measurements of shrinkage of disturbed cores or clods (e.g. Yule and Ritchie, 1980a).

Although the assumptions of normal and equidimensional shrinkage are widely accepted, exceptions to both these properties have been documented. Jayawardane and Greacen (1987) have demonstrated in a moderately swelling soil that normal shrinkage occurs only in layers having a CEC higher than 300 mmol (p^+) kg^{-1} soil. Talsma (1977) reported greater shrinkage in the horizontal than vertical plane of undisturbed cores, while Towner (1986) induced a similar response in samples prepared from finely ground kaolinite by imposing a vertical stress on the samples.

The relationship between field shrinkage and that measured in the laboratory is not constant. Chan (1981) showed that 75 mm diameter core samples collected from depths shallower than 0·3 m followed a 3-dimensional shrinkage curve, whereas deeper samples followed a unidimensional curve. *In situ* shrinkage curves have not been widely determined. However, Jayawardane and Greacen (1987) list four advantages of *in situ* methods over those that use disturbed samples to measure the shrinkage curve:

i) They represent bulk changes of a large soil volume, including cracks and voids.

ii) They are not destructive, so that random sampling errors are considerably reduced

iii) They are made under naturally existing overburden conditions

iv) They avoid experimental errors associated with small cores.

Swelling pins and the neutron moisture meter were used as an *in situ* measure of soil swelling in this experiment to characterize field swelling in horizontal and vertical planes. Values obtained are compared with laboratory shrinkage curves, and the implications of the findings to data obtained from the neutron moisture meter and other field measurements are discussed.

5.2.2 Materials and methods

Site description

Field measurement of soil swelling was undertaken during the 1986/87 cotton season. Two neutron moisture meter access tubes were instrumented in each plot of the rip + maize and direct list + maize treatments described in Section 8.3. This pair of treatments was selected as they represented the greatest contrast in soil physical properties of the treatments studied. The soil is a vertisol, Ug 5.24, described in Section 4.5.

Swelling pins and installation

The swelling pins, the dimensions of which are shown in Figures 5.1 and 5.2, were made of 6 mm diameter extruded aluminium rod. Aluminium, unlike brass and steel, is virtually transparent to neutrons and does not affect the sensitivity of the neutron moisture meter (Bell and McCulloch, 1966, quoted by Prebble *et al.*, 1981).

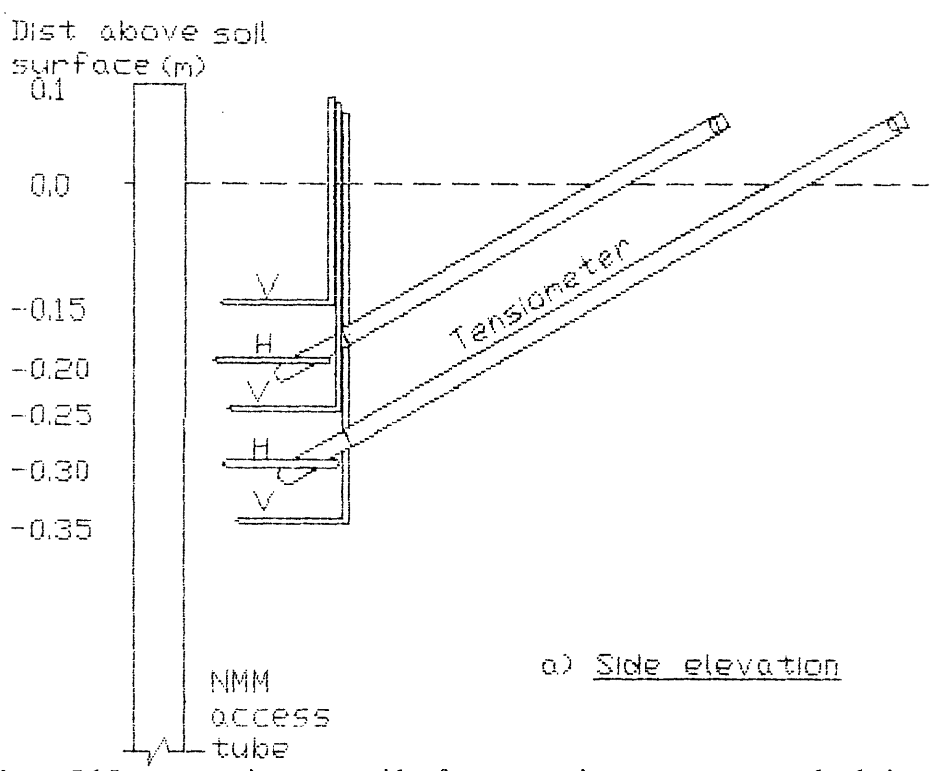


Figure 5.1 Instrumentation on one side of neutron moisture meter access tube during field measurement of soil shrinkage, Field 30, Auscott, Warren, 1987, showing side elevation.

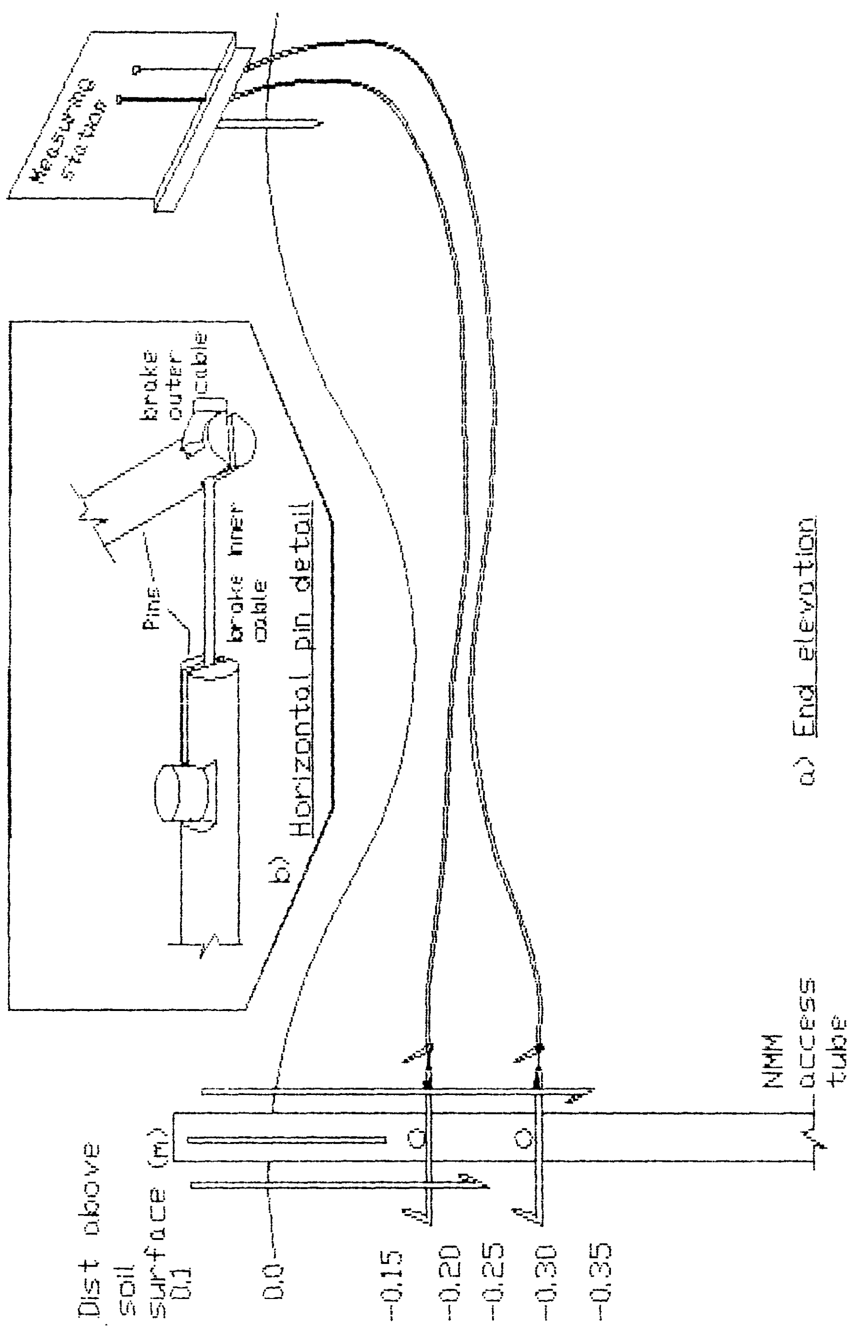


Figure 5.2 Instrumentation on one side of neutron moisture meter access tube during field measurement of soil shrinkage, Field 30, Auscott, Warren, 1987, showing a) end elevation and b) enlarged detail of the method used to link adjacent horizontal pins using a bicycle brake cable.

Swelling pins were installed parallel to the plant row and on opposite sides of the neutron moisture meter access tubes, which were also instrumented with tensiometers. Prior to installation, duplicate neutron moisture meter readings were taken at 0·2 and 0·3 m. Thereafter, the pins were installed in an access pit 0·2 m wide, 0·3 m long, and 0·4 m deep. As each pit was dug, 2 cores, 50 mm high by 75 mm diameter were taken at depths of 0·2 and 0·3 m according to the method of McIntyre and Barrow (1972). The cores were sealed in plastic bags and transported to the the laboratory for determination of field bulk density (ρ_b) and water content.

Pins measuring vertical movement were installed at 0·15, 0·25, and 0·35 m below the top of the hill (see Appendix 2), while pins measuring horizontal movement were installed 0·16 m apart, 0·2 and 0·3 m below the centre of the hill (Figures 5.1 and 5.2). All pins were coated with a graphite based lubricant to minimize corrosion. A builder's spirit level was used to ensure that pins were horizontal whilst they were being pushed into the soil. Movement of horizontal pins was measured by attaching one pin to the inner cable of a bicycle brake cable, and the other pin to the outer sheath of the cable. Cables were routed to a measuring station on an adjacent hill via a 0·15 m deep trench (Figure 5.2).

For each pin measuring vertical movement the height of top of each pin was measured relative to the top of the access tube by using a spirit level as a horizontal datum, and measuring the vertical offset with vernier calipers. The depth of the pins measuring horizontal movement was also measured using the spirit level as a datum, with the vertical offset being measured with a steel tape measure. It was assumed that the access tube, the bottom of which was 1·1 m below the soil surface, was not affected by swelling and shrinkage movement as variation in water content at this depth during the period of measurement was negligible. Horizontal separation of pins measuring horizontal movement was measured with a steel tape measure, and the length of inner cable protruding from its outer cable measured with vernier calipers at the measuring station.

The mass of soil solid being characterized by the swelling pins was calculated as the volume of soil contained within a rectangular prism bounded by the swelling pins, multiplied by the bulk density of the core samples. These measures were used as interim values in calculations until the separation distances were remeasured and mass between pins were recalculated from soil samples taken within the volume enclosed by pins at the end of the cotton season.

Tensiometers were installed in the prism of soil under study. Their installation and results derived from them are described in Section 8.3.

After installation of the pins and completion of measurements the pit was backfilled. The soil used to fill the pit was recompacted, with extra effort made to thoroughly compact a wall of soil between irrigation furrows and the backfilled pit.

Swelling pin measurements through the season

Measurements of swelling pin height and pin separation, and neutron moisture meter counts were made periodically between installation in December, 1986, and 4/2/87. From 4/2/87 until 19/2/87, measurements were recorded daily whenever possible to determine the swelling relationships over one drying cycle. No pin measurements were recorded after 19/2/87; the pins were removed following the last set of neutron moisture meter readings on the main experiment in April. Although an attempt was made to take measurements as close as possible to 9 am each day, the diurnal fluctuation of pin height was believed to be small (<0·5 mm according to Yaalon and Kalmar, 1972) so that the time of reading was unimportant.

Swelling pin removal

Removal of swelling pins required more extensive excavation than installation to enable the height below the datum of each end of the pins to be measured. The separation distance between pins measuring horizontal swelling was also measured at both ends of each pin.

After taking neutron moisture meter readings at 0·2 and 0·3 m depths, a trench 0·2 m wide and 0·4 m deep was dug around the rectangular prism of soil between the pins which was monitored during the season. Excess soil was pared from each side of the prism and the heights of both ends of each pin relative to the adjacent access tube was measured using a spirit level and steel tape measure as described above. Two soil clods were removed from within this prism and sealed in plastic bags for transport to the laboratory. Clods were taken as samples, as core sampling at this time was precluded by the fragility of the soil column remaining after excavation. Clod volume was determined using the wax coating technique of McIntyre and Loveday (1974), and clod gravimetric water content (θ_g) determined by weighing the clods after the wax had been peeled off them, then drying to constant weight at 105^{o}C and reweighing.

The volume and mass of soil enclosed by the swelling pins was recalculated using the methods described above. Bulk density values estimated throughout the season were then recalculated using the more recently measured values of mass and separation of pins.

Shrinkage from clods

Six wet clods (volume 150 to 300 cm^3) were sampled at both 0·2 and 0·3 m below the top of the hill on 6/2/87, one day after the irrigation at the start of the period in which intensive monitoring of swelling gauge movement was undertaken. Samples were carefully sealed in plastic bags and transported to the laboratory, where they were coated with Saran resin (Brasher *et al.*, 1966). As the clods were very weak, medical gauze was used to support them.

Saran coated clods were weighed to ascertain soil water content, then reweighed in water to determine their volume by Archimedes principle. This process was repeated twice daily for the first three days, then at progressively longer intervals as the clods dried at ambient temperature in the laboratory. Clods were reweighed in water only if their weight had declined by 0·5% since the previous volume determination. After two months the clods were dried to constant weight at 105^{o}C in order to calculate water content of samples at each measurement time on an oven-dry basis. The density of Saran was assumed to be 1·3 Mg m^{-3}, and a loss of 20% of its air dry weight on oven drying was assumed (Brasher *et al.*, 1966).

A 3-stage linear regression model was fitted to the shrinkage relationship between ν and θ_g (McGarry and Malafant, 1987a).

5.2.3 Results

Swelling estimated from swelling pins

The ratio of change in swelling pin height to change in water content increased with depth from 0·11 at 0·2 m to 0·19 at 0·3 m (Table 5.1). This trend appeared to continue below the deepest pin with the ratio being 0·33 for depths greater than 0·35 m. The horizontal pins at 0·2 m measured one quarter of the shrinkage of vertical pins, whilst at 0·3 m they measured one third of the shrinkage of the vertical pins.

Table 5.1 Vertical and horizontal movement (mm) of swelling pins over a drying cycle between irrigations, and their separation (S; mm) Field 30, Auscott Warren, February, 1987. (se is standard error of mean of 24 sites, W_D is change in cumulative water for depth from 1 to 12 DAI (mm), v_D is change in v from 1 to 12 DAI calculated from vertical and horizontal pin movement).

Depth	movement		S	movement		S	_		$v_D:W_D$
(m)	mean	se	mean	mean	se	mean	mean	se	
0·15-0·25	2·21	1·59	99	0·96	1·04	164	20·0	5·1	0·111
0·25-0·35	1·79	1·36	98	1·00	·88	168	9·4	3·0	0·190
>0·35	5·00	2·09					15·1		0·330

A result of the small amount of shrinkage measured by the vertical swelling pins, and even smaller shrinkage measured by the horizontal pins, is that the lines fitted by regression of v measured by swelling pins against θ_g predicted by the neutron moisture meter at 0·2 m have very low slopes (Table 5.2). Whereas Yule (1984) indicates that the slope should be 0·3, the slope at 0·2 m is 0·128. The slope of the shrinkage curve measured by swelling pins at 0·3 m depth of 0·26 is much closer to the value predicted by Yule (1984). Marked differences between the intercepts fitted at 0·2 and 0·3 m were also recorded, with the intercept at 0·3 m 0·139 Mg m^{-1} higher than at 0·2 m.

Table 5.2 Slope (b) and intercept (a) of regressions fitted to shrinkage curves estimated by swelling pins between 1 and 12 DAI, Field 30, Auscott Warren, February, 1987. Coefficients are averages for curves fitted to shrinkage measured at 24 sites.

Depth (m)	a	b
0·15-0·25	0·766	0·128
0·25-0·35	0·627	0·260
5% lsd	0·027	0·071

Swelling estimated from Saran coated clods

Shrinkage curves fitted to the Saran coated clods showed all three phases of shrinkage in 7 of the 12 clods sampled. The remaining five clods were not wet enough at sampling to exhibit structural shrinkage. The correlation coefficient (r) was 0·99 or higher for the 3-stage linear model fitted to all 12 clods. The boundary between structural and normal shrinkage (swelling limit) averaged over all clods was at a θ_g of 0·22 kg kg^{-1} (standard error (s.e.) 0·01 kg kg^{-1}), with the boundary between normal and residual shrinkage (shrinkage limit) at 0·09 kg kg^{-1} (s.e. 0·01 kg kg^{-1}). All fitted coefficients were similar at both depths sampled with the exception of higher ν of oven dry samples, and shallower slope of structural shrinkage at 0·2 than 0·3 m (Table 5.3).

Table 5.3 Coefficients fitted by three stage linear regression to shrinkage in the laboratory of clods collected from 0·2 and 0·3 m. Coefficients for each depth are presented separately only if they were significantly different. (α is oven dry specific volume, θ_A and θ_B are gravimetric water content at shrinkage and swelling limits respectively, B1, B2, and B3 are slopes of residual, normal, and structural shrinkage phases, sd is standeard deviation of estimates of coefficient).

Coefficient	Both depth		0·2 m		0·3 m	
	mean	sd	mean	sd	mean	sd
α	0·543	0·020	0·553	0·006	0·533	0·025
θ_A	0·090	0·010				
θ_B	0·223	0·011				
B1	0·049	0·068				
B2	0·904	0·062				
B3	0·681	0·109	0·620	0·109	0·762	0·196

Swelling estimated from samples taken at pin installation and removal

Specific volume of both cores collected at pin installation and of clods collected at pin removal was significantly higher at 0·2 than 0·3 m depth (Table 5.4). The ν at 0·3 m increased with water content between the samplings at pin installation and removal, indicating little change in the structure between the two sampling times. The reverse was observed at 0·2 m, with the ν being higher for the samples at pin installation than samples 0·03 kg kg^{-1} wetter at pin removal, indicating either that compaction had occurred between the two sampling times, or that wax coating measured fewer interaggregate pores than 75 mm diameter cores.

The precision of the shrinkage models fitted to swelling estimated from samples taken at pin installation and removal was limited by the small range of water contents sampled compared to the range observed at the study site during the neutron moisture meter calibration (Table 5.4 vs Table 5.8). Models fitted by regression of core and clod measured ν against θ_g predict that ν changes more rapidly

Table 5.4 Gravimetric water content (θ_g, kg kg^{-1}), and specific volume (v, m^3 Mg^{-1}) of cores collected during installation of swelling pins, and clods collected during removal of swelling pins. Field 30, Auscott, Warren, 1987.(max and min are maximum and minimum values respectively.)

Measurement	Depth		θ_g			v	
time	(m)	max	mean	min	max	mean	min
Cores, pin	0·2	0·230	0·191	0·153	0·920	0·750	0·648
installation	0·3	0·170	0·209	0·286	0·763	0·660	0·600
Clods, pin	0·2	0·249	0·220	0·163	0·854	0·725	0·606
removal	0·3	0·271	0·231	0·165	0·785	0·688	0·607

than θ_g (Table 5.5), which is anomalous (Jayawardane and Greacen, 1987). Measured changes in v are thus correlated with factors other than changes in θ_g.

Table 5.5 Models fitted by linear regression to change in specific volume (v) with change in gravimetric water content (θ_g) of samples collected at a range of water contents during installation and removal of swelling pins, Field 30, Auscott Warren, 1987. (a and b are constant and slope fitted by linear regression, n is number of samples at each depth, se is standard of estimate; $se_{y.x}$ is the standard deviation of the estimate of y for fixed x).

	Depth (m)	a	se	b	se	$se_{y.x}$	r^2	n
cores, pin	0·2	0·535	0·087	1·13	0·046	0·004	0·100	48
installation	0·3	0·470	0·034	0·94	0·159	0·001	0·418	48
clods,	0·2	0·416	0·064	1·46	0·290	0·002	0·342	48
removal	0·3	0·403	0·030	1·23	0·129	0·001	0·659	48

5.2.4 Discussion

Shrinkage measured by swelling pins in this experiment is much lower than that measured by either shrinkage of Saran coated clods in the laboratory, or field sampling of cores and clods over a range of water contents. It is also lower than the 5% change in thickness of soil layers measured by Jarvis and Leeds-Harrison (1987). Given the nearly normal shrinkage of Saran coated clods, the ratio between vertical shrinkage and change in water content should be between 0·33 and 0·4 (Jayawardane and

Greacen, 1987). In the experiment reported here, a comparable ratio was observed below 0·35 m, but not at 0·15 to 0·25 m or 0·25 to 0·35 m. The ratios recorded at these depths were 0·13 and 0·26 respectively. Vertical shrinkage much less than normal has also been reported for a bed of aggregates of swelling soil by Bridge and Collis-George (1972).

The small vertical shrinkage measured in the field may be partly due to structural shrinkage. Some surface aggregates may move apart as they shrink, due to irregularities on their surface as illustrated in Figure 5.3, which may prevent full expression of surface deflation. This occurs whenever interaggregate pores are aligned in any plane other than vertical, a phenomenon commonly observed in surface soil. The increased vertical shrinkage with depth may be due to an increase in the size of aggregates with depth, noted by Stace *et al.* (1968), Chan (1981) and at this site (Appendix 3). This would decrease the effects of surface irregularities, and shrinkage measured by swelling pins becomes closer to that predicted by Fox's (1964) model. Increasing density with depth, illustrated in Table 5.9, also contributes to the increased vertical movement with depth, as less structural shrinkage can occur in denser soils. Anisotropic shrinkage caused by overburden as observed by Talsma (1977) is unlikely to contribute substantially to the small vertical shrinkage measured, as the effect of overburden should increase with depth, whereas vertical shrinkage more closely approximated theoretical values as depth increased in this experiment.

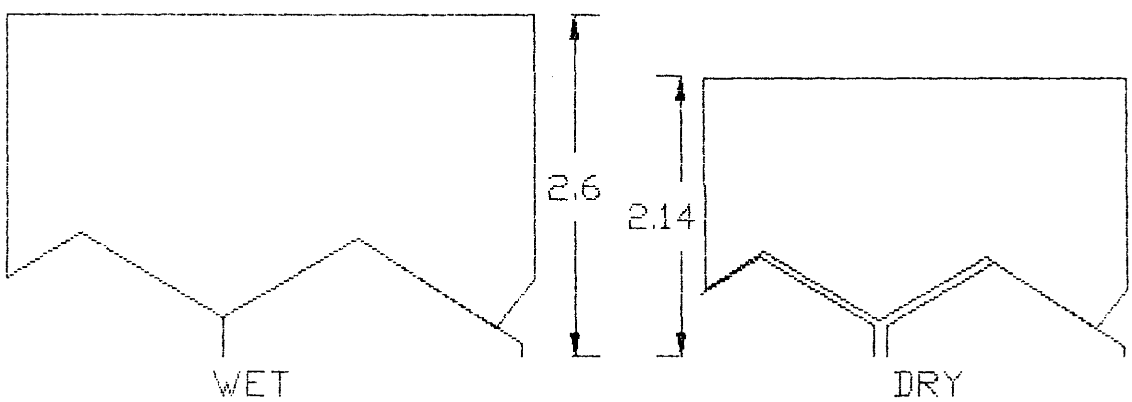


Figure 5.3 Schematic effect of the postulated effect of aggregate surface irregularities resulting in a smaller than expected change in surface height as the soil shrinks. (Dry aggregates 0·8 times the size of wet aggregates, thus expected dry height is 2·08 units.)

The lower shrinkage measured by horizontal compared to vertical pins may be due to changes in pin movement caused by the location of pins in relation to aggregates. Three possible effects of shrinkage on pin movement are illustrated in Figure 5.4. All three possible outcomes of pins moving closer together, further apart, and remaining at the same separation as the soil shrank were recorded, thus negating any comparison of horizontal and vertical shrinkage in this experiment.

The magnitude of error in profile water capacity introduced by ignoring the changes in layer thickness with changes in volumetric water content (θ_v) for the irrigation cycle over which pin shrinkage was monitored is shown in Table 5.6. The calculations in Table 5.6 simulate changes in a

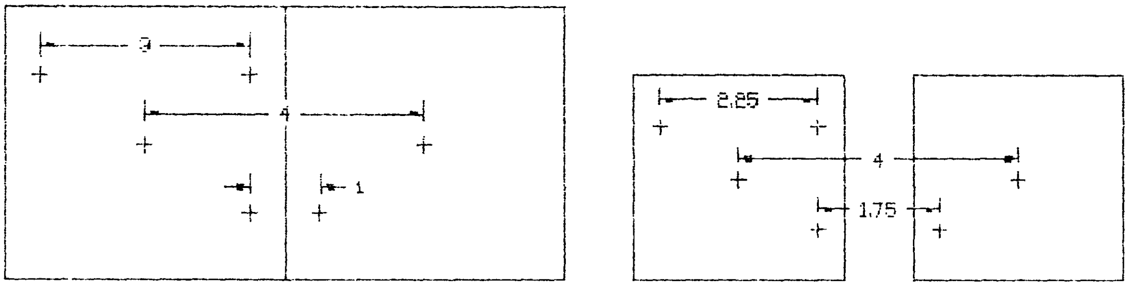


Figure 5.4 Diagram of the effect of the location of measurement points within blocks which shrink by 25%, but do not move with respect to one another, on the the change in distance separating the points. (Distance is in arbitrary units.)

layer of soil 0·1 m deep centred on each measurement depth. In the uncorrected profile, the layer thickness remains the same as the soil dries, whereas each layer in the corrected profile shrinks according to relationships of Table 5.1 as the soil dries. Layer thickness (T) of the corrected profile 12 days after irrigation (DAI) is defined:

$$T = 0{\cdot}1 - V_s(\theta_{v1DAI} - \theta_{v12DAI}) \qquad 5.2.1$$

where V_s is the ratio between change in v and water content from Table 5.2. Profile water capacity (ΣW_D) is calculated as:

$$\Sigma W_D = 2.5 * W_{D\ 0.2m} + W_{D\ 0.3m} + W_{D\ 0.4m} + W_{D\ 0.5m} + W_{D\ 0.6m} + W_{D\ 0.8m} \qquad 5.2.2$$

The 0·0026 m error in profile water capacity introduced by ignoring shrinkage is similar to errors caused by neutron moisture meter random count plus relocation error (McGowan and Williams, 1980). This error, 3·5% of the corrected change in water content, is much lower than the 30% error predicted by Yule (1984) for two reasons. First, at 0·2 and 0·3 m, where large changes in soil water content occurred, only small changes in layer thickness were measured. Second, at depths greater than 0·35 m, where the ratio of change in layer thickness to change in θ_v was higher, only small changes in θ_v were measured.

Errors in measurement of air filled porosity (ε_a) caused by ignoring swelling will be greater than errors in measurement of cumulative water capacity, which are illustrated in Table 5.7, due to the formation of macropores within the volume of soil monitored by the swelling pins. These are discussed in further detail in Section 5.3.4. The effect of sample size on measured ε_a is also discussed in Section 8.3.4, where the different measures of swelling are combined with water retention curves obtained from tensiometers installed at the same sites to give indications of the pore size distribution in this soil.

Table 5.6 Corrected changes in cumulative profile water capacity measured with neutron moisture meter from 1 to 12 DAI compared with uncorrected changes. (θ_v is volumetric water content in m^3 m^{-3}, T is layer thickness in m; W is cumulative water in layer in m, W_D is difference in W between days 1 and 12).

Depth	Uncorrected				Corrected			
(m)	θ_v	T	W	W_D	θ_v	T	W	W_D
1 DAI								
0·2	0·450	0·1	0·0450					
0·3	0·414	0·1	0·0414					
0·4	0·405	0·1	0·0405					
0·6	0·395	0·1	0·0395					
0·8	0·360	0·1	0·0360					
12 DAI								
0·2	0·243	0·1	0·0243	0·0207	0·243	0·0978	0·0238	0·0212
0·3	0·319	0·1	0·0319	0·0095	0·319	0·0983	0·0314	0·0100
0·4	0·342	0·1	0·0342	0·0063	0·342	0·0983	0·0336	0·0069
0·6	0·366	0·1	0·0366	0·0029	0·366	0·0992	0·0363	0·0032
0·8	0·358	0·1	0·0358	0·0002	0·358	0·0999	0·0358	0·0002
Total			0·0707				0·0733	

Table 5.7 The effect of changes in volume of soil prism measured by swelling pins between 1 and 12 days after irrigation (DAI) on measured air filled porosity (ε_a) calculated from changes in volumetric water content (θ_v) within the prism measured with neutron moisture meter (Volume diff is the difference in prism volume between 1 and 12 DAI).

	1 DAI				12 DAI				Volume
Depth	Height	Width	Volume	ε_a	Height	Width	Volume	ε_a	Diff
(m)	(m)	(m)	(m^3)	(m^3 m^{-3})	(m)	(m)	(m^3)	(m^3 m^{-3})	(m^3)
0·2	0·1	0·164	0·00269	0·057	0·1	0·163	0·00266	0·249	0·013
0·3	0·1	0·168	0·00282	0·055	0·1	0·167	0·00279	0·137	0·011

5.2.5 Conclusions

Field shrinkage measured at 0·2 and 0·3 m using swelling pins was much less than expected from extrapolation from laboratory results. Field shrinkage measurements indicate that the errors introduced to water content measurement by ignoring swelling are no greater than those introduced by sources such as relocation error in placement of the neutron moisture meter source in the access tube. Consequently, little accuracy (3·5% error only) would be lost at this site by ignoring swelling in neutron moisture meter calibrations. Errors in the measurement of soil water and ε_a introduced by swelling increase with depth, especially beyond the depths monitored closely in this experiment. However, the importance of these errors is reduced by the decreasing range of water content measured with increasing depth.

5.3 NEUTRON MOISTURE METER AND GAMMA DENSITY METER CALIBRATIONS

5.3.1 INTRODUCTION

The portable neutron moisture meter, which relies on the slowing of fast neutrons in a process known as thermalization to determine water content, was developed in the mid 1950's. Its chief advantage over gravimetric sampling, its main alternative, is that it is non-destructive, allowing repeated measurement of water content to be made on one volume, thus increasing the precision of water content measurements (Hodgson and Chan, 1987). Once access tubes are installed, the speed of sampling with the neutron moisture meter can approach an order of magnitude quicker than gravimetric sampling (Greacen, 1981). Since soil water content determines many soil processes, the neutron moisture meter has found extensive application in soil science and crop production (Williams *et al.*, 1981).

Volumetric water content (θ_v) is related to thermal neutron counts (c) of the neutron moisture meter using the relationship:

$$\theta_v = (c - a') / b' \qquad 5.3.1$$

where a' and b' are coefficients from the curve fitting process described in Section 5.3.2. Although hydrogen is the main element which thermalizes fast neutrons, other light nuclei in the soil including oxygen, carbon and, to a lesser extent, nitrogen increase the flux of thermal neutrons to the neutron moisture meter detector (Wilson and Ritchie, 1986). Thermal neutron flux is reduced by the presence of small quantities of strong neutron absorbers in the soil such as calcium, boron, lithium and chlorine (Gardner, 1986). The influence of elements other than hydrogen, and the presence of hydrogen other than in free soil water (water not chemically bonded to soil materials) leads to numerous examples where the accuracy with which θ_v is predicted by the neutron moisture meter is improved by incorporating either or both texture and density in neutron moisture meter calibrations (Lal, 1974; Greacen and Schrale, 1976; Greacen and Hignett, 1979; McGowan and Williams, 1980; Jayawardane *et al.*, 1984; Hodgson and Chan, 1987).

Swelling of soils introduces errors into neutron moisture meter calibrations above those found in non-swelling soils. Although ignoring swelling has been shown to lead to errors of up to 30% when measuring integrated water capacity (Bridge and Ross, 1984; Yule 1984), the small (< 3·5%) error calculated in Section 5.2 means swelling can also be safely ignored in this measurement. This argument is appropriate for describing the water relations of swelling soils, but is invalid for measurement of soil aeration, in which the macropores can play a vital role.

The second major source of error in the use of the neutron moisture meter in swelling soils is cracks in the vicinity of the access tube. Given the argument presented above, the concerns of Greacen and Hignett (1979) regarding underestimation of changes in water content due to measurement of unidimensional shrinkage when soil shrank onto the access tube are of little importance. Intersection of cracks by the access tube is of much greater concern. Cull (1979) and Jarvis and Leeds-Harrison (1987) demonstrated preferential wetting around access tubes which intersected shrinkage cracks. Solutions to this problem suggested by Cull (1979) and Jarvis and Leeds-Harrison (1987) include filling the space between the access tube and soil with either loose topsoil or sand when the soil is dry, inserting new access tubes whenever significant shrinkage cracks form around access tubes, discarding the results from access tubes around which shrinkage cracks form, or using core samples when shrinkage invalidates neutron moisture meter data. For the neutron moisture meter calibration described here, access tubes were inserted between cracks less than a week before samples were taken, thus avoiding problems caused by shrinkage cracks.

Volumetric water content (θ_v) is highly correlated with gravimetric water content (θ_g), air filled porosity (ε_a), and bulk density (ρ_b) in swelling soils. Successful calibrations of the neutron moisture meter with respect to these properties by Jayawardane and Meyer (1985) and Hodgson and Chan (1987) indicate that these calibrations deserve investigation at the experimental site.

Changes of density in vertisols with changes in water content mean that direct *in situ* measurement of ρ_b would be advantageous. Greacen and Hignett (1979) have suggested that simultaneous measurement of θ_v with a neutron moisture meter and density with a gamma density meter would improve the accuracy of water content measurement in relation to that obtained by using the neutron moisture meter alone.

Both a neutron moisture meter and a gamma density meter were calibrated at the experimental site. Correlations between neutron moisture meter counts and θ_g, ε_a, and ρ_b were measured and analysed.

5.3.2 Materials and methods

Sampling

The soil on which the neutron moisture meter and gamma density meter were calibrated is a Ug 5.24 and is fully described in Section 4.5. Samples were taken from three sites. The driest samples in the calibration were obtained from a site adjacent to the experimental site, which had been dried down to the lower limit of extractable water by corn (*Zea mayes*). Moist samples were taken soon after harvest of the wheat crop from the experimental field 100 m from the dry site, while the wettest samples were taken from an area 20 m from the moist site, on which water was ponded for 24 hours then allowed to drain for 48 hours before sampling.

Aluminium access tubes were installed 1 m apart two to three days before sampling at the three sites. Three, five and four tubes were installed respectively in the wet, moist and dry sites. Care was taken to avoid intersecting visible cracks at the dry site. Holes for the access tubes were made by extracting soil cores using a tube of 50·5 mm outside diameter, 46 mm inside diameter (i.d.), with a cutting tip of 36 mm i.d. to a depth of 1·4 m. A hydraulic ram, supplemented by a jackhammer mounted on a tractor was used to drive the tube into the soil. Access tubes of the same external diameter as the coring tube were then pushed into the soil using the hydraulic ram.

Prior to measurement, 20 standard counts were taken in an access tube suspended in a 200 l drum filled with rainwater. Four, 15 second, counts were then taken 0·2, 0·3, 0·4, 0·5, 0·6, 0·8, 1·0, and 1·2 m depths using both neutron and gamma components of a Campbell Pacific Nuclear (CPN) 501 dual gamma density meter and neutron moisture meter (gamma source 50 mCi ^{137}Cs, neutron source 10 mCi ^{241}Am). Two, 15 second, counts were also taken at each depth using a CPN 503 neutron moisture meter (neutron source 50 mCi ^{241}Am). Fewer counts were taken with the CPN 503 than the CPN 501 as the standard count of the former was an order of magnitude lower than the latter, thus the error introduced into calibration from a count of a given duration due to variation in neutron emissions would be an order of magnitude lower (Haverkamp *et al.*, 1984). Neutron and gamma counts were converted to count rate ratio (n) by dividing the field count by the water drum standard count.

Two neutron moisture meters were tested to determine which would be preferable for field measurements. If the CPN 503 was suitable for determining ρ_b in addition to water content it would be used in preference to the CPN 503, which had the advantage of being lighter.

After neutron and gamma counts were recorded, a 1.5 m deep backhoe trench was dug adjacent to access tubes to permit core sampling. Three core samples were taken in sharpened rings, 50 mm high and 75 mm diameter, within a radius of 175 mm of the access tubes at each depth at which counts were recorded, using the procedure of McIntyre and Barrow (1972). Samples were sealed in plastic bags for transport to the laboratory where they were trimmed and weighed before being dried to constant weight at 105^{o}C then reweighed. θ_g, ρ_b, θ_v and ε_a (using a particle density (ρ_s) of 2·7 Mg m^{-3} (Greenwood, 1984)) of the cores were then calculated from these weights (ρ_b is field bulk density and is calculated by dividing volume measured at field water content by oven dry mass).

Choice of regression models

Greacen *et al.* (1981) demonstrated that the accuracy of neutron moisture meter calibration is improved if n is regressed on θ_v, rather than if θ_v is regressed on n. Accuracy is increased since the regression coefficient (b) can be corrected for variance in θ_v, but not variance in n. Variance in θ_v is estimated by taking replicate samples at each point, and subjecting them to an analysis of variance. Conversely, sampling variance of n is due, not only to the usually negligible random counting error, but also to the heterogeneous distribution of free water, constitutional water, bulk density, and neutron absorbers in the sphere of influence of the probe (Greacen *et al.*, 1981). The most accurate procedure, which was adopted for neutron and gamma calibrations, results from the regression of n on θ_v with a correction to the regression coefficient for error in θ_v. The model used for neutron moisture meter calibration was:

$$n = a + b\theta_v \qquad 5.3.2$$

Quadratic models were not tested as Hodgson and Chan(1987) found for a similar grey clay that they did not improve accuracy of the calibration at depths greater than 0·2 m.

Christensen (1974) demonstrated that the relationship between gamma counts (c_γ) and density is altered by soil water content, with count rate changing inversely with water content over densities from 1 to 2 Mg m^{-3}. Christensen (1974) recommended that a model of the form:

$$\rho_b + 1.114\theta_v = a + b*c_\gamma \qquad 5.3.3$$

be used to correct for changes in water content, where ρ_b is field bulk density. This correction was used in this calibration, which along with Greacen *et al.*'s (1981) regression recommendation, resulted in the model:

$$n_\gamma = a + b(\rho_b + 1.114\theta_v) \qquad 5.3.4$$

where n_γ is gamma count rate ratio.

Separate moisture and density calibration lines were initially calculated for each depth. These lines were combined where a comparison of regression lines using ANOVA indicated that slopes and intercepts were not statistically different (Snedecor and Cochran, 1980).

Correction for swelling

Complications introduced to water content measurement by soil swelling, and models which account for swelling, are discussed in Sections 3.2 and 5.2. Fox's (1964) shrinkage model, in which density changes are corrected for 3-dimensional shrinkage (ρ_{b3D}, equation 3.2.1), were used to calculate corrected ε_a and θ_v (ε_{a3D} and θ_{v3D}) as follows:

$$\theta_{v3D} = \theta_g \, \rho_{b3D} \qquad 5.3.5$$

$$\varepsilon_{a3D} = 1 - \rho_{b3D} / \rho_s - \theta_{v3D} \qquad 5.3.6$$

where ρ_s is the density of soil solids. Similarly, θ_v corrected for unidimensional shrinkage (θ_{v1D}) was calculated using equation 3.2.2:

$$\theta_{v1D} = \theta_g \, \rho_{b1D} \qquad 5.3.7$$

Greacen and Schrale (1976) reduced the scatter of their calibration points by using an empirical factor based on the assumption that neutron count rate at constant total water content (equivalent water content of constitutional hydrogen remaining in soil after drying at 105^{o}C, plus free water or θ_v) is proportional to the square root of bulk density. i.e:

$$n_{\rho_b} = (\rho_{b3DM} / \rho_{b3DI})^{0.5} \qquad 5.3.8$$

where n_{ρ_b} is neutron count at total water content, ρ_{b3DM} is the mean ρ_{b3D} for a given soil depth, and ρ_{b3DI} is ρ_{b3D} at a given depth and time. This correction was applied whenever a density correction was included in ε_a or soil water calibrations.

Test of accuracy

Core samples were taken at 0·3 m around 24 access tubes during installation of swelling pins (Section 5.2.2) using similar methods to those used in obtaining samples for the neutron moisture meter calibration. Measured θ_g, ρ_b, θ_v and ε_a obtained from these cores were compared with those predicted by simultaneous neutron moisture meter readings.

In addition, the accuracy of two methods of predicting θ_{v3D} and ε_{a3D} with the neutron moisture were compared. In Method 1, θ_{v3D} and ε_{a3D} were predicted directly from n_{ρ_b}. In Method 2, the first step was to determine ρ_{b3D} by substituting θ_g predicted by the neutron moisture meter into equation 3.2.1. Next, θ_g and ρ_{b3D} were substituted into equation 5.3.5 to predict θ_{v3D} (θ_{v3Dc} in Table 5.14). Finally, ρ_{b3D} and θ_{v3D} were substituted into equation 5.3.6 to predict ε_{a3D}, which is designated ε_{a3Dc} in Table 5.14.

The criterion used to determine accuracy was the mean relative error (MRE) used by Hodgson and Chan (1987):

$$MRE = |measured - predicted| / predicted \qquad 5.3.9$$

5.3.3 Results

Values obtained

The range of θ_v sampled, from a minimum of 0·2 m^3 m^{-3} to just above 0·4 m^3 m^{-3}, was uniform from 0·2 to 0·6 m depth (Table 5.8). This range then became smaller with depth to 1·2 m, with the increase in θ_v with depth of the driest tube sampled being greater than the decrease in θ_v of the wettest tube (Table 5.8). A similar depth trend, which is attributed to poor infiltration at depth, was observed for θ_g.

Table 5.8 Ranges and means of measured gravimetric water content (θ_g, kg kg^{-1}) and volumetric water content (θ_v, m^3 m^{-3}), and θ_v corrected for undimensional (θ_{v1D}) and 3-dimensional (θ_{v3D}) shrinkage of samples collected during calibration of a CPN 503 neutron moisture meter. Thirty six samples were collected at each depth. Field 30, Auscott, Warren, 1985.

Depth	θ_g			θ_v			θ_{v1D}			θ_{v3D}		
(m)	max	mean	min	max	mean	min	max	mean	min	max	mean	min
0·2	0·273	0·217	0·122	0·400	0·326	0·207	0·396	0·337	0·226	0·400	0·325	0·194
0·3	0·268	0·213	0·116	0·403	0·336	0·213	0·397	0·338	0·221	0·404	0·329	0·190
0·4	0·278	0·215	0·118	0·409	0·340	0·214	0·411	0·344	0·228	0·419	0·334	0·196
0·5	0·278	0·214	0·113	0·410	0·338	0·203	0·404	0·338	0·218	0·412	0·324	0·183
0·6	0·273	0·207	0·114	0·415	0·333	0·211	0·406	0·334	0·222	0·415	0·322	0·189
0·8	0·257	0·207	0·130	0·398	0·340	0·237	0·397	0·343	0·250	0·406	0·335	0·220
1·0	0·250	0·208	0·153	0·392	0·343	0·273	0·387	0·343	0·278	0·396	0·337	0·266
1·2	0·246	0·210	0·170	0·384	0·344	0·288	0·378	0·341	0·296	0·389	0·399	0·281

Mean, minimum, and maximum values of ε_a decreased with increasing depth. No values of ε_a greater than 0·1 $m^3\ m^{-3}$ were recorded for depths of 0·8 m and greater (Table 5.9).

Table 5.9 Ranges and means of measured air filled porosity (ε_a, $m^3\ m^{-3}$), and calculated air filled porosity corrected for 3-dimensional shrinkage (ε_{a3D}, $m^3\ m^{-3}$) of samples collected during calibration of a CPN 503 neutron moisture meter. Field 30, Auscott, Warren, 1985.

Depth	ε_a			ε_{a3D}		
(m)	max	mean	min	max	mean	min
0·2	0·172	0·107	0·045	0·211	0·111	0·053
0·3	0·114	0·070	0·033	0·198	0·092	0·034
0·4	0·134	0·062	0·013	0·189	0·084	0·017
0·5	0·127	0·061	0·031	0·256	0·108	0·036
0·6	0·102	0·053	0·020	0·192	0·090	0·019
0·8	0·089	0·045	0·012	0·147	0·060	0·020
1·0	0·089	0·045	0·014	0·120	0·058	0·013
1·2	0·084	0·047	0·024	0·104	0·060	0·021

Minimum ρ_b, associated with high θ_v, increased with depth from 1·45 Mg m^{-3} at 0·2 m to 1.56 Mg m^{-3} at 1·2 m. Mean ρ_b, but not maximum ρ_b, followed a similar depth trend (Table 5.10). A shrinkage curve for the 1·2 m samples showed that shrinkage as measured by small cores was closer to a unidimensional model than a 3-dimensional model (Figure 5.5).

Table 5.10 Ranges and means of measured bulk density (ρ_b, Mg m^{-3}), calculated bulk density corrected for 3-dimensional shrinkage (ρ_{b3D}) and water content ($\rho_{bW}=\rho_b+1.114*\theta_v$) of samples collected during calibration of a CPN 503 neutron moisture meter and a CPN 501 gamma density meter. Field 30, Auscott, Warren, 1985.

Depth	ρ_b			ρ_{b3D}			ρ_{bW}		
(m)	max	mean	min	max	mean	min	max	mean	min
0·2	1·71	1·53	1·45	1·60	1·52	1·47	1·94	1·89	1·77
0·3	1·84	1·60	1·51	1·65	1·56	1·51	2·08	1·98	1·90
0·4	1·81	1·61	1·48	1·66	1·57	1·52	2·06	1·99	1·93
0·5	1·86	1·62	1·48	1·68	1·54	1·49	2·10	2·00	1·92
0·6	1·93	1·66	1·50	1·67	1·58	1·53	2·18	2·03	1·95
0·8	1·82	1·66	1·55	1·71	1·63	1·58	2·09	2·04	1·99
1·0	1·78	1·65	1·57	1·68	1·63	1·59	2·09	2·03	1·98
1·2	1·73	1·64	1·56	1·66	1·62	1·59	2·04	2·03	1·97

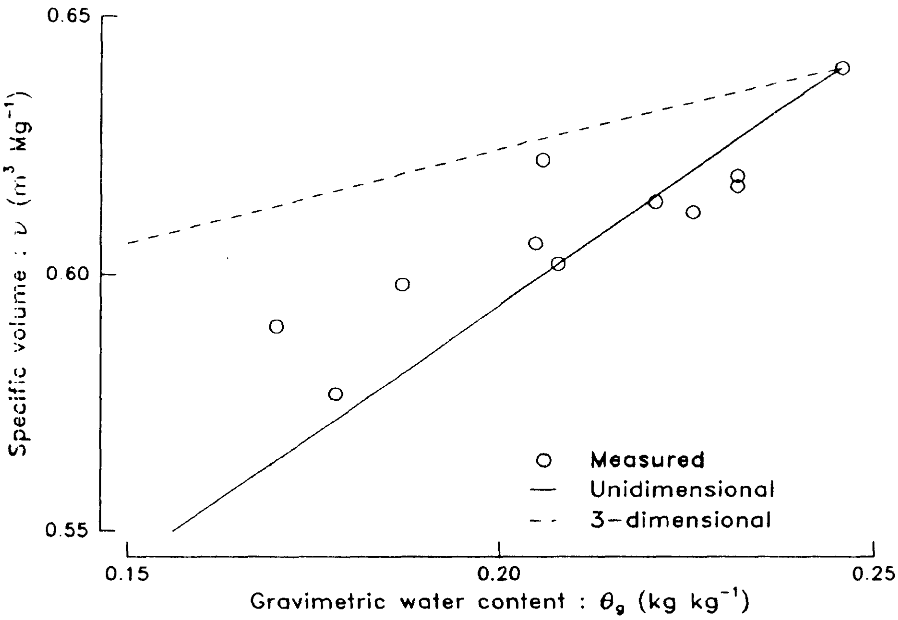


Figure 5.5 Relationship between gravimetric soil water and specific volume measured at 1·2 m, Field 30, Auscott, Warren, 1985.

Corrections for shrinkage

A further test for the type of shrinkage sampled is a comparison of θ_{v1D} and θ_{v3D} with unadjusted θ_v values. As expected, the wettest θ_v values calculated by the three methods are similar, with the range of wettest θ_v predicted by the three methods for any sampling depth being less than 0·01 m^3 m^{-3} (Table 5.8). In contrast, for all depths shallower than 0·8 m, the range of minimum θ_v predicted by the three methods is greater than 0·03 m^3 m^{-3}. For both mean and minimum θ_v, θ_{v3D} predicts the driest values, with uncorrected θ_v being closer to θ_{v1D} than to θ_{v3D}. The range of θ_{v3D} averaged over all depths is 11% greater than the range for uncorrected values, which, in turn, is 10% greater than the range for θ_{v1D}. Similar comparisons can be made for corrected and uncorrected density values as ρ_b and θ_v are directly related by equations 5.3.5 and 5.3.7.

Differences between uncorrected and corrected ε_a values are greater than differences for θ_v and ρ_b. Correction for 3-dimensional shrinkage increased mean ε_a by at least 27% over uncorrected values for all depths greater than 0·4 m.

Predictions

Water content

The most precise of the three calibrations used to predict water content was regression of n on θ_v (Table 5.11). Although the other two calibrations, regression of n_{ρ_b} on θ_{v3D} and regression of n on

θ_g, were less precise, they compare favourably with a calibration in grey clays published by Hodgson and Chan (1987). In all three calibrations in this experiment, precision increased from 0·2 m to 0·5 m, then decreased slowly to 1·2 m.

Table 5.11 Regression coefficients, and two measures of precision of calibration (coefficient of determination (r^2) and standard error of Y for fixed X ($se_{y.x}$)), for CPN 503 neutron moisture meter calibrations of count rate ratio (n), or count rate ratio corrected for bulk density (n_{ρ_b}) on measured volumetric water content (θ_v, $m^3\ m^{-3}$), θ_v corrected for 3-dimensional shrinkage (θ_{v3D}), and gravimetric water content (θ_g; kg kg^{-1}). Field 30, Auscott, Warren, 1985.

Depth	n on θ_g				n on θ_v				n_{ρ_b} on θ_{v3D}			
(m)	a	b	$se_{y.x}$	r^2	a	b	$se_{y.x}$	r^2	a	b	$se_{y.x}$	r^2
0·2	0·237	1·33	0·028	0·907	0·168	1·10	0·023	0·935	0·235	0·868	0·027	0·892
0·3	0·274	1·39	0·019	0·948	0·193	1·13	0·016	0·963	0·278	0·889	0·019	0·939
0·4	0·274	1·42	0·015	0·972	0·198	1·12	0·009	0·989	0·278	0·908	0·015	0·967
0·5	0·277	1·42	0·014	0·979	0·191	1·16	0·013	0·983	0·278	0·914	0·014	0·975
0·6	0·281	1·45	0·015	0·975	0·196	1·15	0·013	0·983	0·287	0·919	0·015	0·972
0·8	0·262	1·54	0·013	0·972	0·185	1·16	0·013	0·972	0·269	0·970	0·010	0·964
1·0	0·269	1·52	0·012	0·950	0·187	1·17	0·010	0·969	0·276	0·959	0·014	0·937
1·2	0·282	1·44	0·016	0·824	0·196	1·12	0·014	0·876	0·288	0·905	0·016	0·728

Parallelism tests for regression of n on θ_v showed that the regressions for 0·2 m and 0·3 m were different from one another and from all other depths, but that the 0·4 to 0·6 m depths could be combined, as could the 0·8 to 1·2 m depths. By combining these regressions final equations were obtained:

0·2 m	$n = 0{\cdot}1677 + 1{\cdot}098\theta_v$	(r^2 = 0·935	$Se_{y.x}$ = 0·23).	5.3.10
0·3 m	$n = 0{\cdot}1927 + 1{\cdot}128\theta_v$	(r^2 = 0·963	$Se_{y.x}$ = 0·016)	5.3.11
0·4 to 0·6m	$n = 0{\cdot}1945 + 1{\cdot}141\theta_v$	(r^2 = 0·983	$Se_{y.x}$ = 0·012)	5.3.12
0·8 to 1·2m	$n = 0{\cdot}1865 + 1{\cdot}137\theta_v$	(r^2 = 0·957	$Se_{y.x}$ = 0·012)	5.3.13

ε_a

Regression of n_{ρ_b} on ε_{a3D} yielded a calibration of almost identical precision to regression of n on θ_g (Table 5.12). This reflects the use of measured θ_g to calculate ε_{a3D} used in the regression.

ρ_b

The correlation between density corrected for θ_v and gamma count rate ratio was significant for

Table 5.12 Regression coefficients, and two measures of precision of calibration (coefficient of determination (r^2) and standard error of Y for fixed X ($se_{y.x}$)), for CPN 503 neutron moisture meter calibration of count rate ratio corrected for bulk density (n_{ρ_b}) on air filled porosity corrected for 3-dimensional shrinkage (ε_{a3D}). Field 30, Auscott, Warren, 1985.

Depth (m)	n_{ρ_b} on ε_{a3D} a	b	$se_{y.x}$	r^2
0·2	0·682	-1·39	0·028	0·921
0·3	0·704	-1·43	0·020	0·957
0·4	0·704	-1·46	0·015	0·978
0·5	0·739	-1·49	0·014	0·984
0·6	0·714	-1·48	0·014	0·983
0·8	0·675	-1·53	0·013	0·977
1·0	0·675	-1·51	0·012	0·958
1·2	0·699	-1·44	0·016	0·855

only two of the eight depths tested (Table 5.13). Correction of density for changes in θ_v greatly reduced the range of densities sampled (Table 5.10). As the precision of this calibration was considered inadequate, no further analysis of the gamma meter data, including regression of neutron count rate ratio on water content, was undertaken.

Table 5.13 Regression coefficients, and two measures of precision of calibration (coefficient of determination (r^2) and standard error of Y for fixed X ($se_{y.x}$)) for CPN 503 neutron moisture meter count rate ratio corrected for bulk density (n_{ρ_b}) on bulk density (ρ_b, Mg m^{-1}) and CPN 501 gamma density meter count rate ratio (n_γ) on bulk density corrected for water content ($\rho_{bW}=\rho_b+1.114*\theta_v$). Field 30, Auscott, Warren, 1985.

Depth	n_{ρ_b} on ρ_b				n_γ on ρ_{bW}			
(m)	a	b	$se_{y.x}$	r^2	a	b	$se_{y.x}$*	r^2
0·2	1·49	-0·628	0·049	0·709	3·55	-1·50		0·134
0·3	1·58	-0·626	0·028	0·888	1·89	-0·622		0·201
0·4	1·63	-0·650	0·034	0·858	1·75	-0·552		0·164
0·5	1·55	-0·595	0·024	0·941	1·28	-0·322	0·013	0·650
0·6	1·56	-0·590	0·023	0·944	0·943	-0·181	0·010	0·560
0·8	1·87	-0·775	0·021	0·927	0·643	-0·146		0·001
1·0	1·71	-0·682	0·029	0·725	0·823	-0·105		0·059
1·2	1·51	-0·561	0·027	0·504	0·621	-0·007		0·000

*Value of $se_{y.x}$ not presented if calibration not significant.

Regression of n on ρ_b resulted in a much better calibration than the regression of gamma count on corrected ρ_b. The coefficient of determination (r^2) is greater for the former calibration at all depths greater (Table 5.13). However, the r^2 value at each depth is lower than for any of the moisture calibrations at the same depth (Table 5.11). Calibrations were not pooled between depths as a trend of increasing density with depth was observed (Table 5.10).

Tests of accuracy

The mean relative error (MRE) is lower for the regression of n_{ρ_b} on θ_{v3D} than the regressions of n on θ_v and θ_g (Table 5.14). However, as the difference between MRE's is much less than the standard error of MRE, differences between the MRE of calibrations tested can only be interpreted as trends. The magnitude of MRE for all three neutron moisture meter θ_v calibrations is similar to those of Hodgson and Chan (1987).

Table 5.14 Measured values of gravimetric (θ_g) and volumetric (θ_v) water contents, density (ρ_b), and θ_v (θ_{v3D}) and air filled porosity (ε_{a3D}) corrected for 3-dimensional shrinkage measured in samples from 24 sites at 0·3 m depth, compared with values predicted by neutron moisture meter calibrations. Predictions for θ_{v3D} and ε_{a3D} are compared with values calculated from θ_g predicted by calibration, and 3-dimensional shrinkage relationships (θ_{v3Dc}, ε_{a3Dc}). Field 30, Auscott, Warren, 1985.

	Measured values			Predicted values			mean relative error (MRE)	s.d. of MRE
	Max	Mean	Min	Max	Mean	Min		
θ_g	0·252	0·209	0·164	0·275	0·211	0·181	0·084	0·068
θ_v	0·353	0·313	0·267	0·378	0·332	0·296	0·097	0·053
θ_{v3D}	0·385	0·326	0·263	0·376	0·317	0·266	0·076	0·051
θ_{v3Dc}	0·385	0·326	0·263	0·379	0·328	0·287	0·084	0·051
ε_{a3D}	0·132	0·100	0·050	0·132	0·100	0·064	0·187	0·138
ε_{a3Dc}	0·132	0·100	0·050	0·126	0·093	0·055	0·198	0·125
ρ_b	1·63	1·51	1·40	1·68	1·61	1·53	0·069	0·041

The accuracy of ε_{a3D} predicted by regression of n_{ρ_b} on ε_{a3D} is lower than the accuracy of θ_v predictions (Table 5.14), while the accuracy of prediction of ρ_b is similar to that of θ_v predictions.

Comparison of the accuracy of prediction of ε_{a3D} and θ_{v3D} directly from neutron moisture meter counts (Method 1) with prediction from θ_g predicted by neutron moisture meter counts using Method 2 (ε_{a3Dc} and θ_{v3Dc})was undertaken (Table 5.14). In both cases, a small, insignificant, loss of accuracy occurs as a result of the calculation of values from predicted θ_g.

5.3.4 Discussion

The calibration between uncorrected θ_v and uncorrected n is the most precise soil moisture calibration obtained in this experiment and was selected for measuring θ_v in this study. Corrections for shrinkage should improve the accuracy of the neutron moisture meter calibration, as the failure to sample cracks adequately increases measured ρ_b (Chan, 1981; Yule, 1984; Jarvis and Leeds-Harrison, 1987), and thus increases θ_v and decreases ε_a. However, results obtained in this study have shown that the soil does not follow normal shrinkage over the range of field water contents. Structural shrinkage was recorded for clods sampled after an irrigation near the site of this calibration (Section 5.2.3); this accords with structural shrinkage recorded in a nearby field by T.S. Abbott (personal communication), and in a similar soil at Narrabri by McGarry and Malafant (1987a). Also, obtaining values for $\rho_{b_{min}}$ and $\varepsilon_{a_{min}}$ at depth for the shrinkage models is difficult given the problems in wetting the soil beyond 0·8 m (Hodgson and Chan, 1982). Because of these problems, the small errors introduced by ignoring swelling in measurement of water content (Section 5.2.4), and the absence of better methods of accounting for swelling (Section 3.2), the uncorrected calibration was selected for use in the field trial.

Correction of ε_a for 3-dimensional shrinkage has important implications for predicting whether or not levels of soil aeration are adequate for plant growth. The difference between values of θ_v and $\theta_{v_{3D}}$ (Table 5.8), result from an air space around the soil volume being simulated in the shrinkage model. This air space is not sampled by the 75 mm diameter cores used in this study, as these cores do not adequately sample cracks. McKenzie *et al.* (1987) claimed that published levels of aeration were inadequate because roots grew in a cracking grey clay for which published levels of critical ε_a indicated that aeration was insufficient for growth. The anomaly is at least partly due inadequate crack sampling with 75 mm diameter cores used in the study resulting in an underestimation of ε_a.

Further evidence of the higher sensitivity to error of ε_a compared with ρ_b and θ_v is provided by the higher MRE values for ε_a. This arises as ε_a is not measured directly, but by subtracting solid and water volume from total volume. Thus error in measuring any of these three values will contribute to error in measured ε_a.

It is adequate to substitute θ_g predicted by the neutron moisture meter into shrinkage equations as outlined in Method 2 (Section 5.3.2) when predicting ε_a corrected for shrinkage with the neutron moisture meter. The accuracy with which $\varepsilon_{a_{3D}}$ was predicted by n_{ρ_b} using Method 1 (Section 5.3.2) was similar to the accuracy with which $\varepsilon_{a_{3D_C}}$ was predicted indirectly from the regression of n on θ_g using Method 2 (Table 5.14). As $\rho_{b_{min}}$, ρ_s and $\varepsilon_{a_{min}}$ are constant for a given site, θ_g is the only factor used to calculate $\varepsilon_{a_{3D}}$ using Method 2 which varies from one measurement time to the next. In addition, n_{ρ_b} is calculated by an iterative procedure in which $\rho_{b_{3D}}$ is both predicted by n_{ρ_b} and used to calculate n_{ρ_b}. Thus the simpler method of calculating $\varepsilon_{a_{3D}}$ from the θ_g predicted by the neutron moisture meter (Method 2) rather than using a separate calibration for $\varepsilon_{a_{3D}}$ (Method 1) is recommended.

The poor calibration for ρ_b obtained from the gamma density meter is not surprising when the effect of correction for water content is taken into account. In a swelling soil, increased water content causes a decrease in bulk density, so use of Christensen's (1974) density correction reduces the range of density sampled (Table 5.10). Conversely, the much better calibration of neutron moisture meter than gamma density meter ratio with measured ρ_b reflects the strong influence of water content on density (Figure 5.5).

5.3.5 Conclusions

The use of corrections for changes in density did not improve the precision of the neutron moisture meter calibration, and led to only a small increase in accuracy. The use of shrinkage models is only beneficial when applied to specific situations such as the determination of ε_a. It is thus recommended that the calibration of n on θ_v be used to predict soil water content.

Prediction of ε_a is improved by the use of the 3-dimensional shrinkage model. The simplest means of determining ε_{a3D} is from the θ_g calibration rather than a separate ε_{a3D} calibration, and should be used.

The gamma density meter was a poor predictor of soil ρ_b. The neutron moisture meter provided a more precise density calibration, and should be sufficiently accurate if measurements are taken at each field site to check the calibration.

CHAPTER 6

CROP GROWTH AND SOIL PHYSICAL CONDITIONS IN THE 1984/85 COTTON SEASON

6.1 INTRODUCTION

The influence of deep tillage on soil structure and its effect on plant growth is central to this study. The primary aim of deep tillage is to decompact hard layers, which can restrict root growth and sometimes cause horizontal deflection of cotton tap roots (Beale, 1982). Consequently, a measure of the state of compaction of each of the tillage treatments is important in differentiating between tillage treatments.

The cone penetrometer is the instrument most widely used for measurement of soil strength in the field, as data can be rapidly and easily collected (O'Sullivan and Ball, 1982). Portable recording penetrometers record data automatically, and are more sensitive than non-recording models in detecting abrupt changes in penetration resistance (Anderson *et al.*, 1980).

Information on soil water and plant growth was also required to evaluate tillage treatments. Soil water is one of the main controls of plant growth and it interacts with all other factors affected by compaction (Boone, 1986). Soil water content is thus a datum against which comparisons between other measures, such as density in swelling soils, penetration resistance and aeration, can be made at different times and locations (Gardner, 1986). A quick, accurate measure of soil water, provided by the neutron moisture meter described in Section 5.3.1, is thus important in a study of soil physical properties. Although plant growth is indirectly related to the initial tillage treatments, it may be regarded as the end product of tillage operations and is the main measure by which performance of tillage systems is judged.

Tillage treatments were imposed at the experimental site in May, 1984, and the cotton crop was planted in the following October. Soil water, cone penetration resistance, and cotton growth were monitored in the period January to April, 1985. In addition, geostatistical analysis, described in Section 3.3, was undertaken to investigate the spatial variability of soil moisture at the experimental site.

6.2 MATERIALS AND METHODS

In this section only those factors specific to the 1984/85 cotton crop are described. Overall design of the trial, together with an outline of cultural practices used in managing cotton crops grown on the experimental site, are described in Section 4.

Management summary

Climate in the 1984/85 cotton season was favourable for cotton growth, with yields on the farm surrounding the experimental site being the highest since commercial cotton production started in the 1967/68 season (Figure 1.2). Only 138 mm of rain fell during the growing season, while maximum and minimum temperatures were between the optima of 27-35°C and 15-20°C respectively (Thomson, 1979) for extended periods (Figure 6.1).

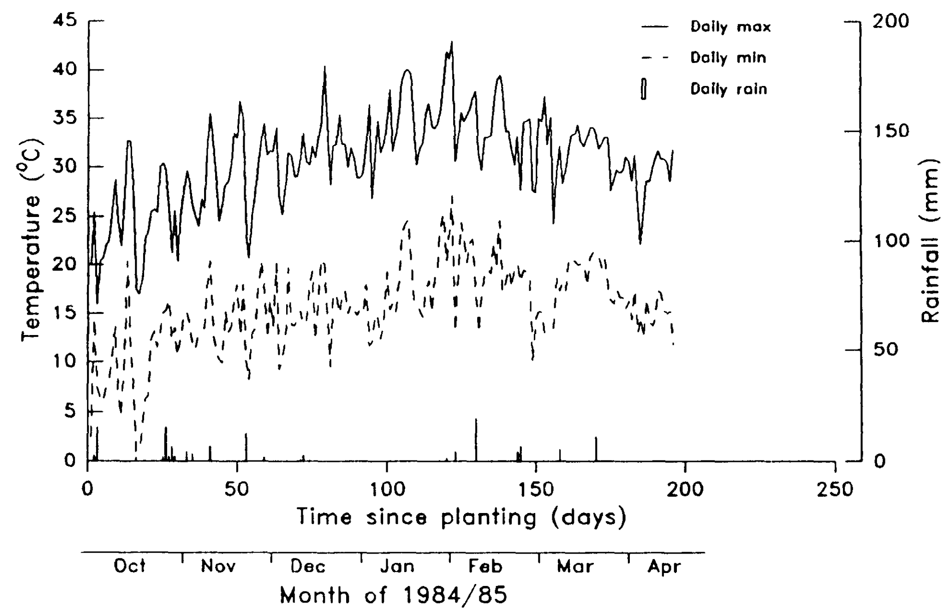


Figure 6.1 Climatic conditions at Field 30, Auscott Warren for 1984/85 season.

The experimental crop was planted on 2/10/84, and 17 mm of rain over the next two days was sufficient to germinate the crop. Five passes of wheeled machinery were made over the field after planting, two for chemical application and three interrow cultivations. During the growing season the field received 11 insecticide applications and five furrow irrigations (Table 6.1). No rain fell during picking of the crop, minimizing any soil structural damage caused by harvesting machinery.

Water content and geostatistical analysis

Soil water content was determined at 0·2, 0·3, 0·4, 0·5, 0·6, 0·8, and 1·0 m depths at 20 locations in each of the nine plots by taking duplicate 15 second readings with a neutron moisture meter and using the calibration described in Section 5.3. Aluminium access tubes 50 mm in diameter had been installed adjacent to cotton plants in the three days prior to irrigations in January along a transect at 26 m spacings from the head ditch to the tail drain.(Appendix 2). Readings were taken during the 24 hrs preceding each subsequent irrigation, and repeated as soon as the soil was traffickable after irrigation. A standard count was determined in an access tube, identical to those used in the field, suspended in a 200 l drum of rainwater. Standard counts were recorded each day to check the consistency of the neutron moisture meter.

Geostatistical analysis of the water content data was undertaken to ascertain the nature of spatial variation (Section 3.3). Semivariograms were fitted to the data using median polish kriging described by Cressie (1986). In geostatistical analysis variation in variance from the mean is the property of interest

TABLE 6.1 Cultural operations and pesticide application during 1984/85 cotton crop, Field 30, Auscott Warren (Ground and Aerial refer to chemical application methods).

Date	Operation	Chemical	Rate
1984			
May	Tillage treatments imposed		
22/8	Cultivator	Trifluralin	3·0 l ha^{-1}
		Fluometuron	1·0 kg ha^{-1}
9/9	Lilliston		
5/10	Planting	Fluometuron	0·6 kg ha^{-1}
		Diuron	1·2 kg ha^{-1}
31/10	Ground herbicide	M.S.M.A.	2·8 l ha^{-1}
18/11	Cultivator		
28/11	Ground insecticide	Endosulfan	2·1 l ha^{-1}
4/12	Cultivator		
10/12	Aerial insecticide	Chlordimeform	0·5 l ha^{-1}
20/12	Aerial insecticide	Endosulfan	3·0 l ha^{-1}
21/12	Aerial fertilizer	$CO(NH_2)_2$	16 kg ha^{-1}
22/12	First crop irrigation		
1985			
2/1	Aerial insecticide	Dipel	0·5 l ha^{-1}
		Chlordimeform	0·5 l ha^{-1}
8/1	Cultivator		
10/1	Aerial insecticide	Endosulfan	3·0 l ha^{-1}
12/1	Second crop irrigation		
24/1	Aerial insecticide	Ripcord	1·0 l ha^{-1}
		Chlordimeform	0·5 l ha^{-1}
25/1	Third crop irrigation		
6/2	Fourth crop irrigation		
7/2	Aerial insecticide	Decis	3·0 l ha^{-1}
18/2	Fifth crop irrigation		
20/2	Aerial insecticide	Rogor	0·3 l ha^{-1}
26/2	Aerial insecticide	Rogor	0·3 l ha^{-1}
22/3	Aerial conditioner	Def	1·4 l ha^{-1}
1/4	Aerial desiccant	$NaClO_3$	14 l ha^{-1}
15/4	Cotton picking		

rather than variation in the mean. Thus the median polish is used in median polish kriging to remove trends in the mean before the semivariogram is fitted. The median polish of θ_v at a given depth and location ($\theta_{v_{ij}}$) is described by the additive model of equation 3.3.4 where $\theta_{v_{ij}}$ is substituted for Y_{ij}, D_i (the depth effect) is substituted for R_i and L_j (the lateral effect or effect of location in transect) is substituted for C_j. The semivariogram was fitted to the residual values from the median polish. In this experiment, the median polish was fitted using a Fortran programme described by Velleman and Hoaglin (1981). The semivariogram was then calculated using a nonlinear least squares subroutine by fitting a spherical model (Table 3.1) weighted by:

$$(\text{Expected variance})^2 \,/\, (\text{Number of pairs for lag}) \qquad 6.2$$

as recommended by McBratney and Webster (1986).

Duration of irrigation

Total water intake of each plot was estimated for the second and subsequent irrigations by measuring the time taken for irrigation water to advance from the head ditch to the tail drain. The advance front was defined as reaching the tail drain when water flowed from at least half the central 60 furrows of a plot into the tail drain. Water flow onto a plot was calculated from the static head estimated by a water level, and syphon performance test charts (Appendix 1). Run-off was not measured because of the high flow rates used (0·3 m^3 s^{-1}) and low head available (< 0·3 m).

Penetration resistance

Cone penetration resistance was measured at 0·015 m intervals from 0 to 0·3 m using a 'Rimik' hand held recording penetrometer having a 30^0 cone with a diameter of 0·12 m. When manually pushed into the soil, the penetrometer senses force with an electronic load cell. Readings made at speeds outside the range stipulated by ASAE standard S313.1 (American Society of Agricultural Engineers, 1982) are ignored. The force recorded during each insertion is stored in a memory module, from which it is downloaded onto a computer for analysis.

At each of five access tubes equally spaced from the head ditch to the tail drain in each plot penetration resistance was measured at six sites, 0·2 m apart, in the centre of a hill. Measurements were made two days prior to and just before irrigation was due on 5/3/85. In actuality, although the cotton was suffering water deficit stress at this time it was not irrigated as an assessment was made at the time that the crop would mature without further irrigation. Concurrent measurements of θ_g were obtained gravimetrically at 0 to 0·02 m and 0·08 to 0·12 m, and using the neutron moisture meter at 0·2, and 0·3 m.

Plant measurements and yield estimates

Plant height and number of fruiting structures were measured at approximately fortnightly intervals from early January, 1985 till early April, 1985. Counts were made on six, 1 m lengths of row, equally spaced along a diagonal transect from the head ditch to tail drain in each plot.

Fruiting structures were counted as either squares, flowers, green bolls, or open bolls. A square is a floral bud, and was counted if it was greater than 1 mm in diameter. A flower forms when its petals separate at their apex, and becomes a green boll when the fused base of the petals and staminal tube separate easily from the fruit. The boll opens when locule dehiscence occurs. Plant height was measured as the vertical distance from the top of the hill to the plant's highest node.

Plant yields were measured in two ways. Seed cotton (lint and cotton seed) was hand picked six days prior to machine harvest from six 5 m lengths of row, at equally spaced intervals from one corner of each plot to the diagonally opposite corner. Secondly, machine-picked seed cotton from half the rows in each plot was measured. This sample size was selected as the seed cotton from this area filled a module, which was the unit in which seed cotton was handled on the farm. Yield from the whole of each plot could not be used to estimate the effect of tillage treatments as a machinery malfunction had left one row in each set to which no nitrogen fertilizer had been applied. The area of each plot from which cotton was harvested for yield estimates excluded the areas on which no nitrogen was applied, and rows near the edge of each plot. Lint yield and gin turnout (ratio of lint to seed cotton) of the machine harvested sample were measured.

As water plays an important role in plant growth, the effect of tillage treatments on cotton growth may be mediated through plant water deficit stress. Two indicators of plant water stress were measured. First, leaf water potential of the youngest, fully expanded, leaf was measured on five plants in one replicate of each tillage treatment prior to each monitored crop irrigation using a Scholander pressure chamber (Scholander *et al.*, 1965). Second, as cell extension is sensitive to moisture stress (Hearn, 1980), the average internode length of plants in six, 1 m row lengths, spaced similarly to the fruit counts, was recorded in each plot just after harvest.

Root density from 0 to 0·6 m depth was estimated using the core break method in which the roots intersecting a face created by breaking a core are counted (Bohm, 1979). Cores were sampled during the course of the picker compaction experiment (Section 7.2). Three transects across half a six row set (Appendix 2) were sampled at 0·25 m lateral spacings in each plot (Figure 7.1) before and after passage of cotton pickers; cores were taken no later than two weeks after harvest. The transect covered only half the set as the set is symmetric, and a transect across the whole set would repeat information from half the set. No samples were taken in one chiselled plot as it had been wheeled before sampling.

Statistical methods

Analysis of variance (ANOVA) was used to determine whether measured variables were statistically different between treatments. Linear regression was used to derive relationships between θ_g and penetration resistance. As described above geostatistical analysis was used to investigate the spatial variation of soil water.

Analysis of the size and variability of variance components (Cochran and Cox, 1957) was used to determine the optimum sampling strategy for future penetration resistance measurements. Estimates of the required sample size to achieve a 0·03 m^3 m^{-3} level of precision for the neutron moisture meter were made using Stein's two-stage sample (Steel and Torrie, 1980), which is described by equation 3.3.

6.3 RESULTS

Water content and its spatial variation

The median polish, which was used to remove trends before obtaining the semivariogram, accounted for much of the variation in θ_v between depths and between locations in the transect from the head ditch to the tail drain. Water content at any one depth was strongly dependent on values of θ_v above and below it, shown by the curve fitted to the depth effect (change in θ_v with depth) by the median polish (Figure 6.2a). The lateral effect (change in θ_v with spacing across the field) gave a less consistent trend of θ_v decreasing from the head ditch to the tail drain (Figure 6.2b). This trend was accentuated in the four access tubes closest to the tail drain.

The fitted semivariograms described lateral (between access tube) variation of residuals from the median polish of θ_v poorly, as this lateral variation had little spatial structure (Figure 6.3).

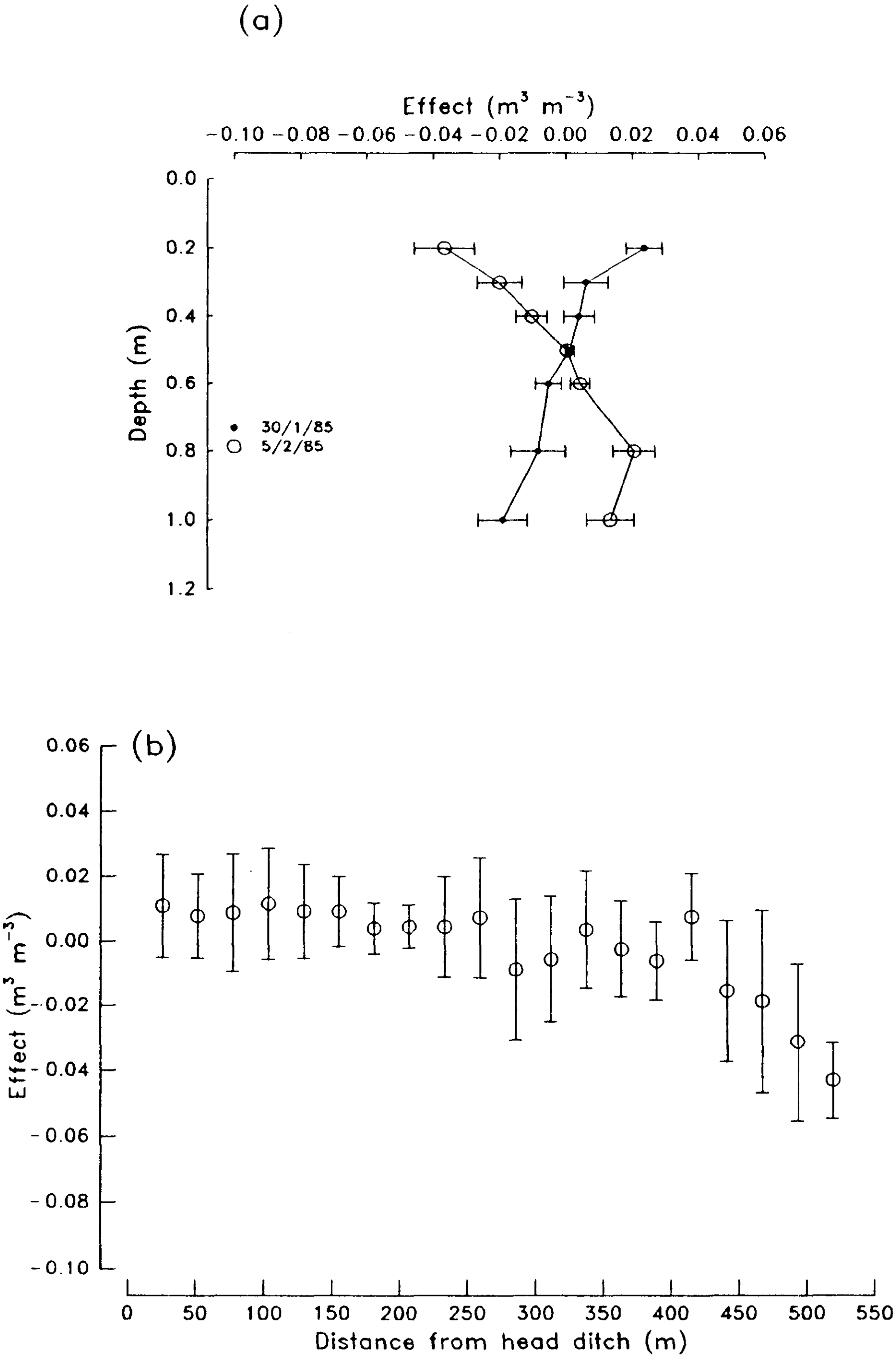


Figure 6.2 Effects fitted by median polish to volumetric water content of nine tillage plots, Field 30 Auscott, Warren.

a) Depth effect soon after irrigation (30/1/85) and one day prior to irrigation (5/2/85)

b) Lateral effect 30/1/85

Bars are twice standard deviation of measurement

Consequently, semivariograms could only be fitted to the lateral variation of residuals of θ_v from the median polish for some plots at some times, and, due to wide scatter in the semivariance, the semivariograms which were fitted represented the lateral variation poorly (Figure 6.3). It was deduced from the poor fit of the semivariograms that the range for lateral variation in θ_v was less than the 26 m separation of access tubes in the transects studied.

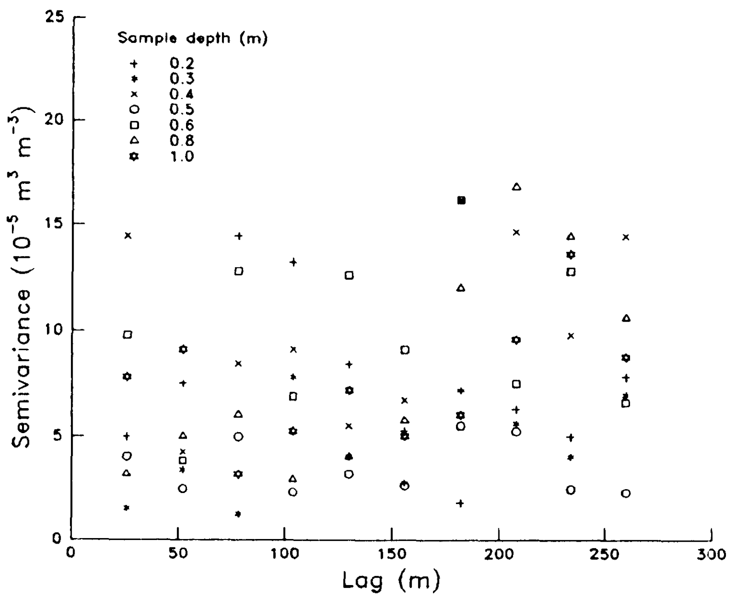


Figure 6.3 Scatter plot of semivariance of residuals from median polish of θ_v for each lag along a 520 m long transect in direct list treatment rep 2 on 5/2/85.at seven depths, Field 30 Auscott Warren.

Analysis of variance of θ_v at each of the seven depths monitored for each of the ten measurement times showed no significant treatment differences. A trend of slightly higher θ_v in the ripped soil than either the direct listed or chiselled soil was noted for all depths below 0·2 m at each recording time (Figure 6.4). This trend was significant in the 1986/87 season The magnitude of changes in soil water content between measurement times decreased with depth, with only small differences in θ_v occurring at 1·0 m (Figure 6.4b).

Variation in the nested ANOVA for θ_v was partitioned to strata of the experimental design. Strata were: blocks in the randomized complete block design, tillage treatments within blocks, access tube sites within each tillage treatment and neutron moisture meter readings within each plot. Standard errors for the reading stratum were an order of magnitude smaller than standard errors for the access tube stratum (Figure 6.5). This indicates that the precision of θ_v measurement is improved little by taking two rather than one reading at a given time in each access tube at each depth. The same analysis indicated that six access tubes in each plot were sufficient to obtain the desired precision of 0·03 m^3 m^{-3} (Figure 6.5).

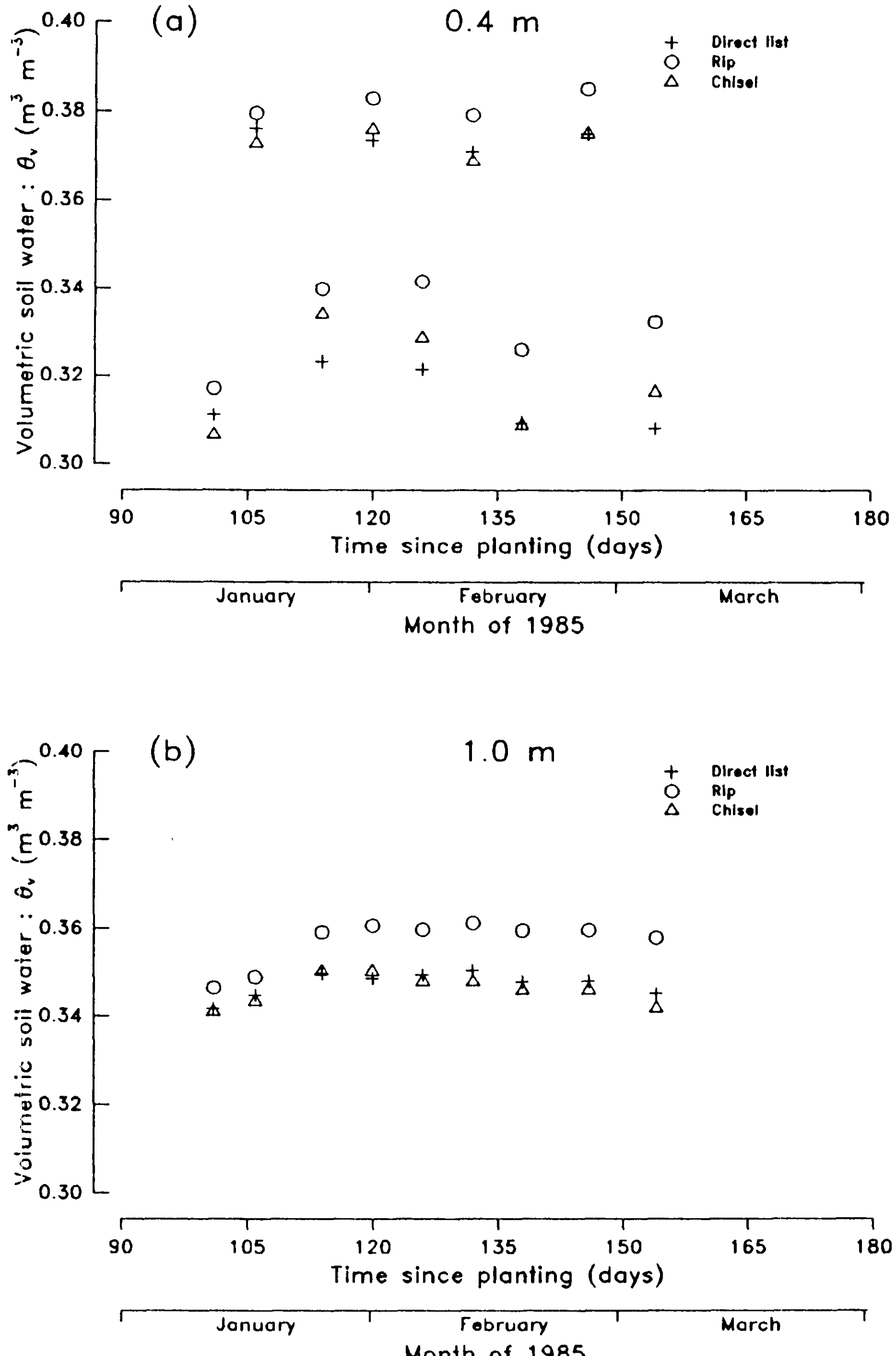


Figure 6.4 Volumetric soil water measured at two depths, a) 0·4 m and b) 1·0 m before (drier values) and after (wetter values) irrigation in three tillage treatments. Each point is a mean of 120 readings. No significant differences between treatment water contents were detected for any measurement time. Field 30 Auscott, Warren.

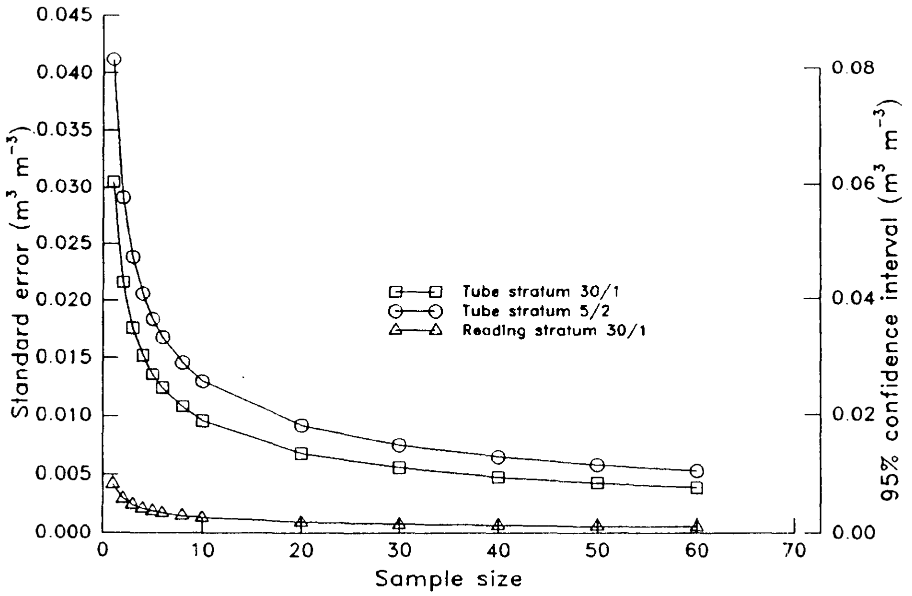


Figure 6.5 Standard error predicted for neutron moisture meter from data collected at Field 30 Auscott Warren in 1985. Strata refer to components of variance in analysis of variance. Readings on 30/1 were in moist soil, while readings on 5/2 were in dry soil.

Duration of irrigation

The duration of irrigation in the ripped plots was greater than for chiselled plots for each of the four irrigations monitored (Figure 6.6). Irrigation duration in the direct listed plots was similar to the ripped plots for the first two irrigations, and similar to the chiselled plots for the second two. The duration of irrigation declined with each irrigation.

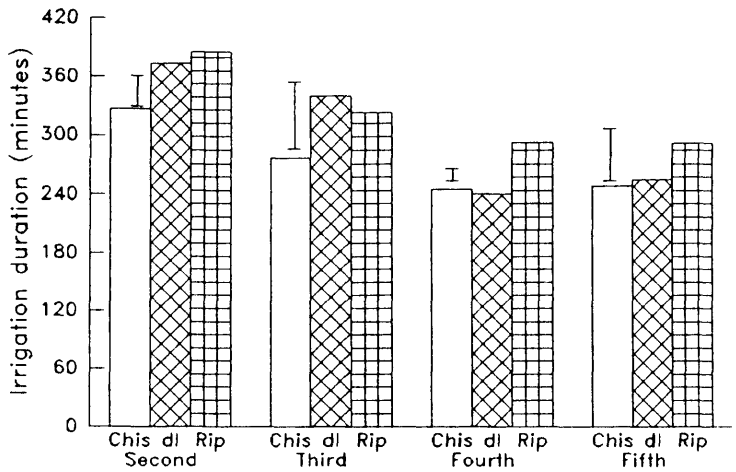


Figure 6.6 Median elapsed time for water to run from head ditch to tail drain in the central 60 furrows in each plot in second, third , fourth and fifth crop irrigations, Field 30, Auscott Warren. Bars are for 5% l.s.d..

Penetration resistance

Penetration resistance profiles for both 2 and 0 days before irrigation was due on 5/3/85 showed few significant treatment differences (Figure 6.7). Values increased markedly between the two measurement times.

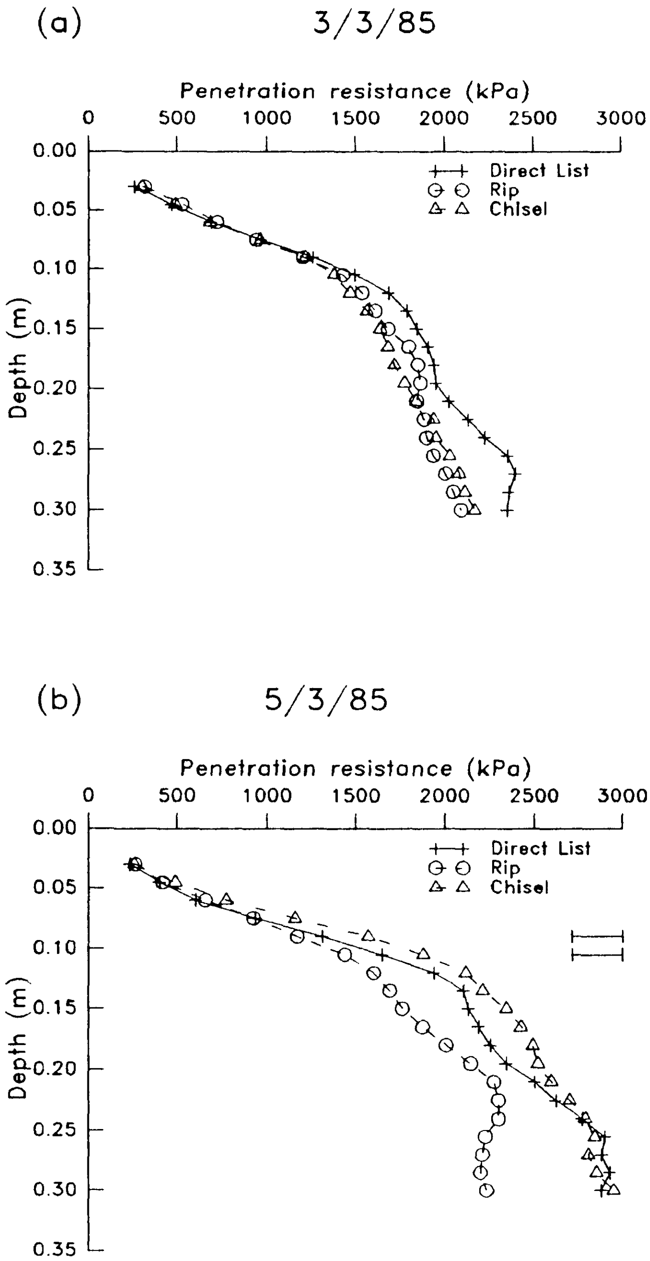


Figure 6.7 Resistance to cone penetration in the centre of cotton hills a)two and b) zero days before irrigation due on 5/3/85. Each point represents the average of 45 readings taken at Field 30, Auscott, Warren. Bars represent 5% l.s.d. for depths at which differences were statistically significant.

Concurrent measurements of θ_g with penetration resistance showed no significant differences between treatments (Table 6.2). Covariate analysis of θ_g with penetration resistance had little effect on penetration resistance values, and is not presented.

TABLE 6.2 Gravimetric soil water (θ_g, kg kg^{-1}) measured concurrently with penetration resistance at two and zero days before irrigation due on 5/3/85 , Field 30, Auscott, Warren (DL is direct list)

Depth (m)	Treatment DL	Rip	Chisel	5% l.s.d.
3/3/85				
0·03	0·142	0·122	0·129	0·027
0·10	0·200	0·207	0·197	0·023
0·20	0·206	0·225	0·208	0·047
0·30	0·228	0·249	0·238	0·031
5/3/85				
0·03	0·124	0·125	0·128	0·038
0·10	0·178	0·185	0·161	0·035
0·20	0·192	0·205	0·192	0·045
0·30	0·219	0·236	0·225	0·035

Linear regressions of penetration resistance against θ_g were calculated for data collected on 5/3/85. Significant coefficients of determination (r^2) were obtained at 0·1, 0·2, and 0·3 m, but not 0·03 m (Table 6.3). However, the larger values of standard error of the estimate of y for a fixed x ($se_{y.x}$) indicated that these regressions could only be used to give general indications of penetration resistance expected for a given θ_g.

TABLE 6.3 Linear regression of penetration resistance (kPa) on gravimetric soil water (θ_g, kg kg^{-1}), Field 30, Auscott Warren, 5/3/85 (a and b are intercept of fitted lines with standard error of coefficient, se; $se_{y.x}$ is standard error of y for fixed x).

Depth (m)	a	se	b	se	r^2	$se_{y.x}$
0·03					0	
0·10	3463	394	-10 500	2226	0·328	400
0·20	3971	575	-9 036	3170	0·145	532
0·30	6060	780	-15 900	3654	0·299	558

Variance components compared in error analysis were: insertions within blocks, treatments and sample sites (IWBTS), sample sites within blocks and treatments (SWBT), and blocks by treatments (BT). In summary, the coefficient of variation of the variance component estimates increased from 20% for the IWBTS level through 50 to 80% for the SWBT level to 100% and greater for the BT level. The potential increase in precision is directly related to the coefficient of variation of the variance component, so the most benefit could be gained by increasing the number of blocks, then the number of sites in each plot, and the least benefit from increasing the number of insertions at each site. As it was not possible to increase the number of blocks, an increase in the number of sampling sites in each plot was recommended in order to increase the precision of measurements.

Plant growth and yield

Cotton plants in the direct listed areas carried more squares than the ripped areas, which had more squares than the chiselled areas on 5/1/85 (Figure 6.8). These were the only differences in fruit counts detected, apart from a higher green boll count in both the direct listed and chiselled than ripped areas five weeks later on 11/2/85.

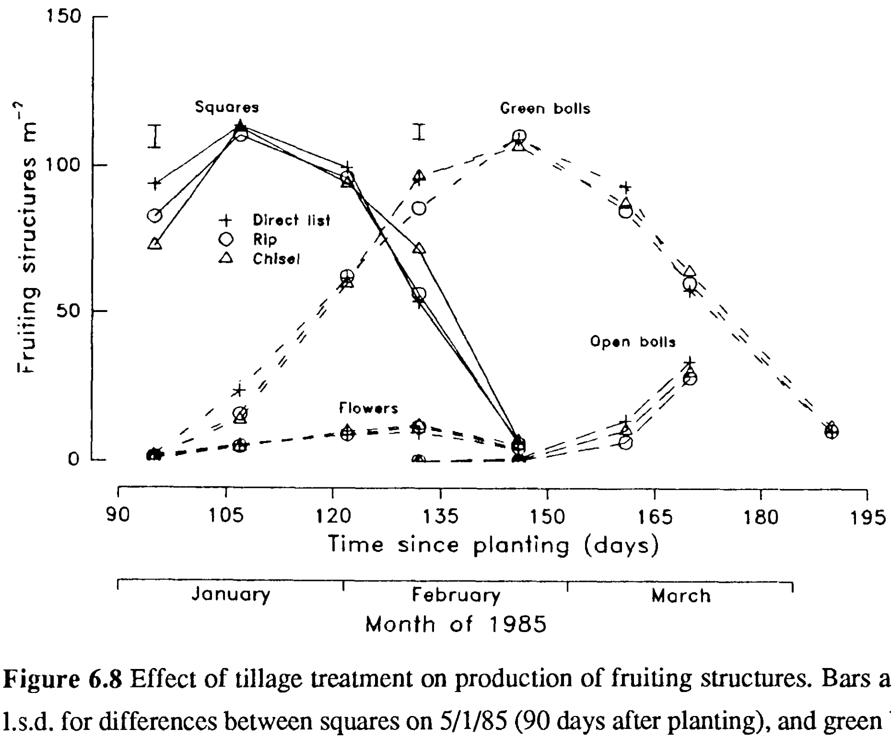


Figure 6.8 Effect of tillage treatment on production of fruiting structures. Bars are 5% l.s.d. for differences between squares on 5/1/85 (90 days after planting), and green bolls on 11/2/85 (132 days after planting).

Plant height in all treatments increased linearly from 0·28 m on 5/1/85 to 0·5 m on 11/2/85, and then slowly declined to 0·45 m at picking due to bending of plant stems as the weight of bolls increased.

Both hand and machine picked yield estimates showed a trend of the direct listed treatments having the highest cotton yield (Table 6.4). Machine-picked yield estimates were 9% higher than hand picked estimates, due to the hand-picking being carried out six days before machine-picking.

TABLE 6.4 Hand and machine picked yield estimates (kg ha^{-1}), Field 30, Auscott, Warren, 1985 (Seed is seed cotton which is lint plus seed, Turnout is the ratio of lint to seed cotton given as a percentage).

Picking method	Yield estimate	Treatment DL	Rip	Chisel	5% l.s.d.
Hand	Seed	3756	3502	3606	384
Machine	Seed	4149	3970	4018	336
Machine	Lint	1493	1466	1417	78
Turnout		36·4	37·9	35·6	1·8

Root distribution indicated by the core break method was similar under both treatments for which statistical analysis was conducted (Table 6.5). Root density was greatest near the surface under the hill, and tended to decline with depth and distance from the centre of the hill, although considerable amounts of roots were still present at 0·4 to 0·5 m, the greatest depth sampled.

TABLE 6.5 Root length (10^3 m m^{-3}) beneath ripped and direct list treatments determined by core break method on samples taken up to two weeks after picking, Field 30, Auscott Warren. The l.s.d. for each location was greater than the tabulated value. (Sample depth was measured from the top of adjacent hills; Hill, Half and Furrow are sample locations across a transect from the centre of a hill to the centre of a furrow).

Depth	Direct list			Rip		
(m)	Hill	Half	Furrow	Hill	Half	Furrow
0·05	3·40			3·87		
0·15	2·61	2·16		2·76	2·39	
0·25	1·65	1·84	1·29	2·49	2·04	1·48
0·35	1·91	2·13	1·48	2·37	2·04	1·32
0·45	2·32	1·96	1·72	1·84	1·56	1·53

Leaf water potential measurements suggested that tillage treatment was influencing water supply to plants. Leaf water potential of the three plots tested was similar at -15 bars on 14/2/85, three days before irrigation on 17/2/85. Two days later, leaf water potential had decreased to -21·3 bars (s.d. 2·5 bars) in the direct listed plot, but was only -18·9 bars (s.d. 2·1 bars) and -17·4 bars (s.d. 1·8 bars) in the chiselled and ripped plots respectively. A mean internode length of 32 mm for an average 17 nodes between the soil surface and plant apex was common to all 3 treatments.

6.4 DISCUSSION

Very few significant treatment differences were measured during the 1985 cotton season. Consistent trends indicated better soil physical conditions in the form of lower penetration resistance and higher θ_v in the ripped than direct listed soil, yet plant growth trends suggested better conditions for plant growth in the direct listed soils. The most important question arising from this conundrum is whether or not real differences between the tillage treatments occurred which we were unable to detect, either through choice of unsuitable indicators of soil conditions for plant growth, or ineffective use of the selected indicators.

Given the importance of water in mediating the effect of soil physical properties on plant growth, some measure of soil water status is essential in assessing the effect of tillage on soil properties. The two measures used in the 1984/85 season gave conflicting impressions of the effect of the tillage treatments on soil water status.

The neutron moisture meter indicated no difference between the water content of each tillage treatment throughout the period monitored, from which it was deduced the water use in all three treatments was similar. Gravimetric soil water (θ_g) measured by gravimetric sampling at 0·03 and 0·1 m was also similar for the three treatments.

The longer duration of irrigation in the ripped than in the chiselled plots indicated, however, greater water use in the ripped plots. Infiltration in vertisols is a self-ending process (Smedema, 1984), with instantaneous infiltration (filling of cracks) accounting for greater than 70% of the infiltration over a period of 6 to 8 hours in soils similar to the one in this study (Collis-George and Freebairn, 1979; Read and Collis-George, 1979). Consequently, only small deep percolation losses occur in these soils, and irrigation duration should be related directly to total water infiltration. The longer duration of irrigation in the ripped than in the chiselled soils should therefore be associated with either increased water use or an increase in profile water of the ripped compared to the chiselled treatments from one irrigation to the next. The latter explanation is at variance with the neutron moisture meter results.

Duration of irrigation is affected by factors other than infiltration, such as slope, furrow roughness and furrow geometry (Holzapfel *et al.*, 1984). Furthermore, no account has been taken of differences in run-off from the plots. The large proportion of water entering the soil as instantaneous infiltration (Collis-George and Freebairn, 1979) means that run-off quickly attains the rate of water flow onto the plot of 0·3 m^3 s^{-1}. The run-off could not be measured with the resources available to the project as run-off flow rate varies rapidly and the water head available to measure run-off was limited 0·3 m by the shallow drains carrying water from the field. Flow rate through measurement devices of the underflow class, such as the syphons described in Appendix 1, increases with the square root of the available water head, therefore they can not be used to measure flow rates which vary rapidly. It was concluded that the neutron moisture meter provides a more reliable measure of soil water status and no future measurement of irrigation duration would be attempted, nor would any reliance be placed on the irrigation duration data collected.

Penetration resistance, the only direct measure of soil physical condition taken during the 1984/85 season, indicated better conditions for root growth in the ripped than direct listed and chiselled soils. At depths greater than 0·2 m on the day irrigation was due, the mean cone index in the direct listed and chiselled, but not ripped, soil tended to be greater than the 2500 kPa, the value above which Taylor et *al.* (1966) observed no cotton root growth.

The absence of significant treatment differences in penetration resistance at 0·25 m and deeper, given that smaller differences above 0·1 m are significant, may be accounted for by the increase in the size of structural units with depth (Chan, 1981). Variability of penetration resistance increases with the size of structural units, due to resistance changing from being a function of interaggregate strength to a function of intraaggregate strength (Bradford, 1986). The tendency toward lower penetration resistance in the ripped soil, in which aggregate size is smaller, is related to changes in interaggregate rather than intraaggregate properties. This large variability in penetration resistance is also responsible for the poor correlations of penetration resistance with θ_g.

The limited measures of leaf water potential reinforce the indication obtained from penetrometer measures of better rooting conditions in the ripped than direct listed soil. The poorer rooting conditions were not reflected by lower cotton yields in the direct listed plots, as irrigation was applied before leaf water potential fell to the -24 bar level, below which Hearn and Constable (1984) observed cotton yield decline. As leaf water potential measurements did not fall to this level, the similarity of internode lengths between treatments is to be expected. As trends of treatment differences in leaf water potential only became apparent shortly before irrigation, increasing the frequency of leaf water potential measurement will only be beneficial if the crop is subjected to water deficit stress, such as when assessing plant available water capacity (PAWC) of the tillage treatments. As tillage treatment PAWC will not be estimated in this project, no further leaf water potential measurements will be taken during the project.

Cotton growing on direct listed treatments developed fruiting structures earlier, and tended to yield more than on the ripped or chiselled treatments. This discrepancy between results of soil and plant measurements could have arisen as a result of irrigation management overriding soil differences created by the tillage treatments (Carter and Colwick, 1971). The irrigation management regime favoured the direct listed treatments as all tillage treatments were irrigated as soon as the first symptoms of water deficit stress were observed, which was usually in the direct listed plots. In addition, by concentrating on measurement of soil properties at the dry end of the irrigation cycle, the effects of waterlogging, which have been shown to be important in limiting cotton growth in vertisols (Chan and Hodgson, 1981; Hodgson and Chan, 1982; Hearn and Constable, 1984) have been ignored.

A number of changes in the use of the neutron moisture meter and penetrometer were recommended as a result of analyses of data collected in the 1984/85 season. The median polish performed before fitting semivariograms (Figure 6.2b) showed that the area within 80 m of the tail drain is atypical of the rest of the field, and should be discarded from any future measurements. However, the reminder of the field was uniform in terms of water content. The semivariogram fitted to residuals from the median polish followed a transitive model rather than an unbounded model (Section 3.3.2) and had a range of less than 26 m, which is in accordance with values for the range presented by Wierenga (1985) (Section 3.3.2). The from of the spatial variation demonstrated that classical statistical analysis could be applied to information from the neutron moisture meter whether the access tubes are placed 26 m or 260 m apart. Closer tube placement would reduce the time spent walking between samples, permitting more measurements to be made in a day. The median polish also showed that readings at one depth within an access tube are strongly dependent on those above and below. Thus, the readings at 0·3 and 0·5 m provide little extra information over those at 0·2, 0·4 and 0·6 m, and should not be taken.

Analysis of variance components showed that taking more than one reading at each depth gave little increase in precision, and should be abandoned for routine measurements. Similarly, precision improved only slowly by increasing tube number above six access tubes per plot.

Improvements in measuring penetration resistance are restricted by its inherent variability (O'Sullivan et *al.*, 1987). Because of this constraint, the fixed number of measurements that can be taken in a day, and the restrictions on degrees of freedom imposed by the number of blocks and treatments in the experiment, the efficiency of the penetrometer in detecting treatment differences can be improved by making fewer insertions at more sites in each plot.

6.5 CONCLUSIONS

In the 1984/85 season, no yield penalty was suffered by planting cotton into permanent beds formed by direct listing compared to the two alternative seedbed preparation methods where beds were knocked down and reformed.

Despite the paucity of statistically significant differences between treatments, all differences detected indicated better soil conditions in the ripped than direct listed plots. However, under the prevailing climatic and management regimes, cotton plants did not appear to exploit the more favourable soil conditions in the ripped plots.

Improvements in methods of evaluating soil conditions are needed to quantify differences between tillage treatments. To estimate the degree and duration of waterlogging, increased emphasis should be given to conditions soon after irrigation. The small variability across the field means that neutron moisture meter access tubes need not be any further than 26 m apart while, because of the strong correlation of θ_v between depths, readings should be separated by at least 0·2 m depth. Only one neutron moisture meter reading need be taken per depth unless very high precision is required. Subject to the constraints imposed by the design of this experiment, the sensitivity of penetration resistance in detecting treatment differences would be increased by making insertions much further than 1 m apart, whilst remaining sufficiently close to access tubes to obtain associated moisture measurements.

CHAPTER 7

EVALUATION OF METHODS FOR MEASUREMENT OF SOIL PHYSICAL PROPERTIES IN VERTISOLS

7.1 INTRODUCTION

The few differences in soil properties detected in the 1984/85 cotton season suggested a need to test whether differences in soil physical properties affecting cotton growth could be better identified either by using additional indicators or by improved use of current indicators. Two studies were conducted between harvest of the 1984/85 crop and planting of the 1986/87 crop with the aim of improving methods of characterizing the level of physical fertility in vertisols.

7.2 ASSESSING THE EFFECT OF WHEEL PASSAGE AT DIFFERENT WATER CONTENTS

7.2.1 Introduction

A cotton crop needs to be harvested quickly after maturity because of the marked decline in yield and quality with time (Colwick and Williamson, 1968). Cotton picking occurs in a period of decreasing evaporative demand on soil (Table 4.2); defoliation of the plants prior to picking results in negligible loss of water from the cotton field through transpiration. Consequently, significant falls of rain between defoliation and cotton picking are commonly associated with dramatic soil structural damage (D. Anthony, personal communication), due to the low strength of wet soil (Section 2.2.1).

An experiment was conducted to compare the efficiency of penetration resistance and field bulk density as indicators of structural degradation in response to the passage of cotton pickers over soil at three water contents. A subsidiary experiment was conducted to quantify soil damage caused during harvest of the wheat crop grown between the two cotton crops (see Table 4.1). In this experiment, penetration resistance in untrafficked soil was compared with penetration resistance in soil trafficked by a wheat header.

7.2.2 Materials and methods

7.2.2.1 Picker compaction experiment

Experiment establishment

Three moisture treatments - dry, moist and wet - were applied to plots near the head ditch in one 6 row set (defined in Appendix 2) randomly selected from the 15 sets in each tillage plot of the main experiment. Moisture treatments were arranged in a Latin Square design within plots. Water was applied to the plots via a 45 m length of hose so plots had to be located close to the head ditch. This end of the field was selected in preference to the tail drain end as geostatistical analysis had shown that water contents near the head ditch, but not tail ditch, were typical of the rest of the field (Section 6.3). The moisture treatment closest to the head ditch was 15 m from the edge of the cotton field, with the two remaining plots a further 10 and 20 m away. Each moisture plot was 4 m by 4·5 m.

Water was applied to the moist and wet plots on 4/4/85 by ponding and spraying respectively. Around the moist plots a bank of soil was formed to impound water, however substantial leakage occurred through cracks in the soil which were up to 1 m deep. A second water application was ponded on the wet plots on 19/4/85. Leakage through the soil at this time was much less due to soil swelling after wetting of the wet plots by spraying on 4/4/85, leading to the application of a smaller depth of water to the wet than moist plots (Table 7.1). All dry plots were covered with plastic sheet on 4/4/85 to prevent infiltration of water from rain.

Table 7.1 Depth of water (mm) added to wet and moist plots and date of wetting, before passage of cotton picker on 23/4/85, Field 30, Auscott, Warren.

Plot	Moist	Wet	
	4/4/85	5/4/85	19/4/85
1	306	80	250
2	381	80	250
3	266	80	250
4	278	80	250
5	269	80	250
6	291	80	250
7	316	80	250
8	331	80	250
9	369	80	250

After collection of one set of samples as described below, a cotton picker weighing 7980 kg, with a front tyre pressure of 186 kPa and rear tyre pressure of 117 kPa, was driven at a speed comparable to that used in normal picking over furrows in all plots on 23/4/86.

Field sampling

Soil cores were collected from adjacent areas of each moisture subplot before and after passage of the cotton picker. The cores were taken in a transect perpendicular to the cotton rows at 0·25 m intervals starting in the centre of the outermost hill in a set, and running to the centre furrow of that set (Figure 7.1). Cores were collected from sampling tubes, 46 mm internal diameter (i.d.), and 50·5 mm outside diameter, with a tip relieved outward from 38·5 mm i.d. (Figure 7.2). Cores were pushed 0·6 m into the soil using a hydraulic ram, supplemented by a jackhammer, on a tractor-mounted frame. To reduce the likelihood of soil deformation affecting measured density, any core with a length measurably different to the hole from which it was taken was discarded. Cores were sectioned into lengths such that they were equivalent depth intervals of 0·1 m from the top of adjacent hills. The top of adjacent hills was used as a datum, rather than soil surface, to facilitate comparisons between soil before and after wheel passage (Jakobsen and Greacen, 1985; O'Sullivan *et al.*, 1987). Vertical distance from the top of adjacent hills to the soil surface was recorded at each coring site. Sections of cores were placed into airtight jars and stored at 5°C until laboratory measurements were made.

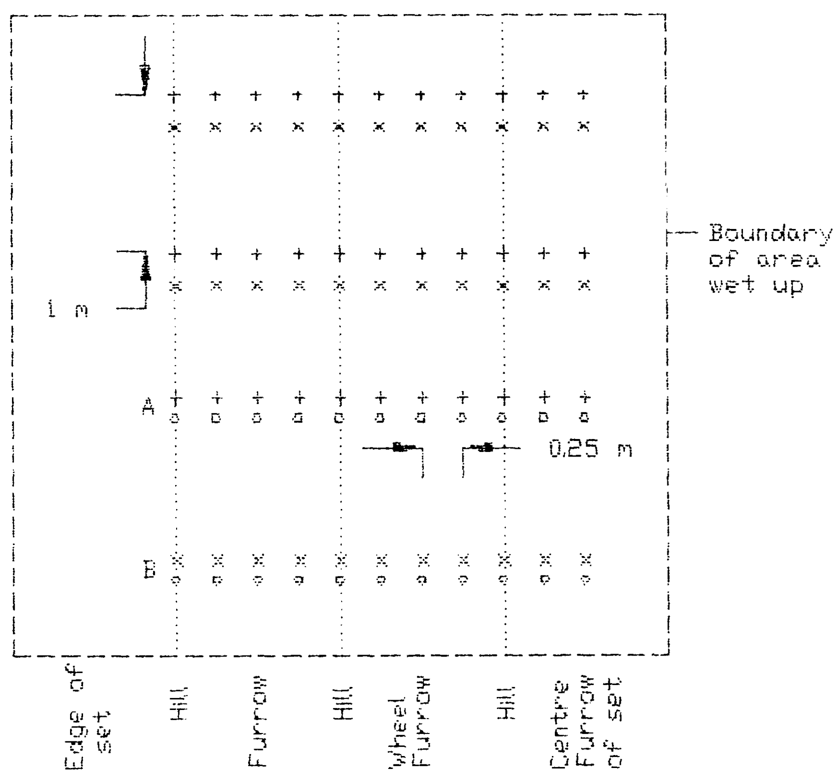


Figure 7.1 Layout of sampling sites within each 4 m by 4·5 m moisture plot of picker compaction experiment.
O indicates site of core sampling, with B before, and A after picking. x indicates site of penetrometer insertion before picking, and + indicates site of penetrometer insertion after picking.

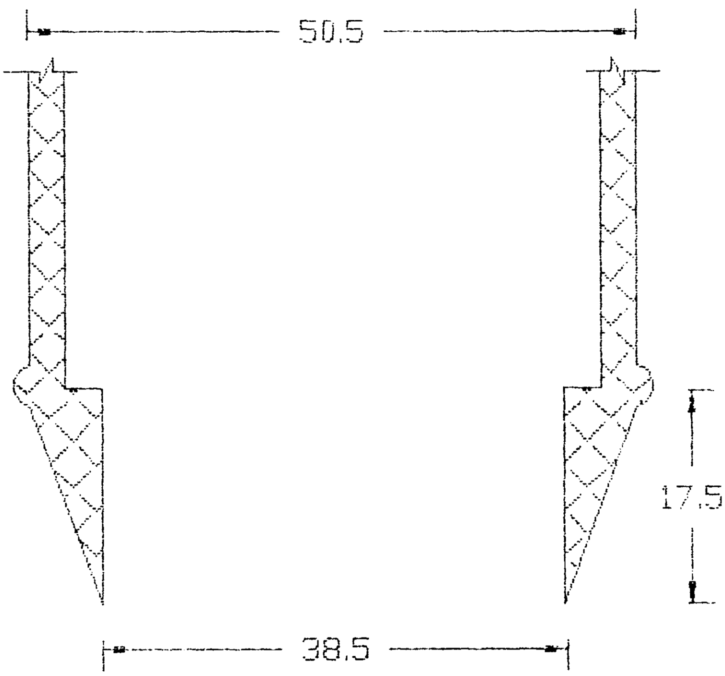


Figure 7.2 Dimensions (mm) of cutting tip of sampling tube used for collection of soil cores in picker compaction experiment.

Within 48 hours of collection of the cores, soil penetration resistance was recorded at 0·015 m intervals from the soil surface to 0·6 m below the top of the hills with a 'Rimik' recording penetrometer. Penetration resistance was measured at 025 m lateral intervals in three transects across moist and wet plots, giving 33 insertions per plot (Figure 7.1). Because of the large number of analyses needed (at least 90 analyses of variance), and a low probability of significant results due to the small number of observations per mean (9), no statistical analysis of penetration resistance data was undertaken.

Laboratory measurements

The volume of soil in sections of the soil cores was determined using the Saran coating technique of Brasher *et al.* (1966). Shrinkage curves were established for a subsample of cores, using techniques described in Section 5.2. These cores were collected after passage of the cotton picker from two depths (0·1 to 0·2 m, and 0·3 to 0·4 m), at two locations in the transect (beneath the centre of the hill, and half way between the centres of the hill and furrow), in all three moisture treatments in one replicate of the main tillage experiment.

Volumetric water content, θ_g, ρ_b, and ε_a were calculated from the soil volume determined above, and wet and oven dry mass. Relationships between θ_g and v, and θ_g and ε_a were determined using linear regression. For comparative purposes ρ_b was corrected to an arbitrary constant water content (0·4 kg kg^{-1}) assuming normal shrinkage. Analysis of variance of changes in corrected ρ_b during passage of the cotton picker was conducted for ripped and direct listed plots. One of the chiselled plots was accidentally trafficked before any measurements were taken, negating subsequent investigation.

7.2.2.2 Header compaction experiment

The effect of the passage of a wheat header on penetration resistance was measured during harvest, at a time when the soil was wet due to irrigation of plants and subsequent rain (see Section 8.3.1).

Paired comparisons were made of wheeled and unwheeled areas at one site in each of the three direct listed plot. At each site, three locations were chosen: hill, furrow wheeled during rowcrop operations (wheeled furrow), and a non-wheeled furrow. Six penetrometer insertions were made at each location in areas wheeled, and six in areas not wheeled by the header. Concurrently, soil samples were collected at 0·03, 0·1, 0·2, 0·3, and 0·4 m for θ_g determination. As in the picker compaction experiment, the top of undisturbed hills was used as a datum.

Analysis of variance was conducted on θ_g and penetration resistance for each depth sampled, while covariate analysis of penetration resistance with θ_g as the covariate was conducted for 0·03, 0·1, 0·2, 0·3, and 0·4 m depths.

7.2.3 Results

7.2.3.1 Picker compaction experiment

The range of water contents at 0·05 m obtained in this experiment was greater than 0·13 kg kg^{-1} (Table 7.2), which declined with depth to 0·06 kg kg^{-1} at 0·4 to 0·5 m. Although the soil classed as wet was wetter than the moist class at the surface, it was drier at depths greater than 0·2 m, reflecting the more thorough initial wetting of the moist areas by ponding compared to spraying. The author observed in soil pits that the majority of damage caused by pickers was at depths shallower than 15 cm, thus the anomalous differences in water content below this depth were not considered important.

Table 7.2 Gravimetric water content (kg kg^{-1}) of three moisture treatments during passage of pickers, averaged over tillage treatments Field 30, Auscott, Warren, April, 1985 (Depth is from top of adjacent hill to centre of sample; Hill, Furrow, and Half are locations across a transect, with Half being half way between hill and furrow).

Depth		Dry			Moist			Wet	
(m)	Hill	Half	Furrow	Hill	Half	Furrow	Hill	Half	Furrow
0·05	0·192	0·166		0·254	0·247		0·275	0·293	
0·15	0·182	0·166	0·138	0·252	0·257	0·252	0·271	0·261	0·279
0·25	0·193	0·183	0·169	0·254	0·256	0·253	0·234	0·238	0·241
0·35	0·191	0·191	0·186	0·242	0·241	0·254	0·223	0·222	0·233
0·45	0·188	0·188	0·184	0·224	0·242	0·242	0·214	0·218	0·238

The effects of passage of the picker were more clearly shown by changes in penetration resistance at constant water content than by ρ_b. Figure 7.3 shows that penetration resistance in the moist plots increased in a 0·15 m deep zone immediately below the wheeled soil surface. This increase

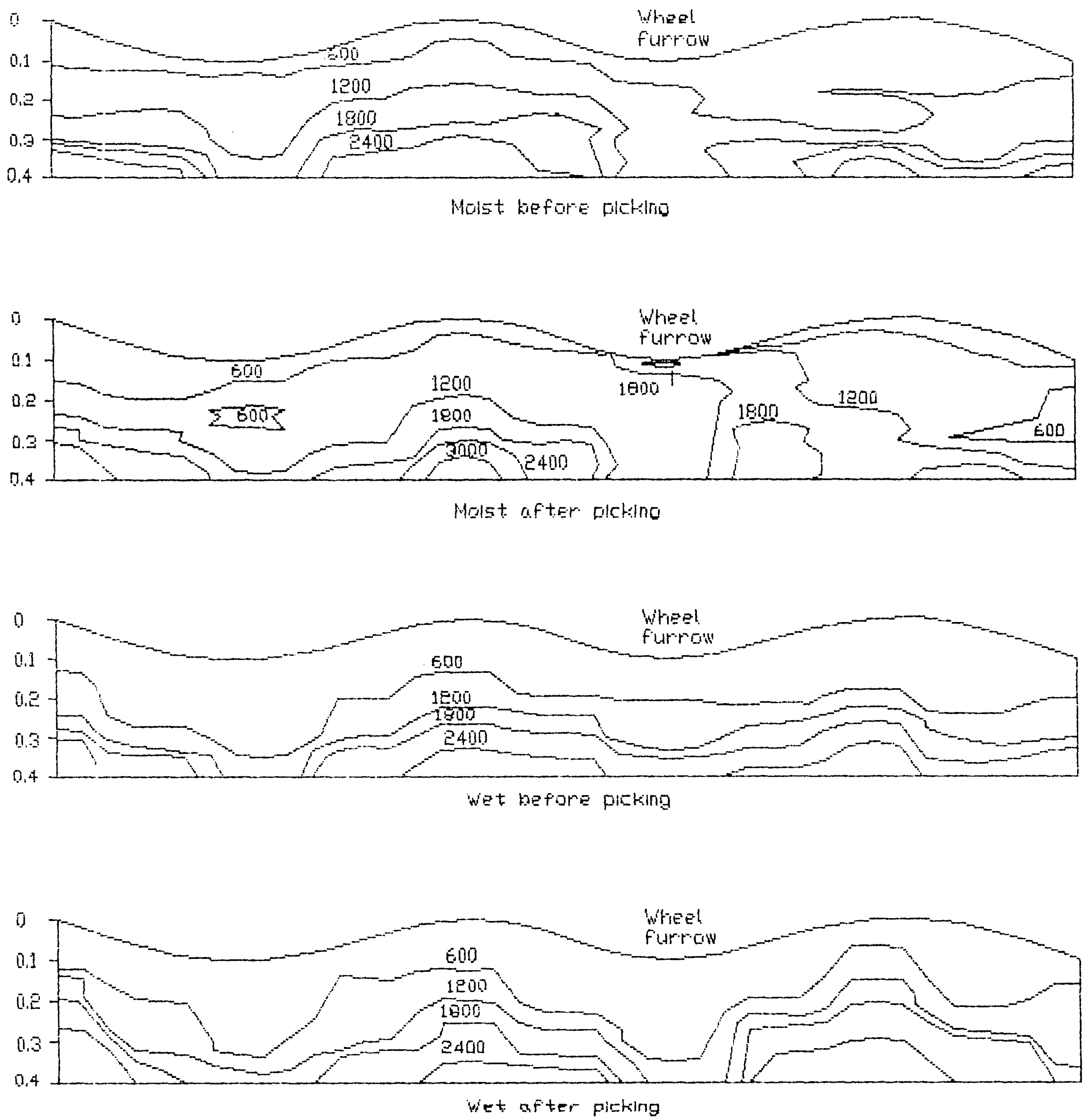


Figure 7.3 Contours of cone penetration resistance (kPa) averaged over three insertions at each location beneath a transect across two and a half rows before and after passage of a cotton picker over a vertisol at two soil water contents. (Wheel furrow is one of two furrows normally wheeled during rowcrop operations, all furrows were wheeled by picker.)

is less evident in the wet plots, probably due to a higher surface θ_g, hence lower cohesion, in these plots. The lower cone penetration resistance below the furrow than below the hill (Figure 7.3) is associated with a higher water content below the furrow than below the hill (Table 7.2). The soil in the dry plots was too hard to deform around the penetrometer cone, which can impose a pressure an order of magnitude higher than picker tyres. Consequently, it was assumed that no soil deformation occurred as a result of passage of the picker over the dry soil.

Shrinkage curves of cores dried in the laboratory showed normal shrinkage over the θ_g range sampled (Figure 7.4). This allowed correction of field densities to an arbitrary constant θ_g, and hence comparison of field density between moisture treatments. Only small changes in corrected density were measured in response to picker wheeling, with very few density increases greater than 0·01 Mg m^{-3}. Density increase tended to be greater in the ripped than direct listed plots, and in moist than wet soil (Table 7.3). A trend of a small decrease in density was noted beneath the hills and at depths of 0·25 m and greater half way between hills and furrows. However, this decrease was less than the 5% l.s.d. of 0·015 Mg m^{-3} in all cases.

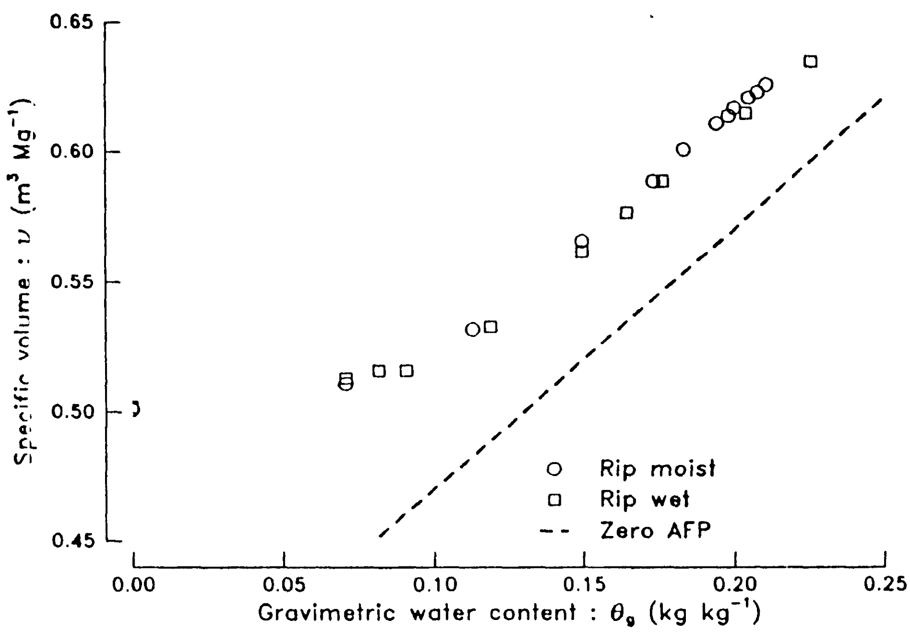


Figure 7.4 Example shrinkage curves obtained during drying in the laboratory of Saran coated cores sampled from 0·35 m.

Lines fitted by linear regression of sampled specific volume (v) on θ_g showed near normal shrinkage at 0 to 0·2 m (slope 0·97), but less than normal shrinkage for all depths greater than 0·2 m (Table 7.4). Lines fitted by linear regression of sampled ε_a on θ_g had poor precision, but showed that ε_a decreased with depth, and that the decline of ε_a with increasing θ_g was greater with depth (Table 7.5). These regressions supported measurement of decreasing ε_a and increasing ρ_b with depth (Table 7.6).

Table 7.3 Change in bulk density (Mg m^{-3}) corrected to 0·4 kg kg^{-1} during passage of cotton pickers over two tillage treatments at three moisture contents. Negative change indicates a density decrease. (Depth is from top of adjacent hill to centre of sample; Hill, Furrow, and Half are locations across a transect,with Half being half way between hill and furrow).

a) Change in bulk density in tillage treatments averaged over moisture content treatments. No differences between tillage treatments were significant.

	Direct list			Rip		
Depth (m)	Hill	Half	Furrow	Hill	Half	Furrow
0·05	0 000			-0·004		
0·15	0·002	0·002	-0·002	-0·005	0·012	0·013
0·25	0 000	-0·002	0·010	-0·004	0·007	0·010
0·35	0·006	-0·008	0·003	-0·006	0·001	0·006
0·45	-0·004	-0·007	0·006	0·003	0·005	0·005

b) Change in bulk density in moisture content treatments averaged over tillage treatments. The only statistically significant comparisons were half way between hill and furrow at 0·35 and 0·45 m, for which the 5% l.s.d. was 0·015 Mg m^{-3}.

	Dry			Moist			Wet		
Depth (m)	Hill	Half	Furrow	Hill	Half	Furrow	Hill	Half	Furrow
0·05	0·001			-0·004			-0·005		
0·15	-0·004	-0·002	-0·036	0·009	0·018	0·050	-0·010	0·006	0·004
0·25	0·006	-0·009	0 000	0 000	0·013	0·025	-0·011	0·003	0·006
0·35	0·011	0·003	0·006	0·005	0·033	0·017	-0·016	-0·017	-0·010
0·45	0·005	0·012	0·012	0·007	-0·001	0·009	-0·013	-0·014	-0·006

Table 7.4 Regressions fitted to shrinkage estimated from specific volume ($m^3\ Mg^{-1}$) and θ_g ($kg\ kg^{-1}$) from samples collected picker compaction experiment, Field 30, Auscott, Warren (a and b are constant and slope fitted by regression with standard error se; n is the number of samples at each depth; $se_{y.x}$ is the standard error of the estimate of y for fixed x).

Depth (m)	a	se	b	se	r^2	$se_{y.x}$	n
0·05	0·469	0·00944	0·969	0·0404	0·801	0·0231	142
0·15	0·447	0·00969	0·954	0·0442	0·784	0·0212	129
0·25	0·450	0·00738	0·868	0·0351	0·811	0·0161	142
0·35	0·446	0·00689	0·868	0·0388	0·838	0·0144	129
0·45	0·443	0·00628	0·863	0·0325	0·833	0·0121	142

Table 7.5 Regressions fitted to the relationship between air filled porosity ($m^3\ m^{-3}$) and θ_g ($kg\ kg^{-1}$) from samples collected during picker compaction experiment, Field 30, Auscott, Warren (a and b are constant and slope fitted by regression with standard error se; n is the number of samples at each depth; $se_{y.x}$ is the standard error of the estimate of y for fixed x).

Depth (m)	a	se	b	se	r^2	$se_{y.x}$	n
0·05	0·170	0·012	-21·4	5·20	0·101	0·030	127
0·15	0·137	0·013	-21·2	6·07	0·080	0·029	129
0·25	0·135	0·011	-30·1	5·10	0·192	0·023	142
0·35	0·128	0·010	-29·8	5·04	0·210	0·021	129
0·45	0·124	0·010	-31·0	4·99	0·210	0·019	142

Table 7.6 Maxima (max) means and minima (min) of air filled porosity (ε_a, m^3 m^{-3}) and field bulk density (ρ_b, Mg m^{-3}) of samples collected during picker compaction experiment. Field 30, Auscott, Warren, 1985 .

Depth		ε_a			ρ_b	
(m)	max	mean	min	max	mean	min
0·05	0·231	0·123	0·054	1·73	1·46	1·27
0·15	0·204	0·092	0·029	1·76	1·54	1·35
0·25	0·139	0·073	0·022	1·85	1·59	1·39
0·35	0·144	0·068	0·015	1·87	1·62	1·38
0·45	0·168	0·065	0·019	1·88	1·65	1·42

7.2.3.2 Header compaction experiment

Gravimetric water content near the soil surface was lower during header wheeling than the moist picker wheeling, but wetter than the dry picker wheeling, and constant for all sites monitored. Gravimetric water content was 0·156 kg kg^{-1} at 0·05 m, 0·204 kg kg^{-1} at 0·15 m, 0·239 kg kg^{-1} at 0·25 m , 0·258 kg kg^{-1} at 0·35 m, and 0·267 kg kg^{-1} at 0·45 m. Large increases in penetration resistance in response to header wheeling were limited to 0·15 m depth (Figure 7.5), with much greater increases in penetration resistance observed in the previously wheeled than non wheeled furrow.

7.2.4 Discussion

The small density changes in response to picker wheeling reinforce the findings of McGarry (1987), who documented differences in soil morphology and cotton growth, but not soil density in response to traffic passing over a wet vertisol. In addition, Kirby (1987) has shown that destruction of aggregates by shearing and not volume change is the main mechanism of structural degradation in vertisols. Boone (1986) noted that soil deformation plays an important, even dominating, role in compaction of wet soils. These findings emphasize that ρ_b is of little value in detecting changes of soil structure in vertisols.

Penetration resistance was a more sensitive indicator of structural degradation. The increased penetration resistance near the soil surface in response to both picker and header wheeling reflects either increased intraaggregate strength of clods formed by wheeling (Chancellor, 1976, quoted by Soane *et al.*, 1981a), or increased interaggregate strength. The former is more likely, as shown by the pattern of coarser products of tillage on deep cultivation of areas wheeled when the soil is wet compared to unwheeled areas (T. Burns, personal communication).

Peak penetration resistance in the previously wheeled furrow in the header compaction experiment exceeded the 2.4 MPa limit for cotton root growth of Taylor *et al.* (1966). Similarly, peak penetration resistance in the previously wheeled furrow of the picker compaction experiment is more

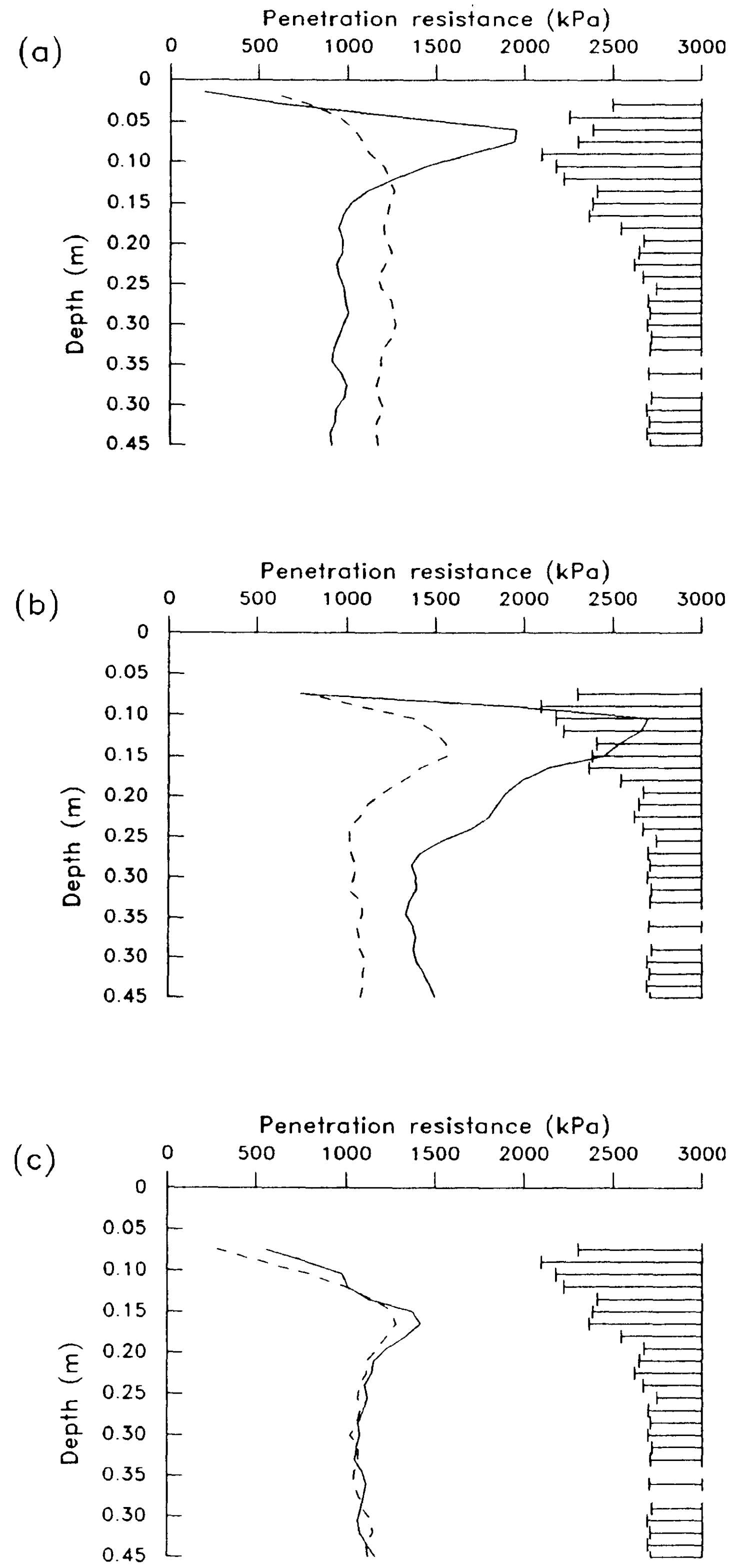


Figure 7.5 Penetration resistance profiles of soil before (dashed lines) and after wheeling (solid lines) by a wheat header at three location, either: a) beneath cotton hills b) furrow wheeled during rowcrop tillage or c) furrow not wheeled during rowcrop tillage (l.s.d. bars, are for the interaction of header wheeling and position (a, b or c), and are common to all three graphs).

than double the 800 kPa at which cotton root growth is restricted to 50% of maximum (Taylor and Ratliff, 1969). This indicates that root penetration would be greatly restricted in soil subjected to this level of compaction, although θ_g (0·25 kg kg^{-1} picker, 0·21 kg kg^{-1} header) is far above the 15 bar water retention of 0·12 kg kg^{-1} (Estimated from 15 bar θ_v in Table 4.3 divided by $\rho_{b_{max}}$ in Table 5.9).

The two experiments reported here indicated that the critical subsurface water content for physical degradation of this soil in response to 186 kPa tyre pressure lies between 0·14 kg kg^{-1} (picker dry furrow, Table 7.1), and 0·21 kg kg^{-1} (header furrow, Section 7.3.2.2), which is slightly drier than the lower plastic limit for this soil (0·23 kg kg^{-1}, Section 4.5). Although any structural degradation is undesirable, the degradation reported here is restricted to a depth of 0·15 m. This degradation can be ameliorated by deep tillage (McKenzie *et al.*, 1984c), or by drying of the soil by plant roots with subsequent cracking (Beale, 1982; McGowan *et al.*, 1983).

Regressions of ε_a on θ_g showed that intraaggregate ε_a of these soils during normal shrinkage is generally low. This supports similar observations of Holmes (1955). Air filled porosity measured in this experiment with cores of small diameter (38·5 mm) did not include interaggregate pores formed during shrinkage. This effect is compounded by the use of Saran coating rather than core volume to determine soil volume. Consequently, these regressions represent ε_a within aggregates, which is a poor indicator of ε_a of a field soil (Figure 8.12).

The less than normal shrinkage fitted to core samples for depths greater than 0·2 m (Table 7.4) was unexpected in view of the normal shrinkage measured in the cores sampled from 0 to 0·2 m, and the normal shrinkage sampled at 1·2 m in the neutron moisture meter calibration (Section 5.3). However, the slope of 0·86 to 0·87 for 0·2 to 0·5 m depths was similar to the 0·9 slope for laboratory shrinkage of clods sampled during the swelling gauge experiment (Section 5.2). Changes in the slope of the normal shrinkage phase with depth can not be due to changes in clay content or cation status as clay content increases rather than decreases with depth to 0·5 m (Section 4.5) and changes in cation status have little effect on soil volume relationships during the normal shrinkage phase (Yule and Ritchie, 1980a). Thus the lower than normal shrinkage is thought to be due to the physical state of the soil, such as anisotropic shrinkage due to precompaction of the soil in the vertical plane (Talsma, 1977; Richards, 1986). In this situation, a soil, after being subjected to a vertical stress sufficient to deform it, exhibits less shrinkage in the vertical than horizontal planes, and total shrinkage is less than normal (Towner, 1986).

7.2.5 Conclusions

Penetration resistance, but not field bulk density, was a useful indicator of structural degradation in response to picker and header wheelings. The small response of bulk density is attributed to aggregate deformation rather than volume change being the main form of structural degradation in vertisols.

The critical subsurface soil water content for structural degradation in response to header or picker wheeling in this soil lies between 0·14 and 0·21 kg kg^{-1}. This is drier than 0·23 kg kg^{-1}, the lower plastic limit of the soil.

7.3 MONITORING STRUCTURE DYNAMICS FOLLOWING AN IRRIGATION OF COTTON

7.3.1 Introduction

A consistent, although non significant, trend of higher water content in the deep ripped compared to direct listed treatments was reported in Chapter 6. This trend suggested that waterlogging might be responsible for the trend of yield depression in the ripped areas in the 1984/85 season. Consequently, it was thought that assessment of soil conditions during the 1986/87 cotton season should include the measurement of aeration status soon after irrigation, which has been shown to be highly correlated with cotton yield by Hodgson and Chan (1982). Air filled porosity (ε_a) was assessed using sequential core samples of the type used by Hodgson and Chan (1982), and tensiometers. Tensiometers, which have previously, not been widely used in vertisols, were used to establish an *in situ* water retention curve, which was combined with total porosity measured in core samples to estimate ε_a. Pore continuity, which Hamblin (1985) considered to be of major significance in crop water relations, was visually assessed using a dye infiltration technique. A second measure of pore continuity was obtained by measuring oxygen flux density (OFD), which Hodgson (1986) had shown to be a more sensitive indicator of structural degradation than ε_a.

The measures outlined above, along with soil water content and penetration resistance, were monitored over a 12 day drying cycle following furrow irrigation of a cotton crop. In recognition of the dynamic nature of water relations, soil water measurements were recorded daily, rather than at weekly intervals as in 1984/85.

7.3.2 Materials and methods

Cotton was not grown on the site of the main tillage experiment in the 1985/86 season to reduce buildup of Verticillium wilt, a soil borne fungal disease caused by *Verticillium* sp. However, an opportunity to assess measures of soil physical status was provided by a nearby experiment on a similar soil (Field 34, Auscott, Warren, Figure 4.1), in which the effect of rotation practices on the physical properties of a vertisol and subsequent cotton growth was being monitored (Abbott *et al*, 1987).

The soil is a self mulching grey clay with sodic subsoil (Ug 6.2; Northcote, 1979). Measurements were taken from a 40 m wide strip that cut across twelve, 600 m long plots on which cotton was being grown. The plots were 4 randomly distributed replicates of 3 rotation treatments, wheat, safflower, and a bare fallow which had been disc ploughed to kill weeds (Figure 7.6; Abbott *et al.*, 1987).

During the measurement period no rain fell. Reference crop evapotranspiration (ET_o) predicted by the Penman method modified according to Pruitt and Doorenbos (1975) varied from 4·7 to 7·6 mm day^{-1}. Temperatures were not limiting for cotton growth.

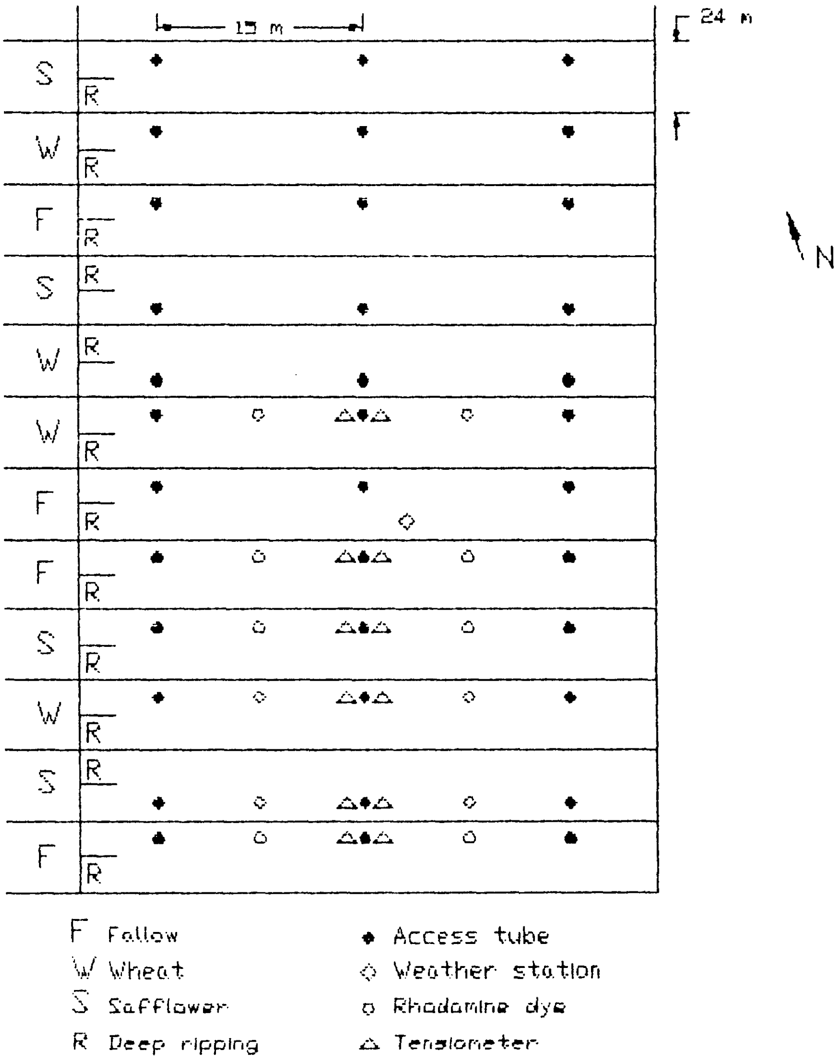


Figure 7.6 Diagram of location of measurement sites, Field 34, Auscott Warren. 1986.

Water content

Volumetric water content (θ_V) was estimated using a neutron moisture meter. In each plot, three aluminium access tubes, 1·5 m in depth, were placed 20 m apart in the centre of a hill, adjacent to a wheeled furrow. The unpublished calibration obtained by D.C. McKenzie, K.W. Hucker, L.J Morthorpe and P.J. Baker ,on a soil also classified as a Ug 6.2, at Field 24, Auscott, Warren (Figure 4.1) was used to convert count rate ratio to θ_V. Measurements of water content were recorded at 0·2, 0·25 (to relate to tensiometry), 0·4, 0·6, 0·8, 1·0, and 1·2 m below the centre of the cotton hill, and repeated 1, 2, 3, 4, 6, 8, 10, and 12 days after irrigation (DAI) on 16/2/86. Crop water use was estimated by a linear regression of cumulative profile water capacity to 1·2 m against time since irrigation (days). Standard counts were recorded daily in an access tube, identical to those used in the field, suspended in a 200 l drum filled with rainwater.

Water potential

Two tensiometers with 17·5 mm diameter cups were installed 0·25 m below the centre of the hill on opposite sides and 0·3 m away from the centre access tube, in two replicates of each treatment. The tensiometers were inserted in holes slightly larger than the cup diameter, augered at 45^{o} to vertical, and backfilled with a slurry of topsoil and water to improve soil to cup contact, as recommended by Bruce and Luxmoore (1986). The above-ground parts of the tensiometers were covered with aluminium foil, except the mercury manometers which were enclosed in a PVC pipe. Readings were taken on the same days as neutron moisture meter readings, as close as possible to 9 am.

The water potential measured by the tensiometer was pressure potential (ψ_p), which includes matric (ψ_m) and overburden (ψ_Ω) potentials, at the centre of the cup (Philip, 1969). Tensiometer data were described using Campbell's (1974) model where:

$$\psi_p = \psi_e (\theta_v / \theta_{vs})^{-b} \qquad 7.3.1$$

where ψ_e is a curve fitting parameter interpreted as the air entry potential, θ_{vs} is saturated θ_v, arbitrarily assumed to be the wettest θ_v measured in any plot, as swelling clays are never fully saturated (Philip, 1969), and b is a second curve fitting parameter.

Campbell (1974) used ψ_m rather than ψ_p in developing his model, whereas pressure potential includes both ψ_m and ψ_Ω (Philip, 1969). However, since ψ_Ω is small (<-4 kPa at 0·25 m), and probably constant over the range of ψ_p values observed (-70 to 0 kPa) (Holmes, 1955), ψ_Ω is considered to have a negligible effect on the interpretation of the regression coefficients in equation 7.3.1.

As equation 7.3.1 is exponential, and only fits a restricted range of the water retention curve, values of ψ_p larger than ψ_e and smaller than the lower drainage limit (-40 kPa) were not used. Inclusion of data larger than ψ_e would require a modified model (Hutson and Cass, 1987), and values lower than -40 kPa are not normally associated with the drainage phase. The goodness of fit of the model to the data was tested by a regression of predicted values of ψ_e on observed values.

Measurement of solid, air and water relations from cores

Core samples were taken according to the procedure of McIntyre and Barrow (1972) using thin-walled, sharpened tubes with an internal diameter 75 mm. Two adjacent cores were taken 2, 4, 7, and 12 DAI, centred on a depth of 0·25 m below the centre of the cotton hill. Additional core samples were taken 4 DAI, centred on 0·05, 0·15, and 0·35 m depths. Cores were taken at a distance of 1 to 5 m from the western two access tubes in each plot. The cores were sealed in plastic bags in which they were transported to the laboratory for determination of solid, air, and water ratios.

OFD was measured on samples taken 12 DAI using the method of Hodgson (1986), adapted from Taylor (1949).

Dye infiltration

A dye infiltration technique used by Loveday and Cooper (1984) was modified to provide a field index of macropore frequency and continuity under moist conditions. Shortly before irrigation, 0·7 m long rows of cotton plants were cut at ground level and removed at two sites per plot in two replicates of each treatment (Figure 7.6). The bare areas were covered with plastic.

Over a 4 to 6 day period after irrigation, these covers were removed, and each moist and swollen hill was carefully levelled to accommodate a 0·3 m diameter infiltration ring. Ten litres of 0·1% (w/v) Rhodamine dye WT solution was immediately added to each ring. As soon as dye infiltration was completed, the soil was trimmed horizontally by hand at 0·05 m intervals to a depth of 0·25 m below the levelled surface; little dye penetrated further. Each exposed layer was photographed vertically using colour slide film, with a scale provided by a thin tape measure.

In the laboratory, each photographic image was projected onto the underside of a light table, via a mirror adjusted to remove distortion. An overlay, with 20 equally spaced parallel lines, was placed over the image on the light table. The number and width of dye intercepts was recorded along these lines, allowing calculation of L_L, the length of dyed soil per unit length of grid line, and I_L, the number of intercepts per unit length of grid line (A. Ringrose-Voase, personal communication).

Penetration resistance

A Rimik recording cone penetrometer, described in Section 6.2, was used to measure penetration resistance at 0·015 m intervals to a depth of 0·45 m. Three insertions per access tube site, all on hills within 5 m of access tubes, were averaged to provide a penetration resistance profile for each of the 36 tubes at 8 and 12 DAI.

Statistical analysis

All data with the exception of water content, dye infiltration and penetrometer data were subjected to analysis of variance. Penetrometer data were examined by covariate analysis, with θ_g as the covariate. Dye infiltration data were analysed using 1-way (depth) repeated measures analysis. Moisture data were analysed using treatment contrasts in a 2-way (depth and time) repeated measures procedure. This procedure used quadratic polynomials to describe a combination of the depth (Roberts and Raison, 1983) and time (Evans and Roberts, 1979) effects by repeated measures analyses (Section 3.3).

7.3.3 Results

Water content

The fallow (uncropped) soil was wetter than both the wheat and safflower (cropped) soils at depths greater than 0·8 m for all measurement times (Figure 7.7). The model fitted to the cropped vs. uncropped contrast from the data shown in Figure 7.7 by 2-way repeated measures analysis was quadratic for both the depth and date variables. This form was selected for the model as fitting both depth quadratic (Dequ) and date quadratic (Daqu) terms had a high probability of improving the model after fitting preceding terms (Table 7.7). However fitting further terms which describe the interaction between depth linear, date linear, depth quadratic and date quadratic effects had a lower probability of improving the model after fitting preceding terms (Table 7.7). The most pronounced trend for the cropped vs. uncropped contrast was a 0·056 m^3 m^{-3} greater θ_v in the uncropped than cropped profiles at 1·2 m depth (Figure 7.8). Water contents were similar in the cropped and uncropped profiles at 0·2 m, becoming relatively drier in the uncropped profiles to 0·6 m, then relatively wetter to 1·2 m. Differences between θ_v profiles in wheat and safflower treatments were smaller than differences between cropped and uncropped profiles. Consequently, fitting each term to the safflower vs. wheat contrast had a lower probability of improving the model than for the cropped vs. uncropped contrast (Table 7.7). The model fitted to the safflower vs. wheat contrast predicted that the wheat profile was drier than the safflower profile near the surface, becoming relatively wetter to 1·2 m. There was little difference between the average water content of wheat and safflower profiles for any day (Figure 7.8).

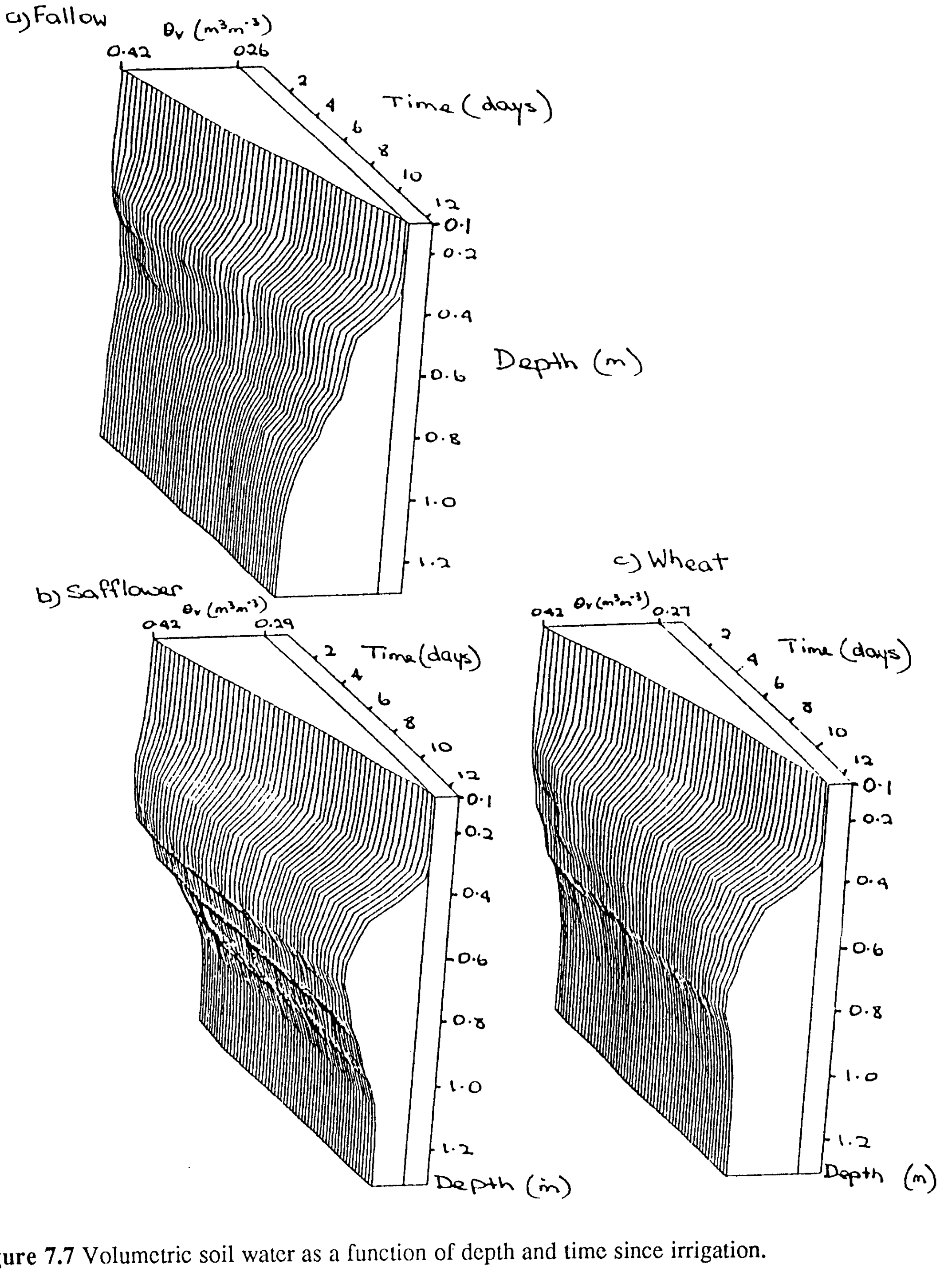
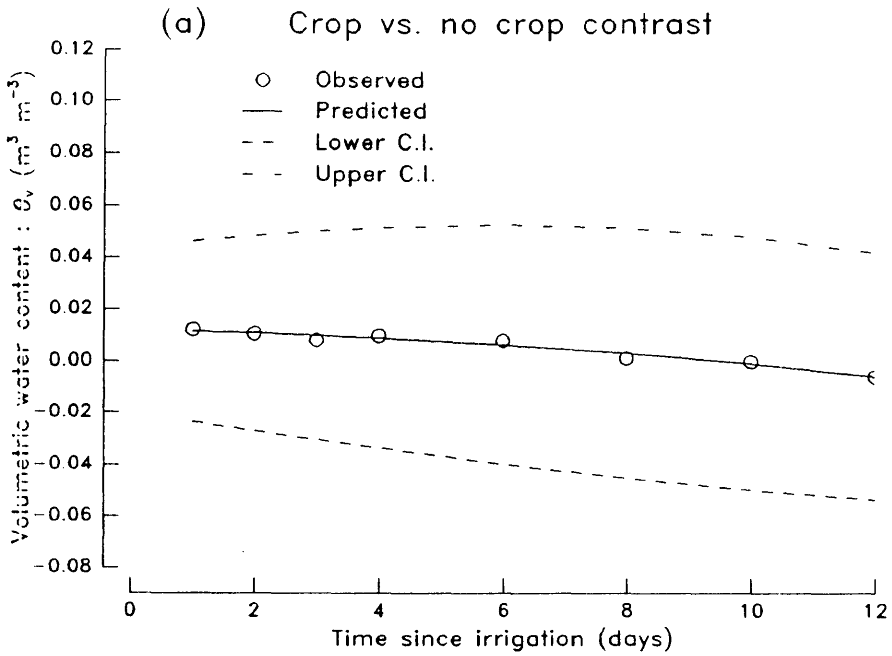


Figure 7.7 Volumetric soil water as a function of depth and time since irrigation.



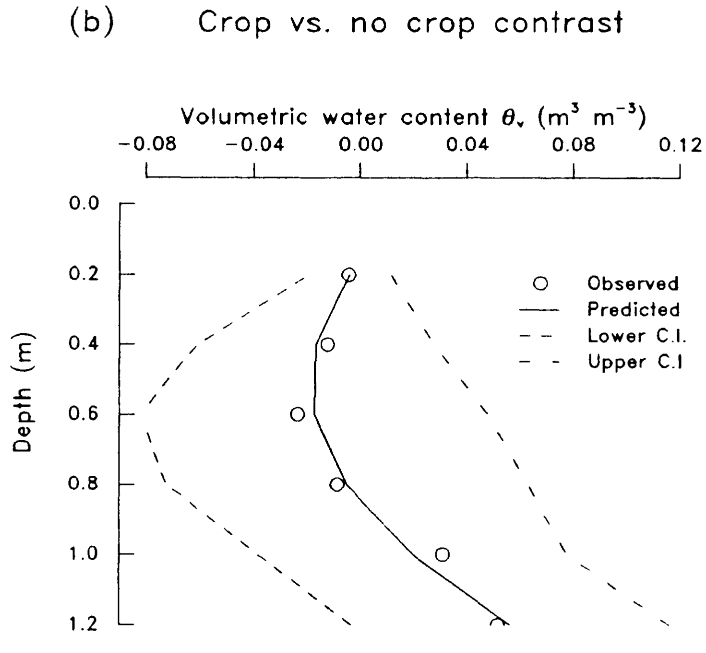


Figure 7.8 Models and 95% confidence intervals fitted to treatment contrasts in volumetric soil water content following irrigation by two-way repeated measures analysis.

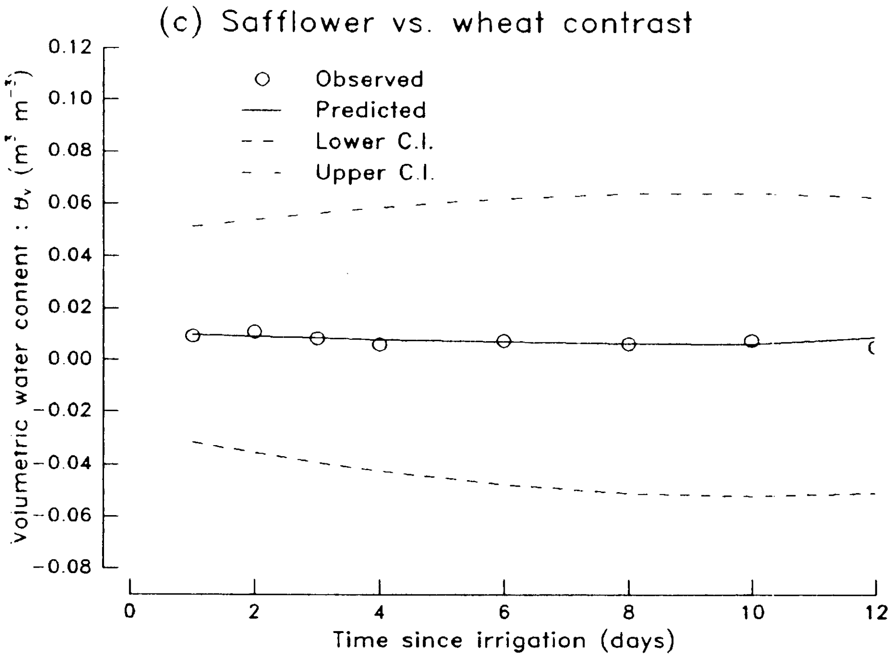
a) Crop vs no crop averaged over all depths

b) Crop vs no crop averaged over all days

c) Safflower vs wheat averaged over all depths

d) Safflower vs wheat averaged over all days.

(C.I. is 95% confidence interval)



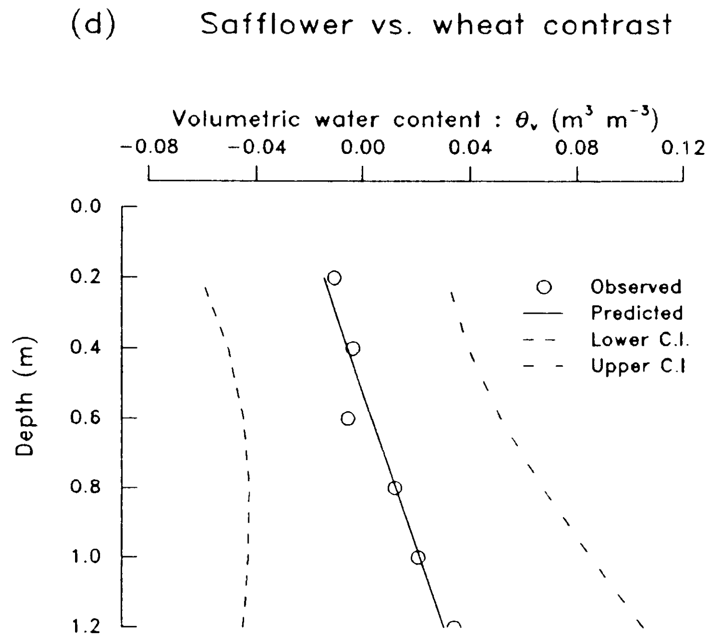


Figure 7.8 (continued) Models and 95% confidence intervals fitted to treatment contrasts in volumetric soil water content following irrigation by two-way repeated measures analysis.

Table 7.7 Probability that fitting given term using stepwise regression in two way repeated measures analysis of treatment contrasts to describe changes in profile θ_v between two crop irrigations improves model after fitting all preceding terms. Field 34, Auscott Warren, 1986. (Cropvnot is cropped vs. uncropped contrast, Safvwht is safflower vs. wheat contrast;Deli = depth linear effect, Dequ = depth quadratic effect, Dali = date linear effect, Daqu = date quadratic effect).

Contrast\				Effect					
	Aver	Dali	Deli	Daqu	Dequ	Deli *Dal	Dequ *Dal	Deli *Daq	Dequ *Daq
Cropvnot	0·452	0·996	0·650	0·979	0·943	0·082	0·515	0·914	0·120
Safvwht	0·512	0·780	0·927	0·112	0·003	0·861	0·769	0·321	0·639

Water extraction over the period studied was more rapid in the uncropped than cropped treatments (Table 7.8), and similar to the potential evapotranspiration.

Table 7.8 Regression models fitted to the relationship between cumulative profile water capacity from 0 to 1·2 m and time since irrigation during 1 drying cycle (17/2/85 to 28/2/86), Field 34, Auscott Warren. The slope of the regression has been interpreted as daily water use, while the intercept has been interpreted as the profile full point (se is standard error of estimate; $se_{y.x}$ is standard error of y for fixed x, ET_o is evapotranspiration from a reference crop).

Treatment	Water use (mm day^{-1})	se	Full point (mm)	se	r^2	$se_{y.x}$
Fallow	8·58	0·45	502	3·1	0·984	22·4
Wheat	6·87	0·32	495	2·2	0·988	11·0
Safflower	6·28	0·30	485	2·1	0·986	9·9
ET_o	6·59					

Water potential

The *in situ* water retention curves at 0·25 m (Figure 7.9) contain no significant treatment differences, despite a trend of higher ψ_e in the fallow than in either of the cropped treatments (Table 7.9). All fitted values of ψ_e were within the representative values for clay soils of 3·99 ± 3.91 kPa (Clapp and Hornberger, 1978). Two plots, one fallow and one safflower, had b values outside the representative values for clay soils of 10.40 ± 3.70 (Clapp and Hornberger, 1978). The goodness of fit of the curves was variable, both within and between treatments, with $se_{y.x}$ varying from 1·5 to 5 kPa.

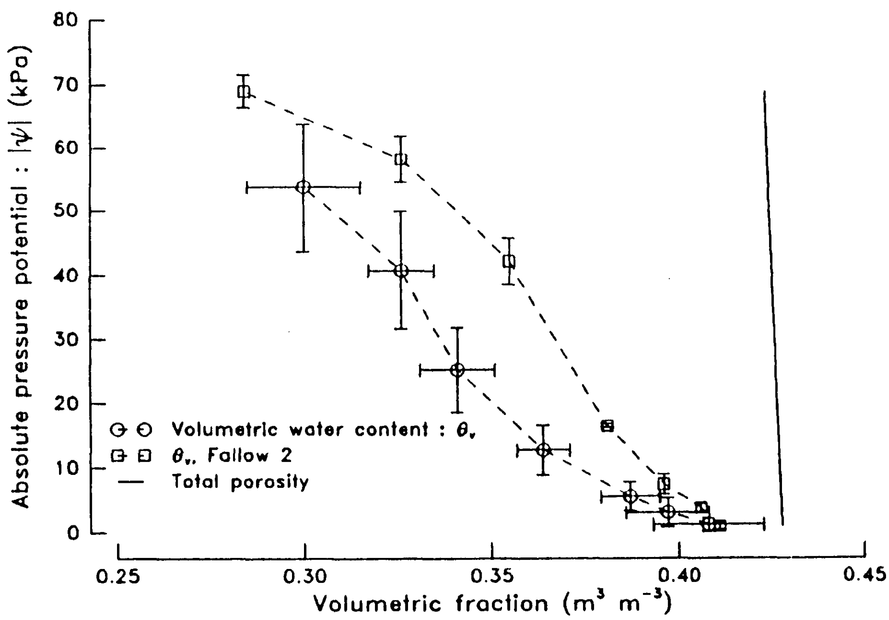


Figure 7.9 Field measured soil water retention curves, with standard deviations, for fallow treatment plot 2, and five other fallow, safflower and wheat plots; measured 0·25 m below the centre of hillsduring a drying cycle between cotton irrigations, Field 34, Auscott, Warren. From the wettest point the points on the water retention curves are 2, 3, 4, 6, 8, 10 and 12 days after irrigation on 16/2/86.

Table 7.9 Retentivity parameters fitted to field pressure potential values from two tensiometers per plot 0·25 m below the centre of hills, Field 34, Auscott Warren (ψ_e is a curve fitting parameter interpreted as air entry potential; b is a second curve fitting parameter; $se_{y.x}$ is standard error of y for fixed x; n is the number of observations used in fitting model).

Plot	-b	ψ_e (kPa)	$se_{y.x}$ (kPa)	r^2	n
fallow 1	11·9	1·6	3·9	0·976	11
fallow 2	17·6	1·9	3·4	0·964	8
wheat 1	13·8	1·1	5·0	0·933	11
wheat 2	11·4	1·6	1·5	0·991	12
safflower 1	15·2	1·1	2·6	0·980	7
safflower 2	12·5	1·7	1·7	0·987	8

Pressure potential was less negative than the average ψ_e of 1.5 kPa for the first 3 days after irrigation. By 4 DAI, the soil had dried beyond ψ_e, but did not reach the critical ε_a level of 0·145 m^3 m^{-3}, above which Hodgson (1986) found adequate oxygen flux density for plant growth in a similar soil, until 10 DAI (Figure 7.9). Values of ε_a at a given ψ_p are determined from Figure 7.9 by subtracting the volume of water filled pores estimated by the water release curve from the total porosity.

The water retention curve for Fallow 2 is presented separately in Figure 7.9 as both tensiometers in this plot had water release curves which were markedly different to any other plot.

Measurements of solid, air and water relations from cores

A greater ε_a at 0·25 m in the cropped than uncropped plots 7 DAI is associated with lower bulk density at this depth for three of the four sampling times, the exception being 4 DAI. The small changes in ρ_b over the measurement period (Table 7.10), in relation to the increased ε_a over the same period, indicate that structural shrinkage is occurring (Section 3.2.1).

Table 7.10 Air filled porosity (ε_a, m^3 m^{-3}) and bulk density (ρ_b, Mg m^{-3}) measured with 75 mm diameter core samples from 0·25 m below the centre of cotton hills, Field 34, Auscott Warren (DAI is time since irrigation, days).

DAI	Treatment			5% l.s.d.
	Fallow	Safflower	Wheat	
ε_a				
2	0·063	0·068	0·066	0·009
4	0·070	0·069	0·070	0·020
7	0·087	0·119	0·163	0·016
12	0·134	0·150	0·163	0·030
ρ_b				
2	1·51	1·45	1·47	0·03
4	1·52	1·52	1·47	0·02
7	1·51	1·45	1·45	0·04
12	1·52	1·47	1·47	0·05

At 4 DAI measured ρ_b increased from 1·3 Mg m^{-3} at 0·05 m to 1·45 to 1.55 Mg m^{-3} at 0·35 m (Table 7.11). Air filled porosity tended to decrease with depth, with all samples collected from depths greater than 0·1 m below Hodgson's (1986) critical value of 0·145 m^3 m^{-3}. The nature of the relationship between ε_a and OFD could not be determined from the set of data described here as too few samples tested had low OFD (<10 g O_2 m^{-2} day^{-1}) for the critical ε_a value to be determined precisely.

Table 7.11 Air filled porosity (ε_a, $m^3\ m^{-3}$) and bulk density (ρ_b, $Mg\ m^{-3}$) measured using 75 mm diameter core samples below the centre of cotton hills, 4 days after irrigation, Field 34, Auscott Warren.

Depth (m)	Treatment Fallow	Safflower	Wheat	5% l.s.d.
ε_a				
0·05	0·192	0·178	0·173	0·044
0·15	0·086	0·102	0·092	0·015
0·25	0·070	0·069	0·070	0·020
0·35	0·064	0·055	0·059	0·007
ρ_b				
0·05	1·30	1·31	1·29	0·08
0·15	1·48	1·43	1·43	0·03
0·25	1·52	1·52	1·47	0·02
0·35	1·56	1·52	1·46	0·03

Although OFD observed in the wheat treatments 12 DAI of 75 g $O_2\ m^{-2}\ day^{-1}$ was 1·5 times the 51 g $O_2\ m^{-2}\ day^{-1}$ observed in the fallow plots, the differences were not significant.

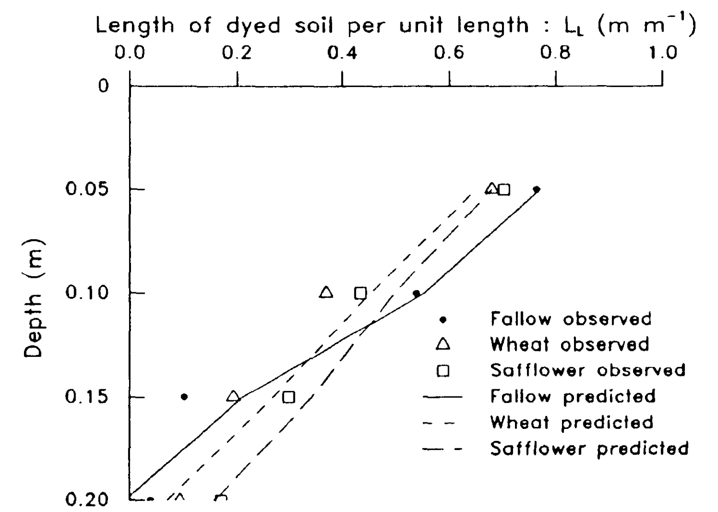
Dye infiltration

Image analysis showed that, down to 0·15 m below the hill surface the volume of dyed soil, as indicated by L_L, was greatest for the fallow area where disturbance by disc ploughing had occurred (Figure 7.10). Macropore frequency (I_L) was also greater. This trend was reversed for both L_L and I_L below 0·17 m, the depth of disc ploughing in the fallowed plots. The volume and frequency of continuous macropores decreased with depth, but this was at least partly due to separation of dye and water by absorption processes (D. McKenzie, personal communication).

Penetration resistance

Penetration resistance profiles recorded 8 and 12 DAI (Figure 7.11) are shown in relation to published critical limits for cotton root growth. Penetration resistance below 0·15 m was sufficiently high to retard root growth at 8 and 12 DAI in all treatments. A 0·06 m thick zone of high resistance was measured in the fallow plots, centred 0·2 m below the hills. The greater penetration resistance in the fallow than either of the cropped plots extended to 0·45 m, the greatest depth monitored.

(a)



(b)

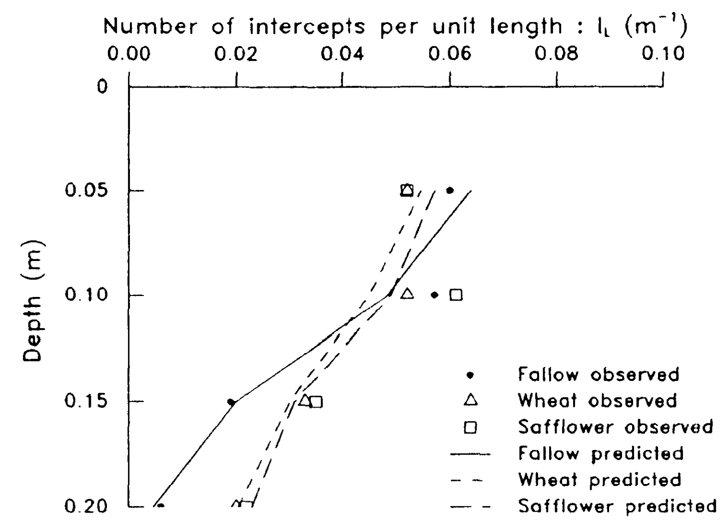
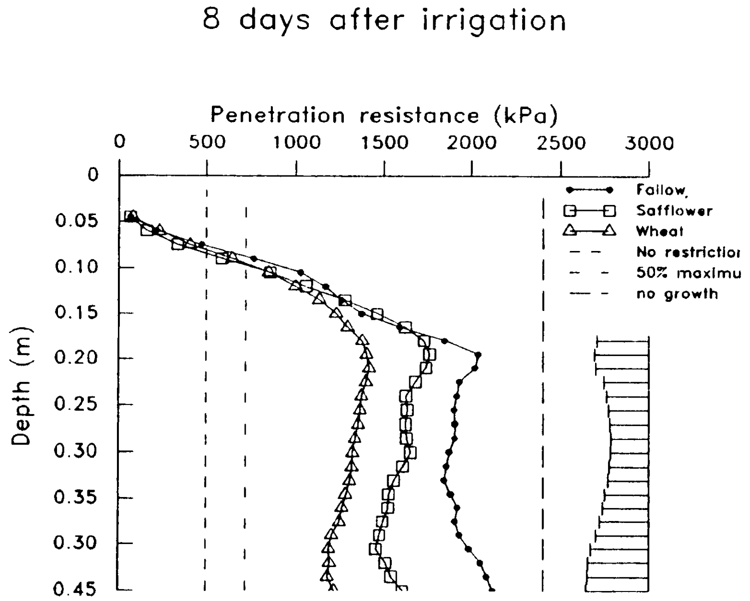


Figure 7.10 Observed values and curves fitted by 1-way (depth) repeated measures analysis to

a) Length of dyed soil per unit length of grid line (Treatment linear and cubic terms are significantly different $P. < 5\%$)

b) Number of intercepts of dyed soil per unit length of grid line (treatment linear coefficients significantly different, $P. < 5\%$).



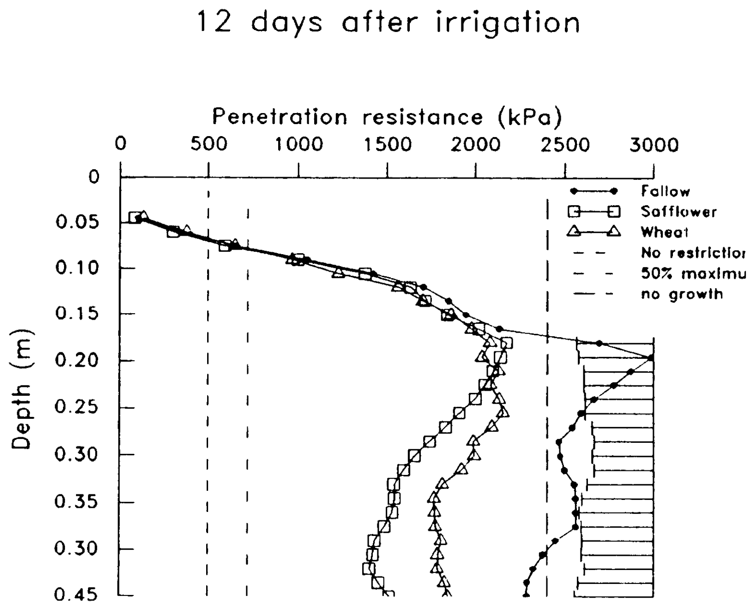


Figure 7.11 Penetration resistance corrected for gravimetric water content as a function of depth and treatment.

Limits for no restriction to root growth and no root growth are from Taylor *et al.* (1966), and 50% of maximum from Taylor and Ratliff (1969). Bars are 5% l.s.d. for depths at which treatments were significantly different.

7.3.4 Discussion

In marked contrast to results presented in Section 6, four of the five physical properties (water content, ε_a measured in cores, dye infiltration and penetration resistance) showed statistically significant treatment differences in this experiment. With the exception of water content, these quantities provide evidence that disc ploughing to kill weeds on the fallow treatment caused structural degradation beneath 0·15 m, the depth of working.

The effects of degradation are best illustrated by the penetration resistance profiles (Figure 7.3), in which the zone of high resistance coincided with a depth immediately below discing depth. In this experiment, penetration resistance has better depth definition than all other measures. The 0·015 m measurement interval is one third that of the 0·05 m separating dye measurements, the next most intensive measure. This factor, together with the relative ease of data collection, is responsible for the wide use of penetrometers in monitoring field experiments (Anderson *et al.*, 1980), overriding difficulties in relating penetration resistance to other properties (Mulqueen *et al.*, 1977).

Dye infiltration showed higher macropore frequency and continuity above 0·15 m in the fallow than cropped treatments, with the reverse occurring below this depth. The dye infiltration technique is time consuming, limiting its application in research involving large field trials.

The pattern of better structure in the fallow than in the cropped plots above 0·17 m was supported by trends of ε_a with depth 4 DAI. Air filled porosity at 0·25 m indicated poorer aeration in the fallow than cropped plots for three of the four measurement times. The technique of collecting sequential core samples was the most practicable means of measuring aeration status. This method could be improved by including measurements of OFD at wetter water contents than used in this experiment in order to establish a critical ε_a for oxygen flow in this soil.

Changes in ε_a estimated from the water retention curves obtained by tensiometry were similar to those estimated from core samples. Both estimates (Table 7.10, Figure 7.9) indicate that ε_a at 0·25 m was less than 0·15 m^3 m^{-3} 7 DAI (Figure 7.9). Use of the tensiometers in this experiment was a test of their application to vertisols. Previous use, such as that by Talsma (1977), was under much wetter conditions than experienced in this study as the soil dried between irrigations. At 0·25 m over the range of water contents between two crop irrigations, there was no apparent discontinuity of the water retention curve to suggest a breakdown of soil to cup contact. The large standard error of ψ_p as the soil dries is disturbing, although this is consistent with the observations of Wierenga (1985). However, the contribution of this error to the size of the confidence interval about the water retention curve is similar to that of the much smaller standard error of θ_v because the water retention curve is steep for θ_v less than 0·375 m^3 m^{-3} (Figure 7.9). The model fitted to the water retention curve would have been more precise if tensiometer readings had been recorded at daily intervals throughout the whole drying cycle. As it has been established that tensiometers can be successfully used in vertisols, opportunities exist to use them to quantify water fluxes during drying cycles. These benefits must be weighed against the time spent in installation and maintenance of the tensiometers, and the inaccuracy introduced if the tensiometers are not well maintained (Bruce and Luxmoore, 1986).

The two measures of aeration obtained from water potential and core measurement show that the soil had a poor aeration status for much of the drying cycle. The ε_a profile 4 DAI shows that cotton roots were subjected to poor aeration at all depths greater than 0·1 m at this time (Table 7.10).

Estimates from the field water retention curve indicate that ε_a at 0·25 m, did not exceed Hodgson's (1986) critical value (0·145 m^3 m^{-3}) for adequate OFD until 10 DAI. This is supported by core measured ε_a, which was 0·11 m^3 m^{-3} 7 DAI, and 0·15 m^3 m^{-3} 12 DAI.

As the neutron moisture meter could not be used to measure water contents shallower than 0·2 m, no inferences regarding structural degradation above this depth can be drawn from water content data. However, the data were useful in estimating crop water use and the water extraction pattern. The higher water content of the fallow than cropped profiles at depths greater than 1·0 m occurred because water extracted from the soil by wheat and safflower crops was not replenished by flood irrigation, as observed on a similar soil by Chan and Hodgson (1981).

ET_o, an indicator of potential evapotranspiration, corresponded closely to crop evapotranspiration estimated by the neutron moisture meter. This indicates that water uptake by cotton plants over the drying cycle was not greatly restricted by the poor aeration observed. As plant evapotranspiration may be satisfied by water absorption from less than 10% of the total root length (Hamblin, 1985), water uptake may not be a true indicator of the suitability of soil conditions for root growth, particularly at depth.

Water uptake during the measurement period was not altered by the structurally degraded layer present in the fallow but not the cropped treatments. This may be a result of shrinkage during drying of the soil in irrigation cycles between planting of the cotton and the period monitored, which destroyed the continuity of the degraded layer (McGowan *et al.*, 1983). This hypothesis is supported by observations of D. McKenzie (personal communication) of poorer cotton growth in the fallow than cropped plots prior to the first irrigation of the cotton crop, but more vigorous growth in the uncropped than cropped plots after the first irrigation.

Cotton lint yields and N uptake were also higher in the uncropped than cropped treatments (D. McKenzie, unpublished data). This was attributed to lower N availability in the cropped plots as no additional N was added to cropped plots to compensate for N exported from the field in harvested grain and N which became available due to mineralization during the fallow period.

7.3.5 Conclusions

Apart from water content, all indicators of soil structure used in this study were able to differentiate between fallow, wheat and safflower treatments to a depth of 0·25 m. Of the techniques used, a combination of core sampling to measure ε_a together with the penetrometer was best able to define structural conditions relevant to root growth down the profile. This conclusion was supported by the greater sensitivity of penetration resistance than bulk density measurement as an indicator of structural degradation caused by wheel passage (Section 7.2). The dye infiltration technique provided consistent data, but was more laborious. Tensiometers provided a useful adjunct to other methods of characterizing soil physical properties, although their value is limited by large demands on time, and sensitivity to installation and maintenance.

Suspicions of extended periods of waterlogging following irrigation outlined in Section 6 were confirmed by the results of this experiment. However, the observed waterlogging did not appear to markedly restrict water uptake.

It was concluded that techniques to measure aeration status described here would be used in the

1986/87 growing season. Tensiometers would also be installed despite their drawbacks, as they will enable the determination of hydraulic gradients, hence give information on the direction of water flow in the soil. Rhodamine dye infiltration has provided information on the effects of structural degradation on water flow, and would be used on a limited scale.

Despite its advantages in summarizing large data sets, use of two-way repeated measures analysis will be abandoned. The main drawback of this analysis is that the results are difficult to describe to the majority of scientists who are unfamiliar with the analysis.