Aug 93 - June 96

Abstract

Project Title: Soil Fabric: Use as a Field Indicator of Instability and Clay and Solute Movement

Project No.: SCU1C

Principal Researcher:
Dr Leigh Sullivan
Senior Lecturer in Soil Science
Resource Science and Management
Southern Cross University
P.O. Box 157, Lismore, NSW, 2480.

Telephone: (066) 203742
Fax: (066) 212669
email: lsulliva@scu.edu.au

An abstract of the final summary report prepared for the Cotton Research and Development Corporation

The objectives of this study were to: 1) determine the role of soil instability and clay translocation in the formation of shiny-faced soil aggregates, 2) determine the roles of clay translocation and vehicular compaction in the formation of subsoil densification in cracking clays used for cotton production, and 3) examine the effect of aggregate surface fabric on the movement of water and solutes in these soils. The results of this study have extended the results of previous research on cracking clays to show that the past practices used in long-term irrigated cotton growing have resulted in substantial deep subsoil densification down to depths of 200 cm, and that such deep subsoil densification is likely to be widespread in these soils. This project has also identified that the cause of the deep subsoil densification in irrigated cracking clay soils used for cotton production is vehicular compaction (as a result of heavy axle loads) rather than clay translocation as has been previously suspected. The results indicate that the present trends and recommendations towards the use of lower axle loads and permanent bed systems in cotton production in Australia are very appropriate for these soils. The scanning electron microscopy study on the fabric of these soils has provided an understanding of the fundamental nature of this soil characteristic and provided a more rational basis for the measurement and subsequent interpretation of this soil characteristic. For example, the results of this project indicate that that dull ped fabrics cannot be taken to infer that structural instability in the form of clay mobilisation and translocation has not taken place in these soils. The fabric studies clearly show that there are clay coatings on the structural surfaces within these soils: the solute movement work indicates that at moisture contents below that where the large pore space is coated by conductive films of water, the presence of such clay coatings leads to preferential flow.

Summarised report

Project Title:	Soil Fabric: Use as a Field Indicator of Instability and Clay and Solute Movement
Project No.:	SCU1C
Principal Researcher:	Dr Leigh Sullivan Senior Lecturer in Soil Science Resource Science and Management Southern Cross University P.O. Box 157, Lismore, NSW, 2480.
Telephone:	(066) 203742
Fax:	(066) 212669
email:	lsulliva@scu.edu.au

A final summary report prepared for the Cotton Research and Development Corporation

Introduction

The fabrics of cracking clay soils used for cotton production are routinely described using the techniques for field soil structure description outlined in the SOILpakβ manual. SOILpakβ indicates, along with other structural indicators, that a proliferation of shiny ped faces indicates good soil structure whereas compacted, poorly structured cracking clay soils generally have dull faces. Given that shiny ped faces often indicate the presence of clay coatings formed by structural instability leading to clay translocation, the interpretation of soil fabric for cotton growing has been unclear due to the lack of information regarding:

- what do the different fabrics represent in terms of soil stability and land management? and if shiny fabrics are due to clay translocation then is this process the cause of deep subsoil densification that has been previously observed in a cotton field at Warren? and
- how do the different soil fabrics affect the movement of water and solutes within soils?

Objectives

- To determine the role of soil instability and clay translocation in the formation of shiny-faced soil aggregates.
- To determine the roles of clay translocation and vehicular compaction in subsoil densification in cracking clays used for cotton production.
- To examine the effect of aggregate surface fabric on the movement of water and solutes in these soils.

Results and Discussion

Subsoil densification

This study has extended the results of previous research on cracking clays to show that the past practices used in long-term irrigated cotton growing have resulted in substantial deep subsoil densification down to depths of 200 cm, and that such deep subsoil densification is likely to be widespread in these soils. This project has also identified that the cause of the deep subsoil densification in irrigated cracking clay soils used for cotton production is vehicular compaction as a result of heavy axle loads rather than clay translocation as has been previously suspected. It is suggested that the peculiar structure of the cracking clay soils may contribute to making these soils very susceptible to deep subsoil compaction and that the suitability of trafficking on these soils under 'dry cracked surface and wet subsoil' conditions may need to be assessed.

Long term experiments conducted overseas have indicated that subsoil compaction below tillage depth causes yield reductions that persist for many years after the compaction event (it should be noted that the subsoil compaction induced in the long term overseas trials was not nearly as severe as the subsoil compaction observed in this project for these Australian cracking clay soils). Although some of the changes associated with deep subsoil compaction may actually be beneficial (for example, decreased water permeability may lead to lower losses of applied water beyond the root zone), the overseas experience overwhelmingly suggests that deep subsoil compaction is detrimental to crop yields. Furthermore,this experience indicates that subsoil compaction deeper than 40 cm is often difficult to successfully and completely ameliorate - and indeed attempts to do so may actually be counter-productive - so that prevention is regarded as the best option for management.

The results gained in this project demonstrate that the present trends and recommendations towards the use of lower axle loads and permanent bed systems in cotton production in Australia are very appropriate for cracking clay soils. Furthermore, whereas for non-cracking homogeneous soils the lateral spreading of stresses beneath wheels would result in deep subsoil compaction zones that may be at least three times as wide as the tyre, the cracking nature of the soils examined in this study may limit the lateral extent of densification beneath beds as compared to other soil types.

Soil fabric

The scanning electron microscopy study on the fabric of these soils has provided an understanding of the fundamental nature of this soil characteristic as is currently used in SOILpakβ for indicating the structural status of cracking cotton soils and provided a more rational basis for the measurement and subsequent interpretation of this soil characteristic. For example, the results of this project indicate that that dull ped fabrics cannot be taken to infer that structural instability in the form of clay mobilisation and translocation has not taken place in these soils. In addition, although SOILpakβ indicates that compacted poorly structured cracking clay soils generally have dull faces whereas well structured cracking clay soils have a proliferation of shiny faces, this was not always the case in the soils examined here and the presence of shiny structural surfaces in these soils is a function of the aggregate surface roughness caused by disruption or stress rather than an indicator of structural instability and clay translocation.

Solute movement

The fabric studies clearly showed that there are clay coatings on the structural surfaces within these soils: the solute movement work indicates that at moisture contents below that where the large pore space is coated by conductive films of water, the presence of such clay coatings leads to preferential flow.

Communication of results

Several articles based partly or wholly on the results of this project have already been published or are being prepared for publication in international refereed journals or conferences (see list below). An articles on the results and implications of this project is being prepared for publication in The Australian Cotton Grower. Our results and methods will be an important part of the SOILpakβ section on soil structure and fabric evaluation and preliminary discussions on this have already occurred. I have requested the opportunity to extend these results at the Soils Meeting of the CRC for Sustainable Cotton Production in December, 1996 and have been duly invited, and will seek to extend these result to other researchers and at other suitable venues as invited.

Publications/presentations to date arising from this project

Sullivan, L.A 1996. The recognition of depositional clay coatings by scanning electron microscopy. Proceedings of the 10th International Working Meeting on Soil Micromorphology. July, 1996, Moscow, Russia.

Sullivan, L.A. 1995. Microtrenches and microridges on the accretive structural surfaces of some clayey soils. Australian Journal of Soil Research 33: 565-568.

Sullivan, L.A. 1994. A new technique for the direct detection of clay translocation in Vertisols used for cotton growing. World Cotton Research Conference-1, Brisbane, 13-17th February, 1994.

Tolmie and Sullivan, 1996. Solute movement: the effect of aggregate fabric. Proceedings of the 10th International Working Meeting on Soil Micromorphology. July, 1996, Moscow, Russia.

Tolmie, P. and L.A. Sullivan 1994. Solute movement in cotton soils the effect of aggregate surface fabric. World Cotton Research Conference-1, Brisbane, 13-17th February, 1994.

Title Page

Cotton Research and Development Corporation

Project Title: Soil Fabric: Use as a Field Indicator of Instability and Clay and Solute Movement

Project No.: SCU1C

Principal Researcher:
Dr Leigh Sullivan
Senior Lecturer in Soil Science
Resource Science and Management
Southern Cross University
P.O. Box 157, Lismore, NSW, 2480.

Telephone: (066) 203742
Fax: (066) 212669
email: lsulliva@scu.edu.au

A final report prepared for the Cotton Research and Development Corporation

1. Introduction

Industry significance

The fabrics of cracking clay soils used for cotton production are routinely described using the techniques for field soil structure description outlined in the SOILpakβ manual. SOILpakβ indicates, along with other structural indicators, that a proliferation of shiny ped faces indicates good soil structure whereas compacted, poorly structured cracking clay soils generally have dull faces. Given that shiny ped faces often indicate the presence of clay coatings formed by structural instability leading to clay translocation, the interpretation of soil fabric for cotton growing has been unclear due to the lack of information regarding:

* firstly, what do the different fabrics represent in terms of soil stability and land management? and if shiny fabrics are due to clay translocation then is this process the cause of deep subsoil densification that has been previously observed in a cotton field at Warren?

* secondly, how do the different soil fabrics affect the movement of water and solutes within soils?

The first aim this project was to determine the nature of the soil fabrics that are routinely described using the SOILpakβ manual. Specifically, are the changes in soil fabrics that have commonly been observed to have occurred subsequent to cotton production the result of soil instability in the form of clay dispersion and translocation? or they due to compaction and smearing? or is there some other explanation?

The answers to the above questions have important implications for crop productivity and in limiting any effects of cropping on surrounding environments. For example, the movement of dispersed clay particles can transport nutrients and other absorbed substances (e.g. pesticides) to riverine environments. Furthermore, soil fabric can impact directly on crop performance as the presence of clay coatings around peds can result in impeded root growth as well as reduced uptakes of nutrients (Sullivan 1994).

In addition, clay translocation has been suggested as a possible cause of the deep subsoil densification observed in the study of McKenzie et al. (1991). Thus, if clay translocation is found to have been substantial in densified subsoils the cause of this serious form of soil degradation will have been identified. This answer is important as the prevention practices that may be used against clay translocation are very different from those that would be used if the cause of the observed deep subsoil densification is by vehicular compaction.

The final aim of this project was to examine the effect of soil fabric as described in the SOILpakβ manual on the movement of water and solutes in these soils. This has obvious importance to irrigation practice, crop nutrition and in establishing controls on the off-paddock movement of any dissolved or suspended substances such as pesticides and nutrients.

Background

Soil structure affects both crop performance and off-paddock environmental impacts by influencing such processes as the movement of water, suspended solids and solutes, and root growth. For example, the movement through soil of solutes from sources such as fertilizers, pesticides and urban waste is currently of widespread concern regarding possible impacts on sections of our inland rivers as well as our groundwaters.

Although undeniably important, our understanding of the processes whereby soil structure influences solute movement is lacking. A large part of this problem would seem to be due to fact that the current soil behaviour models are limited to viewing soil as a homogeneous mixture of solid components with some large macropores. The soil micromorphology literature indicates that this concept is simplistic and often inappropriate. Certainly, common soil features such as clay coatings may have a large influence on solute movement in soil (Sullivan 1994; Tolmie and Sullivan 1996). In particular, under certain flow regimes such coatings substantially increase the rate of movement of solutes and water through soil bodies.

Recent research on a cracking clay from the lower Macquarie Valley (McKenzie et al. 1991) indicated that at this site long-term cotton production had resulted in increased clay dispersion in the surface soil layers and in deep subsoil densification down to a depth of at least 120 cm. The authors of this study suggest that these forms of soil degradation may be related, with the subsoil densification possibly being a result of "vertical translocation of dispersed clay in the cultivated area (filling) macropores" in the deep subsoil. It is important that although subsoil densification caused by compaction from tractors and harvesters etc. has been usually considered to be confined to the top 60 to 80 cm of the soil profile. This much deeper subsoil densification would be less easily rectified. If indeed the cause of this deep subsoil densification was due to clay translocation then this problem would be even greater concern. Greenland (1977) regards this form of degradation as "the most insidious form of structural damage". The above results and suggestion of McKenzie et al. (1991) are especially relevant to the study by Sullivan and Koppi (1994) that showed that the shiny ped faces from some cracking clay soils of northern NSW consisted of extremely thin clay coatings formed by translocation.

The importance of the above findings to cotton production is that the presence of clay coatings on peds: 1) may influence solute and water movement in these soils leading to increased preferential flow through and leakage from the root zone.

2) would provide an clear explanation for the formation of shiny fabrics in these soils and hence indicate implications for the management of these soils.
3) represent a process that could be responsible for the deep subsoil densification that has been observed in a cotton field near Warren by McKenzie et al. (1991).

2. Objectives

These were:

(1) to determine the role of soil instability and clay translocation in the formation of shiny-faced soil aggregates.
(2) to determine the roles of clay translocation and vehicular compaction in the formation of subsoil densification in cracking clays used for cotton production.
(3) to examine the effect of aggregate surface fabric on the movement of water and solutes in these soils.

3. Results and Discussion

The nature of the fabric in cracking soils used for cotton production.

Several ped surfaces were observed based on the type of relief visible in the field using a X10 hand lens using dry soil. These were:

1) flat,
2) undulating, and
3) rough.

For the cracking clay soils used for cotton production, both the flat and undulating surfaces (hereafter called 'fabrics') were usually shiny, whereas the rough fabrics where always dull.

The flat surfaces were either striated or non-striated. The striated fabrics were usually large with an areal extent of at least 10 cm^2 in area and often up many hundreds of cm^2 are termed 'slickensides' and have formed by one soil surface moving over another as a result of soil swelling and shrinking cycles. The non-striated fabrics were usually much smaller in aerial extent (e.g. on ped surfaces of only several mm^2) and are often called "stress cutans". There were also the special case of striated fabrics that are the smeared surfaces caused by the passage of implements through the soil when too wet.

SEM examination of the shiny undulating ped surface fabrics demonstrated that these were comprised of clay coatings usually very thin (but up to 1mm in some deep subsoils) and covering all of the ped surfaces examined. SEM examination of the rough ped surfaces (these were always dull) showed that these surfaces were also covered by very thin clay coatings.

The reason for the appearance or absence of lustre on these surfaces when viewed through a x10 hand lens (despite, in some cases, being coated by clay coatings) can be best explained by reference to the four main fabric situations in soil:

1) Flat ,coated, pressed or smeared soil surfaces.

When the submicroscopic relief of these surfaces is small compared to the wavelength of visible light (ie. around 500 nm) as a result of being coated, pressed or smeared, specular reflection of incident light off that surface will occur at all but incident angles near zero. It is specularly reflected light that can appear as lustre. As these surfaces are flat when viewed through a X10 hand lens, large areas of these surfaces will reflect light specularly in a uniform manner: these surfaces therefore appear shiny over large areas of soil surface when viewed in reflected light.

2) All uncoated, unpressed or unsmeared soil surfaces.

The submicroscopic relief of these surfaces will be large compared to the wavelength of visible light and thus incident light will reflect diffusely rather than specularly, thus giving the soil surface a dull appearance over all of the soil surface regardless of whether these surfaces are flat, undulating or rough when viewed through a X10 hand lens. Essentially all soil structural surfaces unless coated, pressed or smeared will appear dull.

3) Undulating, coated or pressed soil surfaces.

The submicroscopic relief of these surfaces is small compared to the wavelength of visible light so specular reflection of light occurs. However as the surface is undulating when viewed at x10 magnification, specular reflection is only observed from small areas of the soil surface (as compared to when the surface is flat) at any one time. Thus the lustre patterns on the ped surface will appear somewhat speckled: as the soil surface is slowly tilted relative to the observer, these speckled lustre patterns essentially maintain continuity.

4) Rough, clay coated soil surfaces.

The submicroscopic relief of these surfaces is small compared to the wavelength of visible light so specular reflection of light occurs. However as the surface is rough when viewed at x10 magnification, specular reflection observed by the viewer only is received from minute isolated areas of the soil surface. Thus for these situations the ped surface will appear dull.

It is of importance that the appearance of lustre on soil surfaces varies with the magnification used for observations insofar that the apparent surface topography of that soil surface also varies with the magnification used. For example, ped surfaces that appear rough by examination with the naked eye may appear undulating when viewed using a x10 hand lens. Similarly, ped surfaces that appear undulating when viewed at one magnification may appear as flat surfaces when viewed at higher magnifications.The type situations 1), 3) and 4) above are thus dependent on the magnification being used to make the determination of fabric and thus the magnification used for the observation should be stated whenever the soil fabric results are reported.

It should be noted that situation 2) above is sensitive to soil wetness: when the soil is wet these surfaces can appear shiny but when dry the same surface can appear dull. It is thus important to determine fabric when the soil is in the dry condition. Other factors important for determining the ped fabric include:

1) the nature of the incident light is important for ped fabric determination. For example, on sunny days ped fabrics are more likely to appear lustrous as compared to cloudy days when the incident (natural) light is more diffuse in nature (a small penlight torch is very useful for determining ped fabric lustre on cloudy days).
2) the angles of incidence and of observance of the incident light off the ped surface. The shallower these angles the greater the likelihood of the surface appearing shiny. In this study approximately 55^0 was used for the angles of incidence and observance of the incident light off the ped surface to determine ped fabric.

Another complicating factor when determining ped fabric in the field was noted in this study and has also been identified in SOILpakβ. The soil in pits dug in cotton soils were usually much wetter than those dug in adjacent undisturbed sites. It was noted that the surfaces on soil materials dissected from the walls of cotton soil pits immediately after pit exhumation were apparently not always separated into large intact peds but rather had surfaces resulting from fracturing across large peds. The fabrics of these exhumed materials often appeared rougher than pits in the adjacent undisturbed sites. However, after a day or two of drying, the inherent soil structure on the side of the pit was more clearly evident and larger intact peds with shiny fabrics were able to be easily separated from the rest of the soil materials.

SOILpakβ indicates that along with other structural indicators compacted poorly structured cracking clay soils generally have dull faces whereas well structured cracking clay soils have a proliferation of shiny faces. This was not uniformly observed in this project however. For example, at the CRC for Sustainable Cotton Production rotational trial site located near Dalby the reverse occurred: here the native site had a rough fabric and the cultivated site, although having a much denser structure, also had a proliferation of shiny ped surfaces.

Importantly, the results of this investigation indicate that a dull ped fabric in these soils can not be taken to indicate that that soil has not experienced clay accumulation as a result of soil instability in the form of clay dispersion. Indeed, the highly sensitive scanning electron microscopy technique used in this study for detecting clay coatings in soils clearly shows that clay movement is a common natural process in these soils whether cultivated or not. All ped faces examined were clay coated whether shiny or not. In these cracking clay soils lustre is a direct result of the roughness of the underlying coated soil ped surface rather than being an indicator of soil instability and clay translocation. Aggregates that form after disturbance by cultivation will often have a rough surface and hence a dull appearance.

Implications of soil fabric for soil management

This section of the project has provided an understanding of the fundamental nature of fabric examination as used in soil management and description (e.g. as is currently used in SOILpakβ for indicating the structural status of cracking cotton soils) and provided a more rational basis for interpretation of this soil characteristic. For example, the results of this project indicate that that dull ped fabrics cannot be taken to infer that structural instability in the form of clay mobilisation and translocation has not taken place in these soils. Furthermore, as all ped surfaces in these soils are either clay coated or slickensides these soil fabric results suggest that the solute behaviour of these soils will be as described for clay coated aggregates in the section entitled "Effect of soil fabric on solute movement".

Deep subsoil densification cracking clay soils used for cotton production

This study has:

1) extended the results of previous research on a cracking clay from the lower Macquarie Valley by McKenzie et al. (1991) which indicated that at this site long-term cotton growing had resulted in deep subsoil densification down to a depth of 120 cm.
2) identified the cause of the deep subsoil densification in irrigated cracking clay soils used for cotton production.
3) indicated that deep subsoil densification is likely to be widespread in irrigated cracking clay soils used for cotton production.

A preliminary examination was undertaken on three sites - all on cracking, grey clays - one at Warren property, another at Wee Waa, and the other near Bourke. At each site two pits were excavated to 150 cm depth: one pit was located in a paddock which has been used for irrigated cotton production for around 20 years, and the other in a nearby undisturbed paddock (or stock route). In the cotton paddocks the soil was sampled from under a hill adjacent a wheel track. Clod bulk density analysis indicated that there was subsoil densification at all of the three sites examined. Shallow subsoil densification (ie. compaction confined to soil layers above 50 cm depth) was evident in all of the cultivated soils. Deep subsoil densification (this term is used to describe subsoil densification below 50 cm) was observed at all four sites and extended to the lowest sampling depth.

These preliminary subsoil densification results indicated that there was a need to sample well below 150 cm depth to allow examination of even deeper subsoil densification.At both the Warren site (Auscott field 15) and a new site near Pilliga (field 12 of Myall farm) replicated paired site trials was established with soil density, particle size analysis and scanning electron micromorphology being determined in successive layers down to 205 cm depth. Figures 1a and b (*n.b.* all the figures referred to in this report are on the attached page No. 8) show the results of dry bulk density (oven-dry) with depth for the Warren and Pilliga sites, respectively. As is usual, the bulk density of the cultivated soil clods in the surface layer(s) at both sites were less than that for the native soils due to the effects of cultivation.

Warren site subsoil densification

At the Warren site (see Figure 1a) it is very clear that considerable deep subsoil densification has occurred below the cultivation layer down to the 200 cm depth. (Note: the 1995 bulk densities for the cultivated and native soil shown in this Figure were statistically significantly different for all depth layers except 70-85 cm, and 190-205 cm.) The compaction was particularly severe in the 130-145 cm layer where a dry bulk density increase of 11% occurred. The trends in bulk density with depth in Figure 1a suggest that the densification may have extended below 200 cm.

The similarity in the particles size analysis versus soil depth relationships (Figure 1d) for cultivated and native soils at this site clearly indicates that the main reason for the densification in all soil layers was compaction (induced by vehicles) rather than by translocated clay plugging existing pore space as induced by clay translocation from surface layers and irrigation water. Figure 1e, the relationship between the % clay of individual soil clods as compared to the bulk density of that clod for the 130-145 cm layer, demonstrates that compaction is the main cause of subsoil densification even more clearly. It is apparent from this figure that the cultivated soil clods had higher bulk densities at any given clay content. Therefore, the densification in this layer was not due to clay translocation.

This result might seem contradictory with the results mentioned in earlier, namely, that scanning electron microscopy of samples from all of sites indicated the presence of clay coatings on all ped faces other than those affected by stress (e.g. slickensides). However, it should be stressed that clay coatings were ubiquitous on the peds surfaces of the native soils as well the cultivated soils. Thus, clay translocation is a process that is occurring naturally in these soils. The % clay content data for these soils clearly indicates that the suggestion of McKenzie et al. (1991) that enhanced clay translocation in these soils as a result of soil instability could be responsible for the observed deep subsoil densification is not tenable.

Pilliga site subsoil densification

At the Pilliga site (see Figure 1b) it is evident that deep subsoil densification has occurred in the 30 - 85 cm and 130 -145 cm depth layers, but only resulting in a dry bulk density increase of 2% at the lower layer. The similarity in the particles size analysis versus soil depth relationships (Figure 1d) for cultivated and native soils at this site clearly indicates that the main reason for the densification at this site (as at the Warren site) is compaction by vehicles rather than by clay translocation from surface layers and irrigation water.

Comparison of the two replicated sites

The degree and pattern of subsoil compaction down to 85 cm at each site was comparable and any variations can be attributed to either differences in soil textures or immediate past history in relation to trafficking and deep-ripping. However, the degree of subsoil compaction below 100 cm depth was very different in the two sites with Warren site being compacted to both a greater amount and depth range that the Pilliga site below these depths (see Figures 1 a and b).

A full explanation for the difference between these two sites in the degree of compaction at these depths could only be fully answered from further studies with a different focus. However, an indication of the likely reasons for these differences can be gained from a consideration of the different histories of these sites and the bulk density data. The Warren site was prepared for furrow-irrigated cotton production in 1967 (ie. 28 years before the sampling for this study) and experienced particularly intense vehicular trafficking during the initial field preparations for irrigation (McKenzie pers. comm.). In comparison the Pilliga site was prepared for furrow-irrigation in 1983 (ie. 12 years before the sampling for this study) and did not require intensive initial field preparations (Montgomery pers. comm). Figure 1a gives a comparison of the dry bulk densities of nearby sites sampled in 1982 (McKenzie et al. 1991) and the 1995 data generated in this project. Although McKenzies' bulk density data was generated by a different method to that used here and their site was separated from ours by approximately 3 km, the similarity of the bulk density/depth relationships in the two studies suggest that the subsoil densification of the soils on this farm has not worsened in the 13 years since 1982. Although necessarily speculative the above data does suggest that the main factor responsible for the substantial deep subsoil compaction at the Warren site was the initial field preparations for irrigation.

Causes of deep subsoil compaction

Soehne (1958) recognised theoretically that compaction in the surface soil layers is caused primarily by the specific pressure applied at the surface (this can be approximated by the tyre pressure), whereas compaction in the deeper layers is caused primarily by the amount of load (ie. axle load). This theory was confirmed experimentally under both laboratory and field conditions (e.g. Danfors 1974; Taylor et al. 1980; Voorhees et al. 1978): this relationship has also been noted by Kirby and Blunden (1993 and 1994) as being important for cotton production in Australia. Thus, soil compaction theory,the extensive overseas experience, and the experimental results here, all indicate that the substantial amount subsoil densification observed at all of the four experimental sites was caused mainly by high axle loads of the machinery trafficking at each site. Hadas (1994) has argued that other factors such as tyre dimensions, contact stresses the number of passes, soil density and moisture distributions, and soil strength distributions also need to be taken into account when assessing the causes of deep soil compaction.

It is important to note that both the depth and severity of the subsoil compaction observed in this project were much greater that has yet been reported in the literature. For example most deep subsoil compaction reported in the literature refers to compaction in the 40-60 cm soil layer and the deepest previously recorded soil compaction in agricultural situations appears to be down to 100 cm depth at a Ukrainian site (Hakansson and Medvedev 1994).

The reason for the severity of compaction observed at both replicated sites (but especially the Warren site) was beyond the scope of this project, but one probable soil factor that may have contributed to this is the cracking nature of these soils. It has been speculated previously (van den Akker; as cited in Hakansson and Reeder 1994) that the occurrence of vertical cracks in dry cracking soils may lead to the transmission of stress into deep subsoils without attenuation. Certainly the cracking clay soils used for cotton production in Australia have numerous vertical cracks when dry and it is very conceivable that trafficking on these soils when the surface layers were dry but the subsoil layers were not, may have lead to the formation of the observed deep subsoil compaction. If this is indeed the case and deep subsoil compaction is found to limit crop production in the same way that the overseas data suggests, then the suitability of trafficking on these soils under 'dry cracked surface and wet subsoil' conditions may need to be assessed.

Managing deep subsoil compaction

There are some excellent recent reviews on this comparatively new area of research (e.g. Hakansson and Reeder 1994; Hadas 1994) and although this area is also somewhat beyond the initial scope of this project, it may be useful to briefly review some of the overseas findings and implications here.

Most overseas data suggests that traffic on moist soils when the axle load is over 6 Mg (ie. 6 metric tonnes) or 8-10 Mg for tandem axle units, results in deep subsoil compaction (Hakansson and Danfors 1981; Hakansson and Medvedev 1995) even when low pressure tyres are used (Danfors 1994). Guidelines based on such data have been recommended in Sweden (Hakansson and Danfors, 1981). Perhaps similar guidelines could be developed for the cracking clays used for cotton production in Australia, although given the peculiar nature of these soils, the appropriate axle loads might be somewhat different (for example see discussion in the previous section).

It should also be noted that for homogeneous soils the lateral spreading of stresses beneath wheels would result in deep subsoil compaction zones that may be at least three times as wide as the tyre. The cracking nature of the cracking clay soils may limit the lateral extent of densification beneath permanent beds as compared to other soil types.

There is consensus in the literature that tandem wheels are much better than dual tyres in significantly reducing subsoil pressures (Carpenter et al. 1985), but although there is evidence to suggest that long narrow tracks are the best option for control of this compaction there is some disagreement on this point (Hakansson and Reeder 1994).

Implications of subsoil compaction for cotton production

Long term experiments conducted overseas have indicated that subsoil compaction below tillage depth causes yield reductions that persist for many years after the compaction event (the mean crop yield reduction in these trials during the period 4 - 12 years after compaction was 2.5% (Hakansson and Reeder 1994)). It should be noted that the subsoil compaction that was induced in these long term trials were not nearly as severe as the subsoil compaction observed in this project for these cracking clay soils. Hakansson and Reeder (1994) have conceptualised these long term results in the diagram (Figure 1f) which shows that the deeper the compaction, the more persistent the negative effect of that compaction on crop yield.

Many changes to soil behaviour occur when it is compacted. For example, compaction often results in decreases in hydraulic conductivity, air permeability and root growth, as well as increases in the incidence of root disease (Allmaras et al. 1988). Although some of these changes may actually be beneficial (for example decreased hydraulic conductivity may lead to lower losses of applied water beyond the root zone), overseas experience overwhelmingly suggests that deep subsoil compaction is detrimental to crop yields.

As subsoil compaction deeper than 40 cm is often difficult to successfully and completely ameliorate - and indeed attempts to do so may actually be counter-productive - prevention has been regarded as the best option for management (Hakansson and Medvedev 1995).

Effect of soil fabric on solute movement

The effect of aggregate surface fabric in terms of the presence or absence of clay coatings on the movement of water and solutes in these soils was also examined in the laboratory by following the movement of an applied tracer (chloride) under different solution flow regimes (in particular by using different flow rates) down columns of packed aggregates.

The results of these experiments clearly show that at fast flow rates (ie. at moisture contents where water moves in soil mainly in films around aggregates) solute displacement was not affected by the presence of the clay coatings around aggregates. At the slower flow rates (ie. at a moisture content below which the intra-aggregate pore space is saturated) it was clear that the presence of clay coatings around aggregates led to preferential flow as evidenced by the less effective displacement of solutes within the column by the incoming solution. The observed fast flow rate results are likely to be due to better aggregate-to-aggregate contact within the columns that resulted from the development of clay bridges during the aggregate coating process: this would lead to less by-passing of aggregates during solute flow and would enhance solute displacement despite the impermeability of clay coatings.

4. Conclusions, Recommendations and Application to Industry

This study has extended the results of previous research on cracking clays to show that the past practices used in long-term irrigated cotton growing have resulted in substantial deep subsoil densification down to depths of 200 cm and that such deep subsoil densification is likely to be widespread in the irrigated cracking clay soils used for cotton production. It is suggested that the peculiar structure of the cracking clay soils may contribute to making these soils very susceptible to deep subsoil compaction under some soil moisture conditions.

This project has also identified that the cause of the deep subsoil densification in irrigated cracking clay soils used for cotton production is vehicular compaction rather than clay translocation as has been previously suspected. Although some of the changes associated with deep subsoil compaction may actually be beneficial, overseas experience overwhelmingly suggests that deep subsoil compaction is detrimental to crop yields. These results indicate that the present trends and recommendations towards the use of lower axle loads and permanent bed systems in cotton production in Australia (McKenzie 1995; Anthony and Schoenfisch 1995) are very appropriate for these soils.

The scanning electron microscopy study on the fabric of these soils has provided an understanding of the fundamental nature of this soil characteristic as is currently used in SOILpakβ for indicating the structural status of cracking cotton soils, and provided a more rational basis for the measurement and subsequent interpretation of this soil characteristic. For example, the results of this project indicate that that dull ped fabrics cannot be taken to infer that structural instability in the form of clay mobilisation and translocation has not taken place in these soils. In addition, although SOILpakβ indicates that compacted poorly structured cracking clay soils generally have dull faces whereas well structured cracking clay soils have a proliferation of shiny faces, this was not always the case in the soils examined here and the presence of shiny structural surfaces in these soils is a function of the aggregate surface roughness caused by disruption or stress rather than an indicator of structural instability and clay translocation.

The fabric studies clearly showed that there are clay coatings on the structural surfaces within these soils: the solute movement work indicates that at moisture contents below which the intra-aggregate pore space contains conductive films of water, the presence of such clay coatings leads to preferential flow.

Communication of results

Several articles based partly or wholly on the results of this project have already been published or are being prepared for publication in international refereed journals or conferences (see list below). An articles on the results and implications of this project is being prepared for publication in The Australian Cotton Grower. Our results and methods will be an important part of the SOILpakβ section on soil structure and fabric evaluation and preliminary discussions on this have already occurred. I have requested the opportunity to extend these results at the Soils Meeting of the CRC for Sustainable Cotton Production in December, 1996 and have been duly invited and will seek to extend these result at other suitable venues as invited.

Publications/presentations to date arising from this project

Sullivan, L.A 1996. The recognition of depositional clay coatings by scanning electron microscopy. Proceedings of the 10th International Working Meeting on Soil Micromorphology. July, 1996, Moscow, Russia.

Sullivan, L.A. 1995. Microtrenches and microridges on the accretive structural surfaces of some clayey soils. Australian Journal of Soil Research 33: 565-568.

Sullivan, L.A. 1994. A new technique for the direct detection of clay translocation in Vertisols used for cotton growing. World Cotton Research Conference-1, Brisbane, 13-17th February, 1994.

Tolmie and Sullivan, 1996. Solute movement: the effect of aggregate fabric. Proceedings of the 10th International Working Meeting on Soil Micromorphology. July, 1996, Moscow, Russia.

Tolmie, P. and L.A. Sullivan 1994. Solute movement in cotton soils the effect of aggregate surface fabric. World Cotton Research Conference-1, Brisbane, 13-17th February, 1994.

References

Anthony, D. and Schoenfisch, M. 1995. The Australian Cotton Grower, 15:55-56.

Allmaras, R.R. et al 1988. Annual Review Phytopathology, 26:219-243.

Carpenter, T.G. et al 1985. Soil Tillage Research, 6:179-192.

Danfors, B. 1974. Rep. S 24, Swedish Institute of Agricultural Engineering, Uppsala.

Danfors, B. 1994. Soil and Tillage Research, 29:135-144.

Greenland, D.J. 1977. Philosphical Transactions of the Royal Society, London, B. 281:193-208.

Hadas, A. 1994. Soil and Tillage Research, 29:253-276.

Hakansson, I. and Danfors, B. 1981. Proc. of 7th Int. Conf. of ISTVS, Calgary.

Hakansson, I. and Reeder, R.C. 1994. Soil and Tillage Research, 29:277-304.

Hakansson, I. and Medvedev, V.W. 1994. Soil and Tillage Research, 29:85-97.

Kirby, J.M. and Blunden, B.G. 1993. The Australian Cotton Grower, 13:48-50.

Kirby, J.M. and Blunden, B.G. 1994. In 'Challenging the Future: Proceedings of the World Cotton Research Conference-1, Brisbane, Australia, February 14-17, 1994.

G.A. Constable and N.W. Forrester (Eds), CSIRO, Melbourne, pp. 165-168.

McKenzie, D.C. et al. 1991. Australian Journal of Soil Research, 29:443-453.

McKenzie, D.C. 1995. The Australian Cotton Grower, 15:57-59.

Sohne, W. 1958. Agricultural Engineering, 39:276-281.

Sullivan, L.A. 1994. In 'Soil Micromorphology: Studies in Management and Genesis'. Developments in Soil Science 22. A. Ringrose-Voase and G.H. Humphries (Eds.), Elsevier, Amsterdam. pp. 613-622.

Sullivan, L.A. and Koppi, A.J. 1994. Soil Science, 158: 218-223.

Taylor, J.H. et al. 1980. Transactions of the ASAE, 23:568-570.

Tolmie and Sullivan, 1996. Proceedings of the 10th International Working Meeting on Soil Micromorphology. July, 1996, Moscow, Russia.

Voorhees, W.B. et al. 1978. Soil Science Society of America Journal, 42:344-349.

Figure 1a

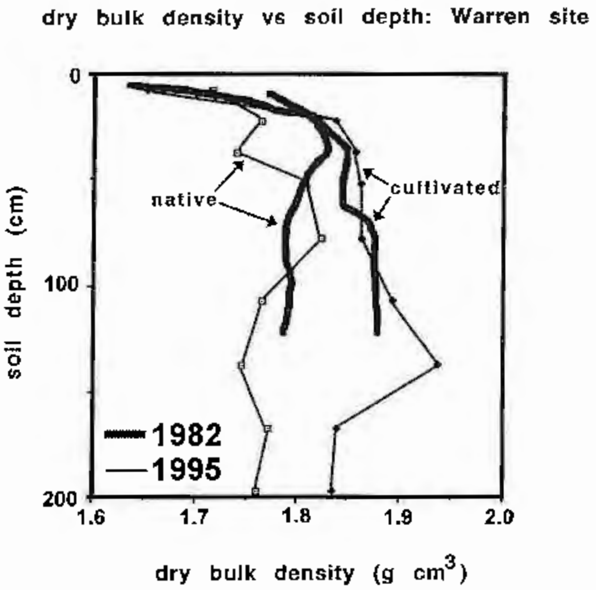

dry bulk density vs soil depth: Warren site

Figure 1b

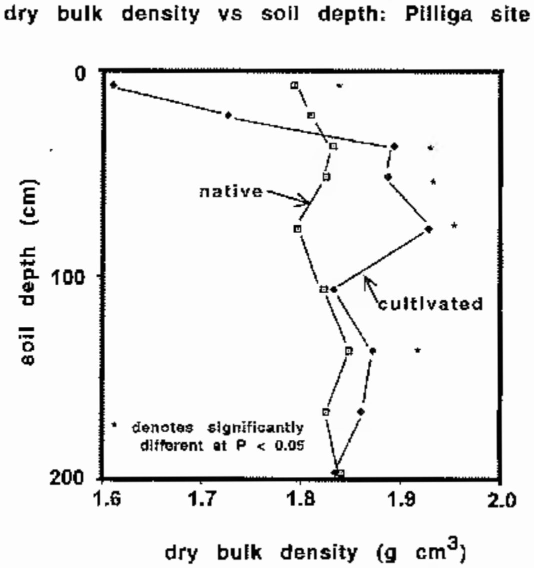
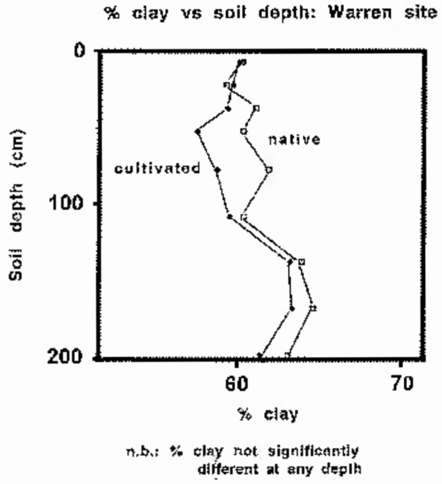
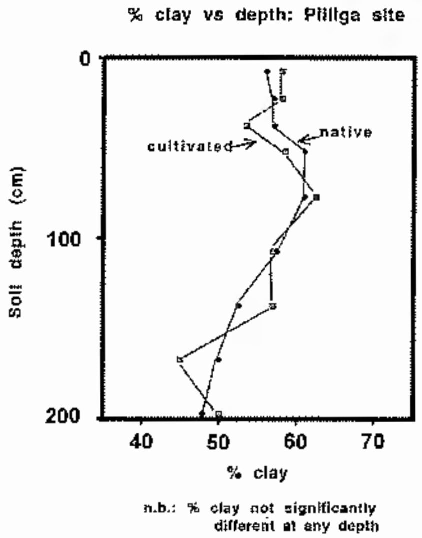

dry bulk density vs soil depth: Pilliga site

Figure 1c


% clay vs soil depth: Warren site

n.b.: % clay not significantly different at any depth

Figure 1d


% clay vs depth: Pilliga site

n.b.: % clay not significantly different at any depth

Figure 1e

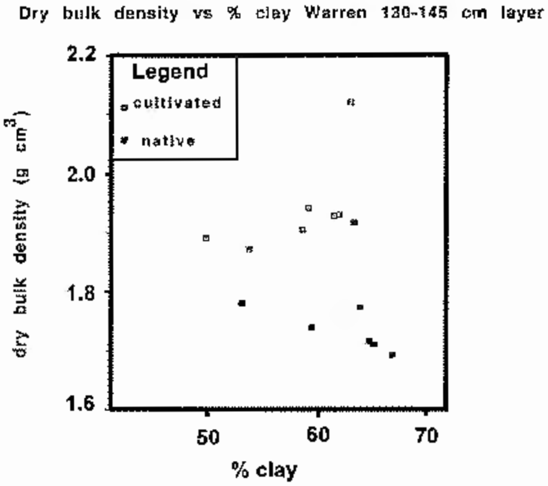

Dry bulk density vs % clay Warren 130-145 cm layer

Figure 1f