PROBLEMS ASSOCIATED WITH SOIL STRUCTURAL ASSESSMENT ON VERTISOLS USED FOR IRRIGATED COTTON PRODUCTION

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Abstract

Techniques for assessing the severity of soil compaction were evaluated, mostly under commercial conditions, at twelve sites with contrasting degrees of damage. The soils at each site are Vertisols used to produce irrigated cotton. The reference technique for soil structural assessment was clod shrinkage analysis. This procedure is prone to sampling bias, but until recently it was widely regarded to be the best available method. We combined a number of the shrinkage parameters to provide a soil structural index (SSI). A broad range of mostly cheaper soil structural and plant measurements were regressed against the SSI. There was no single technique that accounted for more than 49% of the variation in the SSI. Groups of alternative structural form measurements accounted for substantially more of the variation, but their routine use by cotton managers was considered to be impractical. There was a lack of correlation between cotton lint yield and SSI when all the data were considered together. Sites with poor soil structure frequently had high yielding crops, due to high nitrogen application rates and frequent irrigations, which appear largely to have compensated for the adverse effects of soil compaction on crop growth and yield. However, such an approach to farming is inefficient, and may lead to off-site pollution, so the search for adequate procedures to measure the degree of compaction must continue. Associated research carried out since our study was undertaken has demonstrated the potential of image analysis procedures, and of an improved version of the SOILpak scoring system.

Introduction

Yield declines in irrigated cotton (*Gossypium hirsutum* L.) resulting from mechanical compaction in the Macquarie and Namoi Valleys (New South Wales), Australia in the late 1970s sparked a wave of research dealing with its effects on cotton, and with the evaluation of ameliorating techniques (Hodgson and Chan, 1982; McGarry, 1987; McGarry and Daniells, 1987; McKenzie *et al.*, 1987; Daniells, 1989; McGarry, 1990; Hulme *et al.*, 1991; McKenzie *et al.*, 1990, 1991). Cotton growth and profitability often are adversely affected by the poor aeration, high soil strength and/or the disruption of continuous pore channels that are associated with soil compaction. Most cotton in Australia is grown on grey cracking clay soils (Vertisols).

A number of solutions for alleviating compaction problems have been developed, such as crack development using drought stressed rotation crops, deep ripping, and the addition of extra nitrogen and water. Reduced tillage techniques are recommended where compaction within the root zone is not serious. However, problems with the identification of the degree of compaction in the field makes the selection of management options difficult. Presently, routine soil structural assessments in the field rely heavily on the experience of the assessor, who are guided by the SOILpak visual assessment scheme (Daniells and Larsen, 1991). This scheme is part of a soil management decision-support manual for cotton growers and their advisors. In recent years soil management practices have improved as cotton growers became more aware of compaction, so the damage to the soil generally has become more subtle and hence more difficult to detect visually. Growers and consultants often lack the confidence to assess compaction in the field and the means of overcoming its adverse effects.

The primary aim of this study was to determine which of the available techniques for assessing soil structure, either singly or in combination, can be used routinely in the field. Emphasis was placed on methods that assess soil and plant properties related to soil structural form, i.e. 'architecture' of the soil pores and solids (Kay, 1990). The baseline technique for assessing the severity of compaction was clod shrinkage analysis. Several researchers have previously used individual parameters derived from the shrinkage curve to identify soil structural differences on cracking clay soils (Abbott and Daniells, 1987; McGarry and Daniells, 1987; Daniells, 1989; McGarry, 1990; McKenzie *et al.*, 1991), but no attempt has been made to integrate them.

Methods

The study was carried out over three growing seasons between 1989 and 1993 in the Macquarie and Namoi Valleys, two of the major cotton growing valleys in NSW. Twelve sites within these valleys were chosen to evaluate the techniques that were currently available for the assessment of soil factors influenced by soil structural form. These sites encompassed a range of different grey cracking clay soils, and incorporated various degrees of compaction. The different degrees of compaction were either existing soil structural damage due to wet picking or had been induced by driving machinery wheels on the top of cotton ridges.

Soil structural and plant measurements

Soil structure was assessed in August, shortly before planting of cotton. The measurements taken included: soil profile assessments based on the Peerlkamp and Boekel scheme, as modified by Batey (1988); soil strength using the Rimik cone penetrometer, with results at each depth considered as frequencies within six strength categories, and 'Chatillion' handheld penetrometer; clod shrinkage (Brasher *et al.*, 1966); macroporosity following Rhodamine dye infiltration (McKenzie *et al.*, 1987); and bulk density and air-filled porosity (McIntyre and Barrow, 1972). These measurements were taken at depths of 15 and 35 cm below the soil surface. Oxgyen flux density, air-filled porosity, bulk density and water extraction measurements were also taken at two day intervals for the duration of a mid-season irrigation cycle. Lint yields and taproot morphological characteristics were measured at the end of the season. The taproot morphological characteristics were measured at 10 cm intervals, and included taproot diameter, taproot obliquity (angle of the taproot from the vertical), number of lateral roots emanating from the taproot, and taproot flatness. The changes in these properties between depths were recorded as ratios. Gerard *et al.* (1972) noted that as the degree of soil compaction increases, cotton taproots tend to become wider, more tapered and flatter, and have more laterals and a greater obliquity.

Formation of the soil structural index (SSI)

The reference technique for soil structural assessment was clod shrinkage analysis (Brasher *et al.*, 1966; McGarry and Malafant, 1987). We combined a number of the shrinkage parameters to provide a soil structural index (SSI). The SSI was formed using principle component analysis, and incorporated a number of shrinkage parameters which were then weighted according to their importance in discriminating between different sites. All the soil structural and plant measurements were regressed against the SSI to determine a set of models which could, hopefully, be used by extension and research personnel to assess the structural condition of the soil in the field. It was assumed that any soil structural damage present would be most evident at these depths.

Results

An equation for the calculation of SSI is shown in Table 1. It incorporates parameter weightings from the principal component analysis, and the mean and standard deviation values. The parameters with the largest weighting i.e. P_B, P_A, have been shown in other studies to be sensitive to soil structural differences (Abbott and Daniells, 1987; McGarry and Daniells, 1987; Daniells, 1989; McGarry, 1990; McKenzie *et al.*, 1991). Each of the parameters in the SSI equation is shown in Figure 1.

There was no single measurement technique that accounted for more than 49% of the variation in the SSI (Table 2). Techniques that were expected to relate well to SSI performed poorly when all of the data were considered together. Rate of water extraction, measured using aneutron probe, was strongly influenced by cool, wet weather at some of the monitoring sites. Soil strength measurements could not be standardised to a reference water content because most of the study sites did not have an appropriate calibration. Root characteristics apparely were influenced by rainfall and temperature variations at the different sites soon after planting. Hence, models based on 40 structure-related observations were developed using multivariate analysis for the 15 and 35 cm depths. The models incorporate yield; bulk density; air-filled porosity; soil strength measurements using the Rimik penetrometer; taproot diameter, taproot obliquity, number of lateral roots, taproot flatness, and the associated ratios; water extraction over an irrigation cycle and daily water use. As this is a multivariate regression it is not possible to look at the relationship between SSI and each regressor variable in isolation, as some of the variables are correlated. The models are shown in Table 3.

Discussion

Soil structural index (SSI)

The SSI weightings are similar for a number of data sets indicating that the SSI provides consistent results. The SSI ranges from 7.7 to -4.9, with higher values indicating better structured soils.

Deficiencies were apparent with clod collection procedures for the shrinkage analysis. Firstly, the clods collected may not be large enough (Chan, 1981) to gain a true representation of whole field structure. Secondly, the collection of clods was biased towards those clods that were large and firm enough to analyse. This introduced sampling bias where the soil was in good condition, as the only clods able to be collected appeared to be remnants of previously damaged soil.

Despite the problems associated with clod shrinkage sampling, it appeared to provide the most precise measure of soil structural condition. Other techniques that were evaluated had either technical difficulties or were dependent upon inter-related soil conditions. Soil strength, bulk density (core method) and air-filled porosity are all strongly influenced by the moisture status of the soil. Water content is easily measured, but the need to calibrate each soil individually as a function of moisture presently makes these techniques impractical for use by advisory staff on most Australian cotton soils. The technique for measuring oxygen flux density (Hodgson and MacLeod, 1989) was highly dependent upon the quality of the soil sample collected.

Soil structural assessment and yield

Commonly, poor soil structure in terms of high soil strengths and/or low porosity leads to reduced cotton yields (Taylor and Burnett, 1963; Carter and Tavernetti, 1968; Hodgson and Chan, 1982; Khalilian *et al.*, 1983; McKenzie *et al.*, 1990). However, in this study there was a lack of correlation between yield and SSI. Sites with poor soil structure frequently had high yielding crops. This result was attributed to management practices. High nitrogen application rates (Constable *et al.*, 1992) and frequent irrigations (Roth and Cull, 1991) appear to have compensated for the adverse effects of soil compaction on crop growth and yield. This enabled the plant to survive in the area above the compacted layer without experiencing severe water or nutriential deficiencies which are detrimental to plant growth. Any periodic waterlogging, which reduces yield, arising from increased irrigation can to some extent be avoided by growing cotton on ridges that are high enough to provide a well-aerated, inundation-free root zone near the surface.

Soil structural assessment models

The models developed from the multiple regression analysis can be used (if the predictor variables contained within this have been measured) to assess soil structural condition in the field. The resulting SSI can then be used to rank fields and monitor the condition of fields over time. Used in conjunction with the SOILpak manual it provides extension personnel with an objective tool for making management decisions relating to soil structure.

There are however two major disadvantages of these models. Firstly, some of the groups of measurements included in the models that have been shown to be very useful, i.e. the root morphology characteristics, water extraction and yield, relate to the previous crop. Thus, if any soil damage occurs during picking or subsequent land preparation it will not be identified by these models. Models based only on soil measurements, however, have low precision and cannot be used to reliably predict the SSI. At this stage there appear to be no techniques available that will give consistent and reliable results, yet which are also rapid, inexpensive and simple to use. Secondly, we lack sufficient data to predict how low the SSI has to be to inhibit plant development and reduce lint yield for a particular level of management input. Nevertheless, the models can be used to assist with the ranking of fields, in terms of the severity of compaction, to assist with whole-farm irrigation, water allocation, and fertilizer and planting decisions.

The future of soil structural assessment

Soil structural assessment is an important part of the decision making process for cotton growers. It enables cotton growers to identify soil structural problems, and make decisions regarding appropriate soil and cotton crop management.

Hearn (1986) and Constable *et al.* (1992) have shown that even with high rates of applied nitrogen, lint yields on compacted soil never quite reach the same level as on well structured soil. Thus, it is necessary to alleviate soil damage, using techniques such as biological and mechanical ripping, even though some of the amelioration procedures tend to be expensive and time-consuming. The increased costs from extra nitrogen and water applications that are associated with more intensive crop management, along with the environmental concerns of rising watertables and excessive evaporation losses related to frequent irrigation, and the addition of atmospheric pollutants, e.g. nitrous oxide, to the atmosphere, makes living with compaction impractical in the long term.

Therefore it is important that we continue to search for structural assessment methods that are less biased, more precise, easier to use, and cheaper than those discussed above. Fortunately, experience gained during the course of this project has assisted with the continuing development of improved versions of the SOLICON image analysis system (Moran *et al.*, 1990; Koppi and McBratney, 1991; McKenzie *et al.*, 1994), and air permeability devices (Koppi pers. comm.), which have several advantages over the procedures used in this study. Recent improvements to the semi-objective SOILpak scoring system (Larsen, 1994) reduce bias problems.

These new methods, and the findings of our study, will be incorporated into the next version of the SOILpak decision support system. It aims to help growers to maximize their profitability and minimize environmental side-effects by using appropriate soil management techniques, after the assessment of soil physical condition.

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Table 1. The combined-depth equation used to calculated SSI from clod shrinkage parameters.

$$
\begin{aligned}
\mathrm{SSI} = \; & - [(\theta_A - 0.0853) * 15.8229] + [(\vartheta_A - 0.5362) * 20.8425] \\
& - [(\theta_B - 0.2203) * 3.7523] + [\vartheta_B - 0.6736) * 10.6426] \\
& + [(\vartheta_V - 0.6540) * 13.5608] - [(r - 0.0652) * 3.8383] \\
& - [(n - 1.0381) * 1.1282] - [(s - 0.2366) * 0.8713] \\
& + [(D - 0.8015) * 0.4694] - [(d - 0.9729) * 0.2791] \\
& + [(\alpha - 0.5300) * 19.9655] + [(P\alpha - 0.1596) * 19.9655] \\
& + [(P_A - 0.0806) * 12.7951] + [(P_B - 0.0829) * 13.8677]
\end{aligned}
$$

Table 2. Degree of correlation between SSI and each of the measures of soil structure. Only those techniques that exhibited significant correlation with the SSI have been included. Negative signs in brackets before the r^2 values indicate that the factors are inversely related.

Soil structural measurements	r^2 values		
	Combined depths	15 cm depth	35 cm depth
bulk density§	(-) 0.382***	(-) 0.291*	(-) 0.490***
air-filled porosity†	0.323***	0.363**	0.154*
Rimik penetrometer: 15 cm & 35 cm§	(-) 0.099*	(-) 0.150*	ns
root diameter	0.068*	ns	ns
root diameter ratio: 5/15 cm & 25/35 cm	(-) 0.078*	ns	ns
root obliquity ratio: 30-40/40-50 cm	ns	ns	0.254*
no. of lateral roots: 10-20 cm & 30-40 cm	0.118*	ns	0.163*
no. of lateral roots ratio: 0-10/10-20 cm & 20-30/30-40 cm	(-) 0.117*	ns	ns
visual assessment (Peerlkamp Scheme, modified by soil strength frequency 15 cm & 35 cm Batey 1988): 0-0.3 Mpa¶	0.077*	ns	ns
soil strength frequency 15 cm & 35 cm: 0.7-2.5 Mpa¶	(-) 0.073*	ns	ns
water extraction: 20 cm	0.201**	0.292*	0.161*
water extraction: 40 cm	0.135*	0.198*	ns
water extraction: 20-40 cm	0.137*	0.199*	ns

§ approximately at field capacity

† at reference water content (θg) of 20%

¶ refers to the proportion of readings that lie within the 0-0.3 Mpa or 0.7-2.5 Mpa soil strength ranges.

* $p<0.05$; ** $p<0.01$; *** $p<0.001$.

Table 3. Multivariate models relating to SSI to the other structure - related measurements.

1. 15 cm Depth - 7 variable model ($r^2 = 0.621$)

SSI = -180 + (104.52*bd) + (183.92* afp) + 2.94* rdiar, 10/20 cm) - (0.24* robl) - (0.70*nlat) - (0.70*nlatr, 10-20/20-30 cm) + (0.18*ext, 20 cm)

2. 35 cm Depth - 8 variable model ($r^2 = 0.677$)

SSI = 12.28 - (0.002*yield) + (0.002*Rimik) + (4.41*rdia) - (1.91*roblr, 20-30/30-40 cm) + (0.35*nlat) - (11.04*rflat) + (0.08*ext, 20 cm) - (0.65*dwu, 20 cm).

bd - bulk density †±	afp - air-filled porosity †§	nlatr - number of lateral roots ratio	rdiar - root diameter ratio
rdia - root diameter	roblr - root obliquity ratio	nlat - number of lateral roots	rflat - root flatness
robl - root obliquity	ext - total water extraction over one irrigation cycle	dwu - daily water use over one irrigation cycle	Rimik - Rimik penetrometer†‡
† pre-season measurement	‡ not corrected for moisture content	§ corrected to moisture content (grav.) of 20%	

Figure 1. Shrinkage "curve" showing the structural, normal and residual zones of shrinkage, and the derived parameters used in Table 1. θ_A = gravimetric water content at the air-entry point, ϑ_A = clod volume (per unit mass of soil solids) at air-entry point, θ_B = gravimetric water content at the swelling limit, ϑ_B = clod volume at the swelling limit, ϑ_V = clod volume at a water content of 0.2 $MgMg^{-1}$, r = shrinkage "curve" slope during residual shrinkage, n = slope during normal shrinkage, s = slope during structural shrinkage, D = n-s, d = n-r, α = clod volume at zero water content, $P\alpha$ = volume (per unit mass of soil solids) of air-filled pores at zero water content, P_A = volume of air-filled pores at the air-entry point, P_B = volume of air-filled pores at the swelling limit.