COTTON RESEARCH AND DEVELOPMENT CORPORATION

DAN 83C

Management systems for cotton on permanent beds - Maximizing the benefits of rotation crops

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SUMMARY

A survey of cotton growers in 1992 (CRDC Project DAN 76C) showed widespread interest in the use of rotation crops, plus a need for more information about the benefits of legume rotations and the effect of rotation management on subsequent cotton crops. To investigate the effect of rotation crop type and management on soil properties, cotton productivity, and overall farm productivity, 3 field trials located in 2 regions (Namoi and Macquarie Valleys of NSW), were set up in 1993.

Trial A was located at the Australian Cotton Research Institute near Narrabri. This trial was established on the site of a former experiment which ran from 1985 to 1993. During this period the plots received 3 treatments: continuous cotton/intensive tillage; continuous cotton/ minimum tillage; and a wheat-cotton rotation/minimum tillage. In 1993 the plots were split and the following rotations were imposed on sub-plots: continuous cotton; cowpea/cotton; and fallow/cotton. Trial B was located on the property 'Glenarvon' near Wee Waa. This site had grown cotton for several years prior to 1993 when the following 4 rotations were established: cotton/unfertilized wheat; cotton/wheat with 140 kg N ha^{-1}; cotton/unfertilized chick pea (grain harvested); cotton /unfertilized chick pea (grain not harvested). The wheat and chick peas were sown in June 1993, and cotton in October 1994. Trial C was established at 'Auscott-Warren'. The site had been sown with cotton for the 3 years prior to 1993 when the following 7 rotations were established: continuous cotton; cotton/fallow; cotton/field peas; cotton/low input wheat (rainfed, 16 kg N & 17 kg P ha^{-1}); cotton/high input wheat (irrigated, 99 kg N & 17 kg P ha^{-1}); cotton/low input wheat/dolichos; cotton/low input wheat/dolichos fb. 24 kg P & 73 kg K ha^{-1}. The winter rotation crops (wheat and field pea) were sown in June 1993. All plots were sown to cotton in October 1994. Rotation crops were again planted in June 1995 at trial sites B and C. In all sites rotation crop stubble was incorporated. Soil measurements were made in all sites with the aim of detecting changes in structure and fertility which could affect the soil's ability to produce a good crop of cotton, and included pH, electrical conductivity, nitrate-nitrogen, exchangeable cations, dispersion, bulk density, strength and organic matter. Changes in soil moisture; crop growth, development and yield of all rotation crops and cotton; and economic returns were also monitored.

Trials B and C have only run for one rotation cycle so the effects are small and difficult to interpret,

although trends are apparent. At site A, however, cotton yields following 8 years of cotton/wheat rotation were clearly better than continuous cotton. The tillage system used on the continuous cotton was also important, with yields following minimum tillage better than those following maximum tillage. Higher cotton yields were associated with less soil compaction in the 0-15 cm zone, and greater water extraction from the subsoil. These results are supported by Trial C at Warren, where the continuous cotton, which had the poorest soil structure, yielded less than any rotation treatment. In Trial B cotton yields following wheat were 11% higher than those following chickpeas. This was largely due to differences in the incidence of verticillium wilt. In contrast to this, at Warren (Trial C), cotton yields after a winter legume (field peas) were equal to those after wheat, although verticillium wilt was not a problem at that site. To summarize, it is clear that rotation crops can benefit a following cotton crop, although which one is 'best' appears to be determined by the existing physical, chemical and biological environmental conditions at any one site.

Management systems for cotton on permanent beds - Maximizing the benefits of rotation crops

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Abstract

The effects of rotation crops and their management on soil properties, and irrigated cotton productivity and profitability were evaluated from 1993 to 1996 in some typical cracking clays (Vertisols) of the Namoi and Macquarie valleys of New South Wales. The project consisted of 3 field experiments: (a) an experiment on tillage systems and rotations (intensive tillage or minimum tillage sown with continuous cotton, and minimum tillage sown with a cotton-wheat sequence which were imposed in 1985, on which three rotations: cowpea-cotton, continuous cotton and fallow-cotton were superimposed in 1993) located at the Australian Cotton Research Institute near Narrabri; (b) a rotation crop management experiment (wheat+140 kg ha^{-1} N-cotton, unfertilized wheat-cotton, and winter grain legume-cotton sequences where the legume grain was either harvested or incorporated) located near Wee Waa; and (c) a rotation crop management experiment [high input (99 kg N and 17 kg P ha^{-1}, irrigated) wheat-cotton, low input (16 kg N and 17 kg P ha^{-1}, rainfed) wheat-cotton, rainfed field pea-cotton, summer fallow-cotton, low input wheat-dolichos-cotton, low input wheat-dolichos +24 kg P & 73 kg K ha^{-1}-cotton, and continuous cotton sequences] located near Warren. (The low input wheat-dolichos/P+K fertilizer-cotton sequence was replaced by a faba bean-cotton sequence in 1995). Soil properties which were monitored to a depth of 0.6 m in every site included organic matter fractions, plastic limit, strength, shrinkage indices derived from shrinkage curves, exchangeable Ca, Mg, K and Na, pH, nitrate-N and electrical conductivity. Profile water content and water extraction to 1.2 m, nutrient uptake, crop vegetative growth, cotton lint yield and fibre quality were also quantified. Economic returns were evaluated by comparing gross margins for rotation crop-cotton sequences.

Increases in sub-surface soil compaction and strength were primarily due to vehicular traffic intensity rather than tillage *per se*. Chiselling appeared to reduce soil compaction and strength. Dispersion was reduced by increasing organic matter content but increased by tillage and increasing exchangeable Na. In comparison with intensive tillage water was extracted from deeper depths more rapidly with minimum tillage, particularly where the latter was combined with a cotton-wheat rotation. Particulate organic matter and nitrate-N were higher, and exchangeable Na lower with minimum tillage. Rotating a nitrogen-fixing leguminous crop with cotton increased soil N status, with winter legumes (faba bean, chickpea, fieldpea) out-performing summer legumes (dolichos, cowpea). In sites where verticillium wilt was prevalent, compared with low-N crop residues, incorporating high-N residues made the following cotton crop more likely to have a higher incidence of verticillium wilt. In comparison with harvesting, incorporating legume grain did not increase soil N. Evaluating N-balance by utilizing N content of rotation crop residues overestimated the N available to the following cotton crop. Incorporating leguminous crop grain slowed emergence and reduced nutrient uptake by the following crop cotton due to allelopathic effects. N applied as fertilizer to cereal rotation crops was immobilized in the short-term, but mineralization during the following cotton cropping season resulted in its mobilization. Nutrient uptake by cotton was improved by practices which improved subsoil properties and hence, increased subsoil root activity such as: (1) sowing a rotation crop with a long crop duration and high frequency of wetting/drying cycles; (2) greater drying of the soil profile; (3) reduced vehicular traffic; (4) applying N fertilizer to a preceding rotation crop. However, incorporating leguminous crop grain reduced nutrient uptake by cotton due to allelopathic effects. Lint yields, in the absence of diseases, were higher when conditions which facilitated root activity and nutrient uptake occurred. Generally, in comparison with continuous cotton, sowing rotation crops resulted in higher cotton lint yields. Among the rotation crops studied in this project only faba bean was able to both increase soil N and reduce sub-surface soil strength within 1 cropping sequence. Between rotations, highest gross margins were observed where wheat-cotton rotations were sown. Overall, however, highest gross margins occurred with continuous cotton.

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1. Introduction

Cracking clay soils are the most common irrigated cotton growing soils in Australia. Typically, they have a self-mulching layer 2 to 5 cm deep, overlying a zone of blocky peds to depths of 30 to 50 cm. They have a clayey soil texture and form soil cracks which close when wetting occurs due to swelling of the soil. In addition, soil pores and stable aggregates attributable to the interacting activities of soil organic matter, exchangeable cations, plant root systems and microbes occur in these soils. With continuous cotton, soil structural degradation, partucularly that due to shearing and compaction during land preparation and harvesting under wet conditions, can occur. Soil structural degradation can be amelinrated by growing a rotation crop to maximize cracking by drying of the soil profile. Little attention has been paid, however, to the effects of the rotation crop and its management on subsequent stability of soil aggregates and pores, soil fertility and biology. Furthermore, many cottongrowers have shown an interest in utilizing rotation crops and their management as a tool in land preparation for cotton. A survey conducted by Mr. Cooper in 1992 (CRDC Project DAN 76C) showed that although wheat was the preferred rotation crop, many cotton growers were interested in (1) legumes and (2) rotation crop management strategies, and their effects on soil properties, cost effectiveness, cotton agronomy, and pest and disease incidence during the following cotton crop. This report summarizes results obtained over the period 1993-1996 from a long-term study of tillage systems and crop rotation which commenced in 1985, and from 2 studies on rotation crop management which commenced in 1993.

2. Aims and Objectives

To determine and demonstrate the effect of rotation crop management on soil properties, cotton productivity, overall farm productivity and profitability in cracking clays used for irrigated cotton production in the Namoi and Macquarie Valleys of New South Wales.

3. Methodology

Field Experiments

The project consisted of 3 field experiments (2 in the Namoi valley, sites a and b; and 1 in the Macquarie valley, site c) which are described below:

(a) Long-term experiment on tillage systems and crop rotations (referred hereafter as site a):

The experiment was located at the Australian Cotton Research Institute near Narrabri, north-western New South Wales, Australia (150^{o}E, 30^{o}S) which has a semi-arid climate. The hottest month is January (mean daily maxima and minima of 34^{o}C and 19^{o}C, respectively), whereas July is the coldest (mean daily maxima and minima of 18^{o}C and 3^{o}C, respectively). Mean annual rainfall is 616 mm. The soil at the experimental site is a deep uniform grey clay (Ug 5.25; fine, thermic, montmorillonitic, Typic Pellustert). Particle size distribution in the 0.00-0.30 m layer is 53% clay, 21% silt and 26% sand, and that in the 0.30-0.60 m layer is 60% clay, 18% silt and 22% sand. Sub-surface compaction is high with bulk density (of soil clods) at a water content of 0.2 kg kg^{-1} in the 0.00-0.15 m layer being 1.1 Mg m^{-3}, and that in the 0.15-0.60 m layer being 1.8 Mg m^{-3}.

The experimental treatments, which had been imposed since 1985, were maximum tillage (disc-ploughing to 0.2 m depth, chisel ploughing to 0.3 m depth followed by ridging every year; deep ripping to 0.4 m depth in 1987 when the soil was dry) sown with continuous cotton; minimum tillage (planting on ridges retained intact from previous years with soil disturbance being limited to deepening of the furrows with disc-hillers) sown with continuous cotton; and minimum tillage sown with a cotton-winter wheat sequence where wheat was sown with no-tillage. Following harvest, the crops were slashed and all residues retained *in situ*. The plots were furrow irrigated. The last wheat crop was sown in the winter of 1991. Cotton was sown in every plot thereafter until 1993 when three rotation treatments (cowpea-cotton, continuous cotton, fallow-cotton) were imposed. The experimental design was a split-plot design with 4 replications where tillage and cropping sequence combinations imposed from 1985 to 1991 were designated as main plots arranged in randomized complete blocks, and rotations imposed in 1993 designated as sub-plots, which were completely randomized within each main plot. Individual sub-plots consisted of 12-20 rows, 175 m long, spaced at 1 m intervals. Cotton was harvested mechanically in late April, whereas cowpea was not harvested and the grain was retained *in situ*. Fertilizer was applied in September as anhydrous ammonia at rates of 140, 120 and 120 kg N ha^{-1} in 1993, 1994 and 1995 respectively. All treatments were sown with cotton in 1994-95 and 1995-96 with minimum tillage.

(b) Namoi Valley rotation crop management experiment (referred hereafter as site b):

The experiment, which commenced in 1993, was located at "Glenarvon", near Wee Waa, approximately 20 km west of the Australian Cotton Research Institute. Climatic conditions are similar to that in (a). The soil at the experimental site is a deep uniform grey-brown clay (Ug 5.15; fine, thermic, montmorillonitic, Entic Pellustert). Particle size distribution in the 0.00-0.30 m layer is 54% clay, 17% silt and 29% sand, and that in the 0.30-0.60 m layer is 55% clay, 18% silt and 27% sand. Sub-surface compaction was moderate in 1993 with bulk density (of soil clods) at a water content of 0.2 kg kg^{-1} in the 0.00-0.15 m layer being 1.0 Mg m^{-3}, and that in the 0.15-0.60 m layer being 1.6 Mg m^{-3}. The experimental treatments were wheat, which was either unfertilized or fertilized with urea at sowing (140 and 120 kg N^{-1} ha in 1993 and 1995, respectively), and a winter grain legume (unfertilized) which was either harvested or the grain retained *in situ* as a source of nutrients for the following cotton crop. Chickpea was sown in 1993 and faba bean in 1995. The rotation crops were sown with minimum tillage immediately after cotton. The site was furrow irrigated. All treatments were sown to cotton in October 1994. The experimental design was a randomized complete block with 4 replications. Individual plots consisted of 24 rows which were 400 m long.

(c) Macquarie Valley rotation crop management experiment (referred hereafter as site c) (Joint trial with CRC for Sustainable Cotton Production):

The experiment, which commenced in 1993, was located at "Auscott", near Warren, central-western New South Wales, Australia (147^{o} 46'E, 31^{o} 47'S) which has a semi-arid climate. The hottest month is January (mean daily maxima and minima of 33^{o}C and 18^{o}C, respectively), whereas July is the coldest (mean daily maxima and minima of 15^{o}C and 3^{o}C, respectively). Mean annual rainfall is 479 mm. The soil at the experimental site is a deep uniform grey clay belonging to the Mulla Grey Phase soil profile class (Ug 5.25; fine, thermic, montmorillonitic, Entic Chromustert). Particle size distribution in the 0.00-0.30 m layer is 49% clay, 14% silt and 37% sand, and that in the 0.30-0.60 m layer is 49% clay, 13% silt and 38% sand. In 1993 soil bulk densities at a soil water content of 0.2 kg kg^{-1} in the 0.00-0.15 m and 0.15-0.60 m layers were 1.0 Mg m^{-3} and 1.4 Mg m^{-3}, respectively. The 7 rotation systems, sown in 1993 immediately after cotton, were low (rainfed, 16 kg N and 17 kg P ha^{-1}) and high (irrigated, 99 kg N and 17 kg P ha^{-1}) management wheat, low management wheat followed by dolichos with and without P and K fertilizer, field peas, long fallow and continuous cotton. In 1995 the low management wheat-fertilized dolichos sequence was replaced by faba bean. All treatments were sown to cotton in 1994-95. Grain produced by the wheat was removed whereas dry matter from wheat, field pea, faba bean and dolichos were incorporated. The experimental design was a randomized complete block with 3 replications. Individual plots consisted of 40 rows which were 700 m long.

Sampling & Measurements

Soil was sampled from the 0.00-0.15 m, 0.15-0.30 m, 0.30-0.45 m and 0.45-0.60 m layers in all sites from 1993 to 1996. Soil was also sampled from site a (June 1994) and site b (November 1993 and 1995) by digging pits with a backhoe to a depth of 1.5 m in every sub-plot. Three soil clods were taken along their natural cleavage planes from the 0.15-0.30 m, 0.30-0.45 m and 0.45-0.60 m layers of each pit (average clod volume at field moisture content was 1.85 x 10^{5} mm^{3}). Bulk soil from these layers was sampled at the same time. In site b, root growth was measured at the same time in the same pits with the trench-profile method.

Air-dried soil was passed through 2 mm-sieve and the following tests carried out: plastic limit, using a drop-cone penetrometer; particulate soil organic matter (particle diameter of 53 µm - 2 mm) with a combination of dispersion (by soaking overnight in a solution of 2:1 10% sodium hexametaphosphate:1M NaOH and gently stirring thereafter with a magnetic stirring rod), flotation and sieving; pH (in 0.01M $CaCl_2$); electrical conductivity (in a 1:5 soil:water suspension); nitrate-N (by automated colorimetry after extraction with 1M KCl); exchangeable Ca, Mg, K and Na (after extraction with alcoholic 1M NH_4Cl at a pH of 8.5); and dispersion (in bore water; EC= 0.06 dS m^{-1}, SAR = 4.2). Soil resilience, a measure of the self-mulching ability of the soil, was determined by puddling and oven-drying at 40 °C for 72 h, air-dried soil which had been previously passed through a sieve with aperture diameters of 2 mm. The size distribution of the aggregates formed was expressed as the geometric mean diameter of the soil aggregates. Total soil organic carbon was determined by the wet oxidation method of Walkley and Black on soil which had been passed through a 0.5 mm-sieve. The results were multiplied by 1.72 to determine total organic matter. Mineral-associated soil organic matter (particle diameter < 53 µm) was calculated as the difference between total soil organic matter and total particulate soil organic matter. Bulk density of drying soil clods was determined after coating the clods with 'saran' resin dissolved in ethyl-methyl ketone. Bulk density in ridges (0.00-0.15 m depth) at sites a (June 1994) and b (November 1993), and in the entire measured profile at sites a (August 1993), b (June 1993 and October 1994) and c (June 1993 and March 1994) was, however, measured on drying soil aggregates (1-10 mm diameter) previously wetted by evaporation in a humidifier with the kerosene saturation method. Vane shear strength, air permeability and pore characteristics of resin-impregnated soil blocks (using image analysis techniques) were determined in Janury 1994 at site a. Soil strength to a depth of 0.45 m was measured at regular intervals with a recording penetrometer. Measurements were made from the top of ridges with three profiles being measured from the the four central rows of each plot. Concurrently soil water content was measured in the same locations. Soil water content in the 0.20-1.20 m depth interval was measured at regular intervals with a neutron moisture meter which had been calibrated *in situ* . Surface soil water content was measured gravimetrically at the same time. Plant samples were taken at regular intervals during the crop growing season to evaluate dry matter production, leaf area index and boll production. Plants sampled in early March 1994, 1995 and 1996 at site a, and in October 1993 and 1995, and March 1995 at site b were used to evaluate nutrient uptake. N in plant tissues was measured with a near-infra red protein analyzer which had been pre-calibrated with the Kjeldahl method for tissue N. Plant uptake of S, Mo, Zn, B, Mn, Cu, Mg, Ca, K and Na were evaluated by determining nutrient concentration in plant dry matter with an inductively coupled plasma-atomic emission spectrometer after microwave digestion with concentrated nitric acid. (Plant nutrient uptake at site c was evaluated by a CRC collaborator and is not presented in this report). After harvest in May, cotton lint fibre characteristics such as micronaire and length were measured with a Spinlab 900 series, and maturity and fineness with a Shirley FMT3. The effects of tillage and cropping sequence combinations sown from 1985-1991 on diversity and seasonal variation in activity of soil and epegeic invertebrates over an irrigated cotton crop growing cycle were evaluated from 1994 to 1996 at site a by taking soil cores and using pitfall traps. Economic returns were evaluated for the on-farm sites (b and c) by comparing gross margins.

4. *Results and Discussion*

(a) Long-term experiment on tillage systems and crop rotations (site a):

Statistical analyses indicated that there were no significant interactions between main plot treatments (tillage & cropping system combinations imposed from 1985-1991) and sub-plot treatments (rotations imposed in 1993). The effects of the main plot and sub-plot treatments are, therefore, discussed separately.

Effects of tillage & cropping sequence combinations sown from 1985-1991

In comparison with maximum tillage, values of nitrate-N and organic matter were higher and pH, exchangeable Na, ESP and dispersion lower with minimum tillage. The differences appear to be due to an interaction between organic matter decomposition, ion-exchange properties of the soil and tillage intensity. Significant dispersion also occurred with tillage at ESP values lower than the 'threshold' valueof 6% cited in the literature for non-saline soils, and is probably due to mechanical stress brought about by the tillage process. Compaction in beds was in the order of minimum tillage/cotton-wheat < minimum tillage/continuous cotton < maximum tillage/continuous cotton, whereas subsoil compaction in maximum tilled plots was lower than that in minimum tilled plots. Soil strength was also significantly lower in the 0.18-0.35 m depth interval with maximum tillage than with minimum tillage. In comparison with 1986-1988, bulk density was greater in 1994, and indicates that overall compaction had increased with time. Furthermore bulk density and results of image analyses, and reference to the literature show that subsoil compaction was high in all plots, presumably due to the cumulative effects of mechanized traffic over the years. The differences in subsoil compaction and strength between tillage systems suggests, therefore, that chiselling has partially ameliorated traffic-induced subsoil compaction.

Water extraction during extended drying cycles was deeper and more extensive with minimum tillage, particularly when combined with cotton-wheat rotation. This may be due to the crops utilizing pores created by the root systems of preceding crops or associated macrofauna as by-pass channels to avoid the restrictions of the soil matrix, and thereby extend its root system into the deep subsoil. The stability of such "by-pass" channels is likely to be greater with minimum tillage due to the greater stability of soil aggregates therein (see previous paragraph) and the absence of the disrupting activity of intensive tillage.

In comparison with maximum tillage, numbers of ants were greater with minimum tillage in both 1994 and 1995 cotton growing seasons. Highest numbers of collembola were observed in 1994 and beetles in 1995 where a cotton-wheat rotation had been sown with minimum tillage.

Nutrient concentrations in plant tissues were not significantly affected by tillage or cropping sequence. Cotton lint yield with maximum tillage/continuous cotton, minimum tillage/continuous cotton and minimum tillage/cotton-wheat was 1.55, 1.64 and 1.80 t ha^{-1} respectively, in 1993; 1.29, 1.50, 1.72 t ha^{-1}, respectively, in 1994; 1.30, 1.35 and 1.50 t ha^{-1}, respectively, in 1995; and 1.02, 1.11 and 1.24 t ha^{-1} respectively, in 1996. Hence, in comparison with maximum tillage/continuous cotton and minimum tillage/continuous cotton, lint yield with minimum tillage/cotton-wheat was greater by an average of 22% and 12%, respectively, during this study. Lint yield reflected to a large degree the differences in soil structure in beds (0.00-0.15 m depth) and water extraction profiles during extended drying cycles when cotton sown in plots of minimum tillage/cotton-wheat suffered least from water stress due to its ability to extract water from deep in the soil profile. Consequently lint yield in this treatment was the highest. Fibre quality responded likewise. In general, minimum tillage/cotton-wheat resulted in lint which was longer and finer but did not differ in strength in comparison with the other treatments. Mean lint value estimates (in \$ ha^{-1}) for maximum tillage /continuous cotton, minimum tillage/continuous cotton and minimum tillage/cotton-wheat were 3817, 4245 and 4649, respectively. Total crop value was, hence, greatest where a cotton-wheat sequence was sown in combination with minimum tillage. In summary, therefore, compared with maximum tillage, cotton lint yield was higher, and fibre quality superior with minimum tillage. Highest lint yield, best fibre quality and highest gross productivity occurred where a cotton-wheat rotation had been sown in the past with minimum tillage.

Effects of rotations imposed in 1993

Compared with fallowing, sowing either cotton or cowpea in 1993 decreased pH and aggregate size formed after puddling and drying, and increased soil organic matter and plastic limit. Cropping also increased exchangeable cations in the surface 0.3 m of the soil. Nitrate-N in the 0.00-0.15 m depth was 23% higher after cowpea than after fallow.

Reduction in of soil compaction and strength were quickest in the short-term (1 year) where continuous cotton was sown, but was also observed after 2 years in plots where cowpea was sown in 1993. Profile water contents measured during the 1993-1994 growing season indicated that cotton dried out the soil to a greater extent than cowpea due to its longer growth duration. Cotton was sown in mid-October and harvested in late April, whereas cowpea was sown in early December and had senesced by late March. The longer growing period of cotton also ensured that it was subjected to more wetting and drying cycles, and hence soil structural improvement than was cowpea. The fallow plot was not irrigated, and therefore, remained dry for much of the growing season. The greater frequency of wetting and drying cycles in cotton and cowpea plots resulted in more structural improvement than with the fallow-cotton sequence. Profile water depletion in 1994-1995 by cotton following either cotton or cowpea was greater than cotton following fallow. Greater water depletion in the cotton-cotton and cowpea-cotton plots may be due to decaying roots of preceding cotton and cowpea maintaining pore continuity, thereby facilitating root activity and water extraction by the succeeding cotton crop; and structural amelioration caused by more frequent wetting/drying cycles and the combination of decaying root tissues and enhanced microbial activity. Differences in soil strength and water depletion by cotton did not occur between treatments in 1995-1996.

In summary, except for pH, soil chemical changes caused by the cropping systems imposed in 1993 were transient, whereas changes in soil physical properties appear to be more stable. Reduction of soil strength appears to commence some time after cowpea residues have decomposed. The mechanism responsible for such changes is unclarified at present but may include an interaction between soil organic matter and structure both at the macroaggregate and microaggregate scales.

In comparison with cowpea-cotton and long-fallow cotton, continuous cotton had the highest nutrient uptake in 1994-1995, and may be due to the better physical and chemical status of the soil in plots sown to cotton in 1993. Nutrient uptake by cotton in 1995-1996 was not significantly affected by the rotation treatments imposed in 1993. Vegetative growth of cotton in 1994-1995 which followed cowpea, measured as dry matter production and leaf area index, was poorer in comparison with cotton which was preceded by either cotton or fallow. This may be due to allelopathy (due to decomposing cowpea seeds) and competition (due to germinating cowpea seeds) in the former treatment. Mean cotton stand density throughout the growing season was 8.5, 6.0 and 8.0 plants m^{-2} where the preceding cropping treatment was cotton, cowpea and fallow, respectively. Reproductive growth measured as green bolls per plant in plots sown to cotton, cowpea or fallowed in 1993 was 12, 17, 14, respectively, at 135 days after sowing. Cotton in plots sown to cowpea in 1993 appears to have compensated to some degree for the lower plant numbers and reduced vegetative growth by increasing reproductive growth. During 1995-1996, however, cotton in plots sown to cowpea in 1993 did not show any growth reduction. In comparison with sowing either cotton or cowpea, cotton lint yield in 1994-1995 and 1995-1996 were significantly greater in plots which were fallowed in 1993. Lint yields in plots which had cotton, cowpea and fallow in 1993 were 1.32, 1.34 and 1.49 t ha^{-1}, respectively, in 1994-1995; and 1.03, 1.13 and 1.20 t ha^{-1}, respectively, in 1995-1996. The lower yield with continuous cotton when compared with fallow-cotton in 1994-1995 and 1995-1996 is puzzling as soil properties were poorer with the latter treatment in 1994-1995 and did not differ significantly in 1995-1996 (see earlier discussion). A previous study at this site had indicated, however, that combining minimum tillage and continuous cotton reduced cotton yields due to soil microbiological factors which reduce boll weight per plant (confirmed in this study), and which, as yet, remain unidentified. Cotton lint fibre quality was not significantly affected by any of the cropping systems. Overall, the benefits of sowing cowpea in terms of improvements in soil properties and crop yields were either small or negligible in comparison with fallowing or sowing cotton.

(b) Namoi Valley rotation crop management experiment (site b):

Compaction, soil strength and nitrate-N were the only soil properties affected by the experimental treatments. In comparison with fertilized wheat, bulk density in beds was lower with either chickpea or unfertilized wheat. These differences were transient and were absent at the time of sowing cotton in October 1994. Soil strength was higher with chickpea in comparison with either of the wheat treatments, with highest values occurring where chickpea was harvested, and may be due to the soil profiles being drier under wheat at harvest than with chickpea. The additional traffic involved in harvesting chickpea, compared to retaining the grain *in-situ* , appears to have increased soil strength. These differences were maintained throughout the following cotton season (1994-1995), but were not reflected in cotton yields. Soil strength measured in August and December 1995 indicated, however, that sowing faba bean resulted in significantly lower values to wheat. Therefore faba bean may be a more effective rotation crop with respect to structural amelioration than chickpea. Nutrient uptake by the rotation crops was in the order of fertilized wheat > unfertilized wheat > chickpea = faba and reflects their root growth patterns. Soil nitrate-N in October 1994 was greater with chickpea than with wheat. Leaching of nitrate-N into the subsoil was higher in chickpea plots. Fertilizing wheat or retaining chickpea grain *in situ* had no effect on nitrate-N at time of sowing cotton. With respect to wheat this may be due to N immobilization, whereas with chickpea the N in the grain may be lost by volatilization. Nutrient uptake of cotton monitored in March 1995 and soil nitrate-N measured in May 1995 indicated, however, that N immobilized in wheat plots was being released to the soil, presumably by mineralization of organic matter. While this additional N was not reflected in crop yields, it was reflected in cotton vegetative growth and fibre quality. Retaining chickpea grain *in situ* resulted in slower emergence of cotton and reduced nutrient uptake, and higher soil nitrogen levels after cotton harvest. The literature suggests that this may be due to the combined effects of ammonia (which reduces germination) and saponin (which inhibits root activity). These results were reproduced in a laboratory study which used cold-water-extracts of legume and cereal grain. The cold-water extracts of legume grain significantly reduced germination and caused cotton radicles to be stunted and deformed. Pathological examination also indicated that these radicles were infected with higher numbers of parasitic micro-organisms (D. Nehl, Pers. comm.). In 1995 cotton lint yield was greater by 11% where a wheat crop had been sown, and was caused by differences in verticillium wilt incidence. Verticillium wilt incidence was positively correlated to N in rotation crop residues and negatively correlated to amount of rotation crops residues. It was hypothesized that verticillium wilt infestation was controlled by the by-products of crop residue decomposition such as organic acids, and the total time period over which wilt spores were exposed to such by-products. (NB. Chickpea is not an alternative host for verticillium wilt). Laboratory studies confirmed that release of acids occurred over a longer period with wheat residue decomposition than by decomposition of legume residues. A lower pH was, therefore, maintained for longer periods in soils where wheat residues were the main source of organic matter. The infective capability of verticillium spores may be reduced by an extended period of exposure to low pH. Consequently, verticillium wilt infestation rates in wheat-cotton rotations are lower than those in chickpea-cotton rotations. Gross margins calculated for fertilized wheat-cotton, unfertilized wheat-cotton, chickpea (harvested)-cotton and chickpea (grain retained *in situ*)-cotton rotations for the period 1993-1995 were 3649, 3698, 2634 and 2390 $ ha^{-1}, respectively.

(c) Macquarie Valley rotation crop management experiment (site c) (Joint trial with CRC for Sustainable Cotton Production):

Extensive drying of the soil profile facilitates cracking and ameliorates compaction in cracking clays. In this context low management wheat resulted in the driest soil profile in 1993, fallow the wettest, and high management wheat and field pea were intermediate. However, trafficking rather than profile drying was the major determinant of soil strength during the 1994-95 growing season; ie. lowest and highest strength was observed under fallow and continuous cotton plots. With respect to other soil properties, fallow resulted in lowest aggregate stability, particulate organic matter, plastic limit, exchangeable Ca and Mg, whereas highest nitrate-N occurred where field pea was sown. In comparison with leguminous rotation crops and cotton, N immobilization was higher wherever a cereal rotation crop was sown and continued into the cotton phase of the rotation. Continuous cotton extracted least nitrate-N from the soil profile in 1994-1995, presumably due to reduced root activity caused by high soil strength and compaction. Leaching of nitrate-N was high in all plots during 1995, due to the unusually high rainfall in January 1995 (237 mm compared with the long-term average of 51.8 mm). Continuous cotton produced least lint in 1994-1995 with no significant differences between other rotation treatments; ie.1.8, 2.1, 2.2, 2.1, 2.2, 2.0 and 2.0 t ha^{-1} of lint were produced by continuous cotton, long fallow, field pea, low and high management wheat, low management wheat followed by dolichos with and without fertilizer, respectively. During the second rotation phase (in 1995) relative decreases in soil strength were observed with faba bean and wheat.

5. *Summary of Key Results*

Soil physical properties

Increases in sub-surface soil compaction and strength were primarily due to vehicular traffic intensity rather than tillage *per se*. Chiselling can reduce soil compaction and strength.

Soil aggregate stability was improved by increasing organic matter content but decreased by increasing exchangeable Na and tillage.

In comparison with intensive tillage (ie. maximum tillage), water was extracted from deeper depths more rapidly with minimum tillage, particularly where it was combined with a cotton-wheat rotation. This was thought to be due to the occurence of stable macropores with a high degree of pore continuity, through which the roots were able to by-pass zones of high soil compaction.

Crops of long growth-duration (ie. cotton, wheat) were more effective in improving soil structure in sites where structural degradation was high, in comparison with crops of shorter duration (cowpea, chickpea).

Soil chemical properties

Compared with maximum tillage, particulate organic matter and nitrate-N were higher, and exchangeable Na lower with minimum tillage. This is probably due to the lower microbial decomposition rates which occur in minimum tilled soil.

Soil N (N fixed by legumes and applied as fertilizer) losses appeared to occur in all sites by leaching, and by denitrification and volatilization.

Nutrient uptake by cotton

Nutrient uptake by cotton can be improved by practices which increase subsoil root activity such as: (1) sowing a rotation crop with a long crop duration and a high efficiency with respect to water extraction; (2) high frequency of wetting/drying cycles; (3) reducing vehicular traffic; (4) applying N fertilizer to a preceding rotation crop.

Incorporating leguminous crop grain can reduce nutrient uptake by cotton due to allelopathic effects.

Leguminous rotation crops

Rotating a nitrogen-fixing leguminous crop with cotton increases soil N status, with winter legumes (faba bean, chickpea, fieldpea) out-performing summer legumes (dolichos, cowpea). Cotton in sites where high-N crop residues were incorporated were, however, prone to a higher incidence of verticillium wilt in comparison with low-N crop residues. In comparison with harvesting, incorporating legume grain does not result in increases in soil N. This may be due to part of the N being lost by volatilization prior to sowing cotton. Evaluating N-balance by utilizing N content of rotation crop residues can overestimate the N available to the following cotton crop.

Incorporating leguminous crop grain can slow emergence and reduce nutrient uptake by the following cotton crop due to allelopathic effects.

Except for faba bean, leguminous rotation crops, in comparison with cereals, were relatively inefficient in improving soil structural characteristics.

Recycling of N fertilizer applied to cereal rotation crops

Although N applied as fertilizer to cereal rotation crops was immobilized in the short-term, mineralization of organic matter during the following cotton cropping season (ie. February-March) resulted in mobilization of immobilized N in the Namoi valley. In the Macquarie valley immobilization of N appears to continue into the cotton phase of the rotation. These differences may be due climatic and/or mineralogical factors.

Cotton lint yield

Lint yields, in the absence of diseases, were higher when conditions which facilitated root activity and nutrient uptake occurred. Generally, in comparison with continuous cotton, sowing rotation crops resulted in higher cotton lint yields.

Gross margins

Between rotations, highest gross margins were observed where wheat-cotton rotations were sown. Overall, however, highest gross margins occurred with continuous cotton.

6. Conclusions and Recommendations

The results of this project suggest that to maintain and improve soil quality in cotton-based farming systems, a rotation crop should ideally have, at least, the following characteristics:

(1) Ability to provide or recycle nutrients which limit cotton growth (eg. N) during periods of high demand by the following cotton crop. An example of such a rotation crop is one which has a high nitrogen-fixing ability.

(2) Ability to rapidly increase soil porosity, particularly in a degraded soil. Such a rotation crop would be characterized by a long growth duration and a deep and extensive root system highly effective in water extraction (ie. low soil and root resistance to water uptake), thereby facilitating frequent and rapid drying of the soil profile. Such drying patterns would facilitate imposition of frequent wetting and drying cycles, and thereby, maximize soil structural improvement.

(NB. (1) and (2) can also increase subsoil organic matter content (by adding root materials) of high N content. This in turn can improve aggregate stability in the subsoil, thereby increasing pore stability, maintaining pore continuity and reducing low air-porosity due to blocking of pores by dispersed clay and silt particles).

The results of this project suggest that **faba bean (*Vicia faba* L.)** has both the abovementioned characteristics. (NB. The rapid reduction in soil strength observed with faba bean was not observed with any other leguminous crop). Maintenance of good soil structural properties after a rotation crop is, however, dependent on **minimizing traffic and tillage** during the cotton phase. Intensive tillage and/or frequent trafficking will rapidly negate the benefits of sowing rotation crops. In view of the potentially higher verticillium wilt incidence in cotton sown after a leguminous crop, verticillium wilt-resistant cotton varieties should be sown after a faba bean rotation crop in areas of high verticillium wilt incidence. Alternatively, if this is not possible, cereal rotation crops with application of N fertilizer may be a more suitable choice.

Short-term returns are less with rotation cropping than with continuous cotton. Over the long-term, however, this may be reversed, and is suggested by decreasing yields at sites a and c where continuous cottoo was sown. Hence, there is a need to continue these experiments for at least two more cycles.

Suggested future areas of research

1. A strong research focus should be directed towards faba bean rotations in cotton-based farming systems. In the short-term there are three general areas which are worthy of consideration: (a) Genetic and root anatomical factors which cause faba bean to reduce soil strength when sown as a rotation crop; (b) Management practices such as irrigation frequency, quality of irrigation water, plant populations, fertilizer application etc. which may change the efficiency of faba bean as a rotation crop; and (c) Edaphic factors (ie. compaction; salinity; sodicity; texture) which may alter the efficiency of faba bean as a rotation crop.

2. Soil biological factors contributed significantly to reducing cotton yields in sites a and b. This project was able to address this in a very limited way. It is suggested that a concentrated research effort be directed in identifying and managing soil biological factors which reduce cotton yields and their interactions with rotations, crop husbandry and environmental factors. An example is the strong correlation which occurred between mass and nitrogen content of crop residues, and verticillium wilt incidence in the following cotton crop.

3. The role, either positive or negative, of allelepathy in cotton-based rotation systems, and its management needs investigation.

7. *Communication of Results*

Technical journals:

Hulugalle, N.R., and Entwistle, P. (1996). Soil preperties, nutrient uptake and crop growth in an irrigated Vertisol after nine years of minimum tillage. Soil & Tillage Research, submitted for publication.

Hulugalle, N.R., and Entwistle, P. (1996). Effects of sowing cowpea on properties of an irrigated Vertisol and growth and yield of succeeding cotton. Australian Journal of Soil Research, 34: 529-544.

Hulugalle, N.R., Entwistle, P., and Lohry de Bruyn, L.A. (1996). Residual effects of tillage systems and crop rotation on soil properties, soil invertebrate numbers and nutrient uptake in an irrigated Vertisol sown to cotton. In Preparation.

Roesner, E.A., McBratney, A.B., Moran, C.J., and Keppi, A. (1996). Measurement of soil structural attrihutes in the horizontal plane from digital hinary images, part 2. In Preparation.

Rural industry journals:

Hulugalle, N.R., Entwistle, P., Eveleigh, R., and Finlay, L. (1995). "Should you leave legume grain in the field?". Australian Cottongrower, 16(6): 67-70.

Hulugalle, N.R., Entwistle, P., and Cooper, J. (1996). Long-fallow cotton: Effects on soil properties and nutrient uptake in irrigated grey clays. Australian Cottongrower, 17(1): 20-23.

Entwistle, P. (1995). Effects of rotation crops on soil properties in irrigated cotton farming systems. Australian Rural Industry Annual 1995, pp. 41-43.

Cooper, J. (1994). Water extraction by rotation crops. Australian Cottongrower 15(3): 9-10.

Conferences and workshops:

Hulugalle, N.R. (1994). Effect of soil preparation method and cotton-based cropping system on seedbed soil properties in a Vertisol. Proc. 13th Conf. of International Soil Tillage Research Organization. 24-29 July, 1994. Aalborg, Denmark. Eds. H.E. Jensen, P. Schønning, S.A. Mikkelsen, and K.B. Madsen, Vol. II., pp. 789-794. (Royal Veterinary and Agricultural University and Danish Institute of Plant and Soil Science, Copenhagen, Denmark).

Hulugalle, N.R., Entwistle, P., Eveleigh, R., Kahl, J., and Bennett, A. (1994). Effects of rotation crops on properties of irrigated cracking clays. Proc. 7th Australian Cotton Conference, 9-12 August 1994, Broadbeach, Qld., Australia, pp. 355-363. (Australian Cotton Grower's Research Association, Wee Waa, NSW, Australia).

Cooper, J.L. (1994). Water extraction by rotation crops. Proc. 7th Australian Cotton Conference, 9-12 August 1994, Broadbeach, Qld., Australia, pp. 365-370. (Australian Cotton Grower's Research Association, Wee Waa, NSW, Australia).

Cooper, J.L., Hulugalle, N.R. and Entwistle, P. (1996). Comparing rotation crops for sustainable cotton production in the Macquarie Valley of New South Wales. Proc. 8th Australian Agronomy Conference, 30 January-2 February 1996, Toowoomba, Qld., Australia, Ed. M. Ashgar, p. 635. (Australian Society of Agronomy & Australian Institute of Agricultural Sciences, Carlton, Vic., Australia).

Hulugalle, N.R., Entwistle, P., Cooper, J.L., and Allen, S.J. (1996). Effect of long-fallow in cotton-based farming systems on soil properties of an Entic Chromustert. Proc. of Australian and New Zealand National Soils Conference, 1-4 July 1996, Melbourne, Vic., Australia, Vol. 2, pp. 131-132. (Australian Soil Science Society Inc., Melbourne, Vic., Australia).

Lobry de Bruyn, L.A. (1995). A survey of soil invertebrates in wheat-cotton rotations under two levels of tillage management. Proc. CRDC Workshop on Soils and Nutrition, 1-2 December 1994, Narrabri, NSW, Australia, Ed. D. McKenzie, pp. 37-38. (CRDC, Narrabri, Australia).

Lobry de Bruyn, L. A., Sutrisno, and Chilcott, C. (1995). A survey of soil and epegeic invertebrate biodiversity in irrigated cotton under two levels of tillage management and crop rotations. Paper presented at the Australian Entomological Society Conference, 25 - 29 September 1995, Tamworth, NSW, Australia.

Hulugalle, N.R. (1995). Possible adverse effects of heliothis pupae control recommendations on soil structure. Paper presented at CRDC Workshop on Soils and Nutrition, 6-7 December 1995, Narrabri, NSW, Australia.

Hulugalle, N.R., Cooper, J.L., Entwistle, P., Eveleigh, R., Kay, A., and Patrick, I. (1996). Managing wheat rotation crops: Effects of N fertilizer on soil properties, nutrient uptake by cotton and cotton lint yield. Proc. 8th Australian Cotton Conference, 14-16 August 1996, Broadbeach, Qld., Australia, pp. 479-484. (Australian Cotton Grower's Research Association, Wee Waa, NSW, Australia).

Cooper, J.L., Hulugalle, N.R., and Entwistle, P. (1996). Effects of rotation crops on soil properties and cotton yield in the Macquarie valley of NSW. Proc. 8th Australian Cotton Conference, 14-16 August 1996, Broadbeach, Qld., Australia, pp. 485-488. (Australian Cotton Grower's Research Association, Wee Waa, NSW, Australia).

Marshall, J., Thomson, S., Rochester, I., Constable, G., Hickman, M., Hulugalle, N., Charles, G., Allen, S., and Cooper, J. (1996). The benefits of rotation cropping for cotton. Proc. 8th Australian Cotton Conference, 14-16 August 1996, Broadbeach, Qld., Australia, pp. 463-467. (Australian Cotton Grower's Research Association, Wee Waa, NSW, Australia).

Lobry de Bruyn, L.A., Sutrisno, and Trémont, S. (1996) A survey of soil Invertebrate diversity under varying levels of tillage management and rotations in a cotton growing cycle. Proc. 8th Australian Cotton Conference, 14-16 August 1996, Broadbeach, Qld., Australia, pp. 510-505. (Australian Cotton Grower's Research Association, Wee Waa, NSW, Australia).

Hulugalle, N.R., Eotwistle, P., and Lobry de Bruyn, L.A. (1996). Effect of tillage system and cotton-based cropping system on long-term cotton lint yields in an irrigated Vertisol. Paper to be presented at 14th Conference of International Soil Tillage Research Organization, 29 July-2 August 1997, Pulawy, Poland.

Oral presentations:

Hulugalle, N.R. (1995). Current research on rotation systems in cotton-based farming systems of eastern Australia. Seminar organized by Soil Science Society of Sri Lanka at Coconut Research Institute, Lunuwila, Sri Lanka, 20 July 1995.

Hulugalle, N.R. (1995). Recent results from CRDC Project DAN 83C. Presentation to Cotton Industry Consultants Meeting, 29 August 1995, Narrabri.

Hulugalle. N.R. (1994, 1995). Review of results and project activities with collaborating growers, other interested growers, researchers and consultants. (June 1994 and July 1995 in Namoi valley, and August 1994 and September 1995 in Macquarie valley).

Hulugalle, N.R. (1995). Effects of rotation crops on soil properties in CRC/CRDC Farming Systems Trial at Warren. Presentation at Annual Review of CRC for Sustainable Cotton Production, 7 June 1995.

Cooper, J. (1994, 1995). Presentations on CRC/CRDC Farming Systems Trial (Field 13, "Auscott-Warren") during Macquarie valley cotton field days in March 1994 and 1995.

Other:

Short summaries of the CRC/CRDC Farming Systems trial (Field 13, "Auscott-Warren") were included in the Macquarie valley field day handbooks for 1994 and 1995.

Reports on the field trials were included in the Macquarie valley cotton trial reports for 1993-1994, 1994-1995 and 1995-1996 (compiled by J. Holden and A. Kay), and in the Namoi valley cotton trial report for 1994-1995 and 1995-1996 (compiled by R. Eveleigh and M. Hickman).

8. Links to Other Projects

1. The development of SOLICON for soil structure assessment for the agronomist or consultant (CRDC project US 10C) (Assoc. Professor A. Koppi).
2. The development of SOLICON for soil structure assessment for the agronomist or consultant - postgraduate scholarship (CRDC project US 14C) (E. Roesner).
3. Cotton extension agronomist (CRDC Project DAN 77C) (J. Holden) .
4. Operational costs for cotton experiments (CRDC Project DAN 73C) (field operational costs for on-station experiment at ACRI, site a).
5. Travel - N.R. Hulugalle to attend and present paper at 13th Conference of International Soil Tillage Research Organization (CRDC Project DAN 88C) (Data obtained from project DAN 83C was presented at the conference).
6. Systems Experiments - 3 sites (CRC project NSWASYS) (Partial funding, $9000/3years, for field operational costs at Warren, site c).

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