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Part 1 - Summary Details

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Managing carbon in cotton-based farming systems

July 2011 to June 2014

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Table of Contents

1 Project objectives and achievements

Objective	**Status**
Evaluate selected irrigated cropping systems and management practices in terms of carbon sequestration, water storage and WUE, soil quality and profitability.	Achieved. See sections 6.1, 6.2, 6.3, 6.4, 6.5, and 6.6.
Determine relationship between management practices and s carbon sequestration, N accumulation, water storage and WUE	Achieved for irrigated sites in NSW and dryland site in Warra. See sections 6.1.5 and 6.6.5.
Evaluate efficacy of sowing corn in rotation with cotton on soil organic carbon sequestration in the tillage/rotation long-term experiment (LTE) at ACRI	Achieved. See section 6.1.2.
Evaluate efficacy of sowing corn in rotation with cotton on soil organic carbon storage in on-farm sites	Achieved. See sections 6.1.2.
Research outcomes are communicated to the soil health/ nutrition group led by Duncan Weir of the cotton network and the sales network of Du Pont Pioneer (Australia) for extension throughout the industry	Information provided to individual extension staff via copies of publications, conference papers and reports and at industry conferences. Regular discussions held with Duncan Weir, co-ordinator of the CottonInfo team's soil health/nutrition group. Feedback provided to James Holden, Marketing Manager of Du Pont Pioneer (Australia) on performance of cotton-corn rotations. See section 14 for list of outputs.

2 Executive Summary

The aims of the project were to determine the effect of selected management practices on carbon sequestration, soil quality, water conservation, yield and profitability in irrigated Vertosols using a combination of field and laboratory experiments, and desktop studies. Management practices were tillage systems, rotation crops, and stubble management. Measurements included environmental variables such as soil quality, carbon storage and sequestration, greenhouse gas emissions and soil water storage, and agronomic variables such as above- and below-ground crop growth and cotton lint yield. Economic returns in irrigated sites at ACRI were evaluated by comparing seasonal and cumulative gross margins. Partial life cycle analyses of greenhouse gas emissions were made using a desktop approach and SIMAPRO software.

In general, SOC (soil organic carbon) stocks in the 0-60 cm depth ranged between 50 and 70 t/ha. Legumes, although contributing large amounts of carbon to the soil were unable to retain it because their low C/N ratio facilitated rapid microbial decomposition. Carbon inputs of C4 crops such as sorghum and corn were much larger than those of C3 crops such as wheat. A major proportion of that carbon came from their root systems. Long-term SOC sequestration rates were generally negative or neutral. Re-analysis of the results, including two previously unanalysed dryland sites (Warra, Emerald) indicated that in most sites there was an initial rapid decrease in SOC sequestration followed by a stabilisation or an increase (i.e. a reduction of the slope or a positive slope). In most, this change was associated with implementation of soil conservation measures (e.g. replacement of conventional management practices with soil conserving practices such as no-tillage, or replacing saline irrigation water with good quality water). Estimates of carbon inputs, based on above-ground and root dry matter, together with measured sequestration rates indicated that large losses of carbon were occurring, probably due to a combination of accelerated erosion, runoff and microbial decomposition. Factors that influenced SOC storage varied widely between sites but included dry matter inputs, average maximum temperature, soil aeration, water and N fertiliser inputs. Except for temperature, the other variables can be manipulated by cotton growers. Average maximum temperature and soil organic carbon in the 0-60 cm depth had a curvilinear relationship. The temperature optima were highest in the central highlands of Queensland (30.1ºC), lower in the Namoi valley (27-28 ^{o}C), and lowest in the Macquarie valley of NSW (25.5 ^{o}C). Farming practises that could reduce emissions include eliminating inversion tillage, minimising use of groundwater, sowing winter crops in rotation with cotton, and reducing/optimising mineral N fertiliser rates. Substituting a legume an thus, fixed N for mineral N fertiliser although reducing nitrous oxide emissions at time of fertiliser application also required additional inputs in terms of farm operations and irrigation, thus negating the reductions achieved by lowering N fertiliser rates.

Cotton yields and gross margin/ML were generally higher when wheat was included in the rotation with highest values occurring on permanent beds. Including vetch in the rotation did not result in sufficient improvements in cotton yield to compensate for the increase in production costs. In years of plentiful water (or when crop area is the limiting factor) reducing water application rates on a continuous cotton crop was a false economy.

Cotton lint yields, in general, were positively related to water and N inputs, soil aeration in some sites and average annual daily maximum temperature in cooler or poorly-drained sites but were lowered by higher average annual daily minimum temperature. In a sodic soil, a high frequency of the tillage practices intended to aerate the soil may have caused yield decreases, presumably due to exposure of more sodic soils. As with SOC, the factors that influenced cotton lint yields varied across sites. Variable such as frequency of minimum tillage, N rates, water and average maximum and minimum temperatures played significant roles in determining NUE (nitrogen use efficiency) of cotton but varied across sites. No one variable could strongly account for the variations in NUE across all sites. Variable such as depth and frequency of tillage, water inputs, N and SOC played

significant roles in determining WUE (water use efficiency) of cotton. The relative importance of individual variables differed among sites for yield, WUE and NUE.

Between 20011 and 2014, two PhD students, two honours students and three work-experience students were hosted by the project. Project outputs were: 12 journal articles (9 published, 2 under revision, 1 under review), 24 conference and workshop papers, and 8 extension articles (printed and web). A total of 27 public presentations were given by project staff and collaborators.

Key outcomes included:

- Identifying soil and crop management practices, and climatic variables that had direct impacts on soil carbon stocks, yield, water and nitrogen use efficiency in irrigated cotton soils.
- Identifying practices that could reduce carbon footprint of cotton farming systems with life cycle analysis.
- Improvement and refinement of a whole-farm model of profitability for cotton farming systems that can be used as an analytical research tool.

3 Introduction

A major proportion (~75%) of Australian cotton is grown on Vertosols (Vertisols, Usterts), of which almost 80% is irrigated. 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. These soils have high clay contents (40-80 g/100g) and strong shrink-swell capacities such that they form deep soil cracks which close when wetting occurs due to swelling of the soil, but are frequently sodic at depth and prone to deterioration in soil physical quality if incorrectly managed. 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.

Resiliency and sustainability in cotton farming systems are dependent upon a number of interacting factors which include climate, soil quality, plant nutrition, farm management, weed and disease incidence, and economic factors. Frequently, when external constraints such as drought and economic factors impose on farming systems, growers who manage their soils to optimise quality are able to respond more rapidly, thereby sustaining profits. Indices of soil quality include soil porosity, organic carbon and available nutrients.

Management systems whereby soil quality can be modified and managed include tillage and stubble management systems, and crop rotations. Wheat rotation crops sown after cotton can improve soil quality indicators such as subsoil structure, salinity and sodicity, while legumes such as vetch and faba bean can increase available nitrogen by fixing atmospheric nitrogen, and by reducing leaching losses. Furthermore stubble management systems which avoid burning such as *in situ* stubble retention in combination with suitable soil amendments can also improve soil quality. As comparative studies on these systems (wheat and vetch rotations, standing stubble) had not been conducted, measurements commenced in 2002 in several on-station experiments at ACRI and in 2005 in several on-farm trials in Moree, Brigalow and Narrabri. These observations were continued during this phase of this project focussing on water conservation, carbon sequestration, economic profitability and drainage. Management practices (e.g. fertiliser rates, irrigation, rotation sequences, stubble management, depth of tillage etc.) and climatic factors (e.g. rainfall, temperature etc.) that influence C sequestration, N and Water use efficiency in either a positive or negative way were also assessed.

This report focuses on results obtained over the period 2011-14 from eight experiments (six irrigated, two dryland), and a survey of soil properties on cotton farms in New South Wales and Queensland on rotation crop management. Where long-term trends are discussed, data collected since 1993 were also included. In addition, management practices from several past long-term experiments were evaluated as potential surrogate indices for soil carbon sequestration, water and N use efficiency using a multiple linear regression approach.

4 Aims and Objectives

The general aims of the project were to determine the effect of selected crop and soil management practices on carbon sequestration, soil quality, soil water storage, crop growth, yield and profitability.

The specific objectives were to:

a) Determine the effect of selected crop and soil management practices (rotation crops such as corn, vetch and wheat; *in situ* stubble retention; treated sewage effluent as a source of irrigation water) on carbon sequestration, soil quality, soil water storage, greenhouse gas emissions, crop growth, yield and profitability.

b) Investigate whether system characteristics such as water use efficiency and carbon sequestration could be related to qualitative indicators, which could be measured by cotton growers and consultants, such as rotation frequency and tillage intensity. We hypothesized that these qualitative indicators could be used as surrogate indices of soil carbon sequestration, N and WUE.

c) Communicate research outcomes to the CottonInfo team for extension throughout the industry.

5 Methodology

The methodology consisted of several field experiments located in the Namoi (Narrabri), Gwydir (Ashley), Macquarie (Narromine) and Lachlan (Hillston) valleys (section 5.1), laboratory experiments and linear regression model development using results from the experiments described below and from several long-term experiments conducted between 1993 and 2005[1] that were located in the Namoi and Macquarie valleys of NSW.

5.1 Field Experiments

5.1.1 Effects of including corn in cotton farming systems on soil quality and water storage, carbon sequestration, gas emissions, crop growth and profitability

Soil quality, carbon sequestration in soil, drainage, water storage, evaporation, greenhouse gas emissions and cotton and rotation crop growth were monitored in two on-going on-station experiments on rotation crop management located at ACRI (long-term rotation/tillage system experiment established in 1985 and a cotton/wheat/vetch rotation experiment established in 2002); and two on-farm experiments ("Federation Farm", near Narrabri, and "New Haven", near Narromine). Measurements on the on-farm sites were limited to soil quality and carbon sequestration, with additional measured of greenhouse gas emissions being conducted on the site at "Federation Farm". The details of the individual experiments are as follows:

5.1.1.1 Tillage/rotation experiment in Field C1 at ACRI, near Narrabri

The historical treatments were continuous cotton sown after either conventional or on "permanent beds" with most tillage operations being restricted to the bed after cotton picking), and cotton-wheat rotation sown after minimum tillage into standing wheat stubble[2]. The trial was initially established in 1985 with the wheat stubble being incorporated before sowing cotton. Since 2000 the wheat stubble was retained as standing stubble and Round-up Ready cotton (SICALA V2-RR) sown until the 2005-06 season, and "Bollgard-Roundup Ready Flex" varieties thereafter (43BRF during the 2006-07 season and its successors 60BRF during the 2007-08 and 2008-09 seasons, and 71BRF during the 2009-10 and 2010-11 seasons). The experiment was re-designed in 2011 such that all plots were split by either sowing a corn crop during the summer following cotton (with respect to the cotton-wheat, this involved sowing corn immediately after wheat but before the next cotton crop) or retaining the historical cropping system as a control. The experimental design was a split plot design where tillage/rotation system was designated as the main plot treatments and +/- corn as sub-plot treatment, replicated four times in plots 190 m long and 36 rows wide. Cotton and corn crops received 180 kg N/ha as urea after sowing. An additional 60 kg N/ha of urea was applied to cotton and corn crops in January if required. Urea was applied to wheat before sowing at a rate of 20 kg N/ha, and 60 kg N/ha subsequently during later July or early August. Cotton and rotation crops were irrigated at an average rate of 1 ML/ha subject to water availability, rainfall

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[1] Hulugalle, N.R., and Cooper, J.L. (1996). "Final report to Cotton Research and Development Corporation on CRDC Project no. DAN 83C (Management Systems for Cotton on Permanent Beds - Maximizing the benefits of Rotation Crops)", 10 pp.
Hulugalle, N.R., Cooper, J.L., and Scott, F. (1999). "Final report to Cotton Research and Development Corporation on CRDC Project no. DAN 108C (Long-term effects of cotton rotations on the sustainability of cotton soils)", 14 pp.
Hulugalle, N.R., Weaver, T.B., and Scott, F. (2002). "Final report to Cotton Research and Development Corporation on CRDC Project no. CRC 12C (Long-term effects of cotton rotations on the sustainability of cotton soils II)", 44 pp.
Hulugalle, N.R., Weaver, T.B., and Scott, F. (2005). "Final report to Cotton Research and Development Corporation on CRDC Project no. CRC 45C (Maintaining profitability and soil quality in cotton farming systems)", 70 pp.
Hulugalle, N.R., Weaver, T.B., and Scott, F. (2008). "Final Report to Cotton Catchment Communities Co-operative Research Centre on CRC Project 1.04.13 (Maintaining profitability and soil quality in cotton farming systems II)", 70 pp.

[2] The terms "standing stubble" and "*in situ* mulch" are used synonymously in this report.

and soil water content. Corn stalks were managed by adjusting the header height, slashing and root cutting such that only shredded residues were left on the surface after harvest. These residues decomposed by the time of cotton sowing, and thus we were able to maintain a permanent bed system after corn. A description of the practice is given in Appendix 1. Soil quality was evaluated in samples taken during September 2011 and 2013. Six 5-cm diameter soil cores were extracted from each plot with a tractor-mounted soil corer from the 0-10 cm, 10-30 cm, 30-60 cm and 60-120 cm depths. Soil water content in the 20 to 120 cm depth was measured with a neutron moisture meter, and that in the surface by gravimetric sampling. Agronomic measurements included cotton and corn plant mapping, root growth of cotton and corn (2013-14 season) in the surface 10 cm with the core-break method and that in the 10-100 cm depth with an I-CAP image capture system and minirhizotrons, lint yield and fibre quality of cotton, wheat grain yield and quality, and dry matter yield. Static chambers were used to sample greenhouse gas emissions after operations such as tillage, slashing, stubble incorporation, irrigation and fertiliser application.

5.1.1.2 Soil carbon and quality after cotton and corn in on-farm locations

Paired or split fields that had either corn or cotton sown during the previous summer were selected from the Namoi valley, (2011-12), Macquarie valley and the Murrumbidgee Irrigation Area (MIA) (2012-13) and the Border Rivers and Darling Downs (2013-14). Parallel transects were sampled with a spade from depths of 0-10 cm and 10-30 cm for both undisturbed clods and disturbed samples for soil chemical analyses (pH, cations, SOC, $EC_{1:5}$) and determination of particle size distribution.

5.1.2 Managing rotation crop stubble in irrigated cotton systems

5.1.2.1 Cotton-wheat and cotton-vetch cropping systems experiment in Field D1 at ACRI, near Narrabri

The experiment commenced in 2002, and crop rotations and their chronosequences from 2005 to 2008 are summarised in Table 1). The experiment is expected to run for a period of 12 years (until 2014). The rotations studied were: cotton-vetch-cotton (Rotation 1), cotton-winter fallow-cotton (Rotation 2), cotton-wheat-summer and winter fallow-cotton, wheat stubble incorporated (Rotation 3), and cotton-wheat-summer fallow-vetch-cotton, wheat stubble retained as standing stubble (Rotation 4). Vetch in the cotton-vetch sequence was sown immediately after cotton picking and bed renovation in May and slashed/sprayed out in mid to late September whereas that in the cotton-wheat-vetch sequences was sown after suitable rainfall events during late February and slashed/sprayed out in July or August. This practice differs from management earlier in the experiment, when vetch was killed in September. The objective of early vetch termination was to maximise the fallow period between vetch and sowing cotton, thus conserving spring rains for use by the subsequent cotton crop. The vetch stubble was retained as surface mulch into which the following cotton crop was sown.

Land preparation was with minimum tillage (“permanent beds”) with tillage operations (disc-hilling, commonly known as “go-devilling”) being restricted to the bed after cotton picking. When cotton was sown, a “Roundup Ready” cotton variety (SICALA V2-RR) was used until the 2005-06 season, and “Bollgard-Roundup Ready Flex” varieties thereafter (43BRF during the 2006-07 season and its successors 60BRF during the 2007-08 and 2008-09 seasons, and 71BRF thereafter). Vetch growth was poor in Rotation 1 during the 2009 to 2012 period due primarily to a low competitive ability in relation to winter weeds such as milk thistle and dead nettle. As both of these were broadleaved weeds herbicide control options were limited. Vetch in Rotation 1 was, therefore, replaced with oats to facilitate weed control. The oats was not permitted to mature but was sprayed out in September and cotton sown directly in to the oat stubble in October.

The experiment was laid out in 3 RCB, with individual plots being 20 1-m rows wide and 165-m long. Within the more complex rotations, both rotation and cotton phases were sown in the same year to allow evaluation of climatic variability. Cotton in Rotations 1, 2 and 3 which received 160-

180 kg N/ha as urea after sowing cotton. This rate of N was applied to Rotation 1 (unlike in previous seasons) because of poor vetch growth and low N fixation. Application rates of N in rotation 4 were dependant on N fixation by the vetch and estimated losses. Between 2011 and 2014, they were 100 (2011-12), 160 (2012-13) and 120 (2013-14) kg N/ha. In addition, 60 kg N/ha of urea was applied to cotton crops in January 2014. Urea was applied to wheat before sowing at a rate of 20 kg N/ha, and 60-80 kg N/ha subsequently during late July or early August. Cotton and rotation crops were irrigated at an average rate of 1 ML/ha subject to water availability, rainfall and soil water content.

Soil quality was evaluated in samples taken during late September or early October of each year. Soil sampled during September 20111, 20112 and 2013 was analysed for pH, $EC_{1:5}$, SOC and exchangeable cations. Four 5-cm diameter soil cores were extracted from each plot with a tractor-mounted soil corer from the 0-10 cm, 10-30 cm, 30-60 cm and 60-120 cm depths. Soil water content in the 20 to 120 cm depth was measured with a neutron moisture meter, and that in the surface by gravimetric sampling. Agronomic measurements included plant mapping, lint and DM yield and fibre quality of cotton, wheat grain and DM yield, and vetch DM yield, C and N concentrations. Static chambers were used to sample greenhouse gas emissions after operations such as tillage, slashing, stubble incorporation, irrigation and fertiliser application.

A PhD project (Dalila Rendon) that was partly conducted on this site evaluated wolf spider populations using pitfall traps. The “by-catch” (other soil fauna in the traps) was not discarded but was also evaluated by Dr. Vili Heimoana. These fauna and their diversity can be used as bioindicators of soil health. Briefly, the objective of this study was to identify the soil fauna present and their abundance under two cropping systems (cotton-winter fallow-cotton and cotton-wheat-summer fallow-vetch-cotton; wheat stubble retained as standing stubble). Insects were collected in pitfall traps at on 8 occasions between 7th October 2011 and 22nd April 2012. Pitfall traps were set in 3 clusters of 20 for each treatment.

Table 1. Crop rotations and chronosequences in cotton/vetch/wheat experiment in Field D1, ACRI, 2008-011. (The letters a and b denote different phases of the same rotation. Vetch_{GM} = green-manured /stubble mulched vetch)

Rotation	**2011 winter**	**2011-12 summer**	**2012 winter**	**2012-13 summer**	**2013 winter**	**2013-14 summer**	**2014 winter**
1	Vetch_{GM}	Cotton	Vetch_{GM}	Cotton	Oats	Cotton	Oats
2	Fallow	Cotton	Fallow	Cotton	Fallow	Cotton	Fallow
3a	Wheat	Wheat stubble incorporated/ Fallow		Cotton	Wheat	Wheat stubble incorporated/ Fallow	
3b	Wheat stubble incorporated/ Fallow	Cotton	Wheat	Wheat stubble incorporated/ Fallow		Cotton	Wheat
4a	Wheat	Standing wheat stubble/ Fallow/ Vetch_{GM}		Cotton	Wheat	Standing wheat stubble/ Fallow/ Vetch_{GM}	
4b	Vetch_{GM}	Cotton	Wheat	Standing wheat stubble/ Fallow/ Vetch_{GM}		Cotton	Wheat

5.1.2.2 Gypsum x standing wheat stubble experiment at “Federation Farm”, near Narrabri

Treatments were cotton sown into wheat stubble incorporated with an Aer-way cultivator to a depth of ~15 cm which had either 2.5 t/ha gypsum applied in 2000 or standing wheat stubble with no gypsum applied. The plots were 400 m long x 12 rows wide, and were arranged in a 3 RCB design. The experiment was irrigated with treated sewage effluent which is high in exchangeable Na and K, soluble Cl and has a moderately high EC_w. Statistical precision was improved by establishing 5 sampling plots within each individual treatment plot. Soil was sampled prior to sowing cotton and after the wheat-fallow sequence. Results presented in this report relate to samples taken from 2011 to 2013. At each time of sampling, 5-cm diameter soil cores were extracted from each plot with a tractor-mounted soil corer from the 0-10 cm, 10-30 cm, 30-60 cm, 60-120 cm and 120-180 cm depths. The previously-described static chambers were used to sample greenhouse gas emissions after operations such as tillage/stubble incorporation and irrigation during the cotton-growing season.

5.1.2.3 Comparison of cotton-corn (stubble burnt/incorporated) with cotton-wheat (standing wheat stubble/no-tillage, "New Haven", near Narromine

A split-field trial under sprinkler irrigation had been established by the collaborating grower since 2006. Soil (clods and disturbed bulk soil) were sampled using a paired sites design (10 pairs) from the 0-10 cm and 10-30 cm depths during 2011, 2012 and 2013. The chronosequence of the crops sown are shown in Table 2. All crops were no tilled. Plant dry matter was sampled at crop maturity, and grain/lint yields hand-picked at harvest.

Table 2. Chronology of cropping systems, "New Haven", Narromine

Crop system	**2008 winter**	**summer**	**2009 winter**	**summer**	**2010 winter**	**summer**	**2011 winter**	**summer**	**2012 winter**	**summer**	**2013 winter**	**summer**
1	Wheat	Corn	fallow	Cotton	Wheat	Soybean	Fallow	Cotton	Wheat	Wheat stub	Fallow	Cotton
2	Wheat	Soybean	fallow	Cotton	Wheat	Soybean	Fallow	Cotton	Fallow	Cotton	Fallow	Fallow

5.1.3 Sowing two cereal rotation crops (winter cereal fb. summer cereal) after cotton

5.1.3.1. Comparing a cotton-wheat-sorghum sequence with a cotton-wheat sequence on soil carbon

An experiment was established at "Merrowie" near Hillston during October 2008 using 3RCB design, comparing two cropping sequences, *viz*. cotton-wheat-sorghum vs. cotton-wheat on soil carbon stocks. Individual plots were 530 m long and 48 1-m rows wide. The experiment was planned to run for 6 years. For various reasons the collaborator was unable to sow the summer sorghum crop during any of the cropping cycles, and the experiment was terminated in 2012. Soil was sampled from the 0-10 cm and 10-30 cm depths during 2011 and 2012. Plant dry matter was sampled at crop maturity, and grain/lint yields hand-picked at harvest. Concurrently unreplicated observation plots of both cotton and rotation phases of a cotton-wheat-sorghum sequence were established in Field D1, adjacent to the experiment described in section 5.1.2.1, and soil sampled from the 0-10 cm and 10-30 cm depths during September 2011, 2012 and 2013. Plant dry matter was sampled at crop maturity.

5.1.4 Ancillary experiments

5.1.4.1 Carbon contribution by sorghum roots

The contribution of carbon by sorghum roots grown under conventional tillage and no-tillage (sown into standing wheat stubble) was measured during the summer of 2011-12 and 2012-13 in adjacent plots in Field C1, adjacent to the experiment described in section 5.1.1.1. The sorghum was sown during December and furrow irrigated with 100 mm of water when in-crop rainfall was insufficient to meet evaporative demand. The rows (beds) were spaced at 1-m intervals with vehicular traffic being restricted to the furrows. Measurements were made of root growth in the surface 10 cm with the core-break method and that in the 10-100 cm depth with an I-CAP image capture system and a minirhizotron, and C and N concentrations in roots. DM and grain was measured at crop maturity. Root images were analysed with RooTracker 2.03.

5.2 Measurements and data analyses

5.2.1 Soil quality (physical and chemical properties)

Soil was sampled from the experimental sites at ACRI (0-120 cm) and "Federation Farm" (0-180 cm) before sowing cotton (usually during September and October) with a tractor-mounted 50-mm diameter soil corer. Additional samples were also obtained at the same time in the 0-10 cm depth with a narrow-bladed soil sampling spade. At all other on-farm sites, soil was sampled before sowing cotton with a narrow-bladed soil sampling spade to a depth of 30 cm. The soil was transported back to the laboratory and 4 soil clods extracted from each depth. These were used for bulk density determination. After sir-drying the soil was separated onto 3 fractions by sieving, *viz*. 0-10 mm, < 2 mm and < 0.5 mm, and analysed as described below.

Air-dried soil was passed through 2 mm-sieve and the following tests carried out: pH (in 0.01M $CaCl_2$); electrical conductivity, $EC_{1:5}$ (in a 1:5 soil:water suspension); nitrate-N[1] (with with the Kjeldahl method after extraction with 0.02M K_2SO_4); and exchangeable Ca, Mg, K and Na (after extraction with alcoholic 1M NH_4Cl at a pH of 8.5; commonly described as the "Tucker" method). These data were used to derive several sodicity indices: exchangeable sodium percentage, ESP [= (exchangeable Na/Σexchangeable cations) x100], electrochemical sodicity index, ESI (= $EC_{1:5}$/ESP) and $EC_{1:5}$/ESC ratio (ESC, exchangeable sodium content). Total soil organic carbon (SOC) was determined by the wet oxidation method of Walkley and Black on soil which had been passed through a 0.5 mm-sieve. All chemical analyses are those described in the "Australian Laboratory Handbook of Soil and Water Methods"[2]. The SOC was expressed in t/ha, by multiplying their concentration in each depth interval by the bulk density and the depth increment, followed by summing up all the depth intervals.

Surface bulk density was measured on both soil clods after coating with paraffin wax[3] and on air-dried aggregates (1-10 mm diameter) with the kerosene saturation method[4], and the bulk density expressed as a weighted mean (2:1 aggregates: clods). Bulk density in other depths was determined on soil clods after oven-drying at 110 ^{o}C.

The effect of soil P availability under vetch was investigated by Dr. Chris Guppy, one of the project collaborators. Archived samples from the long-term experiment in Field D1 (experiment 5.1.2.1) were analysed for labile P. The results are reported in Appendix 2 of this report.

Historical soil, agronomic and operations data from the experiments in Fields C1 and D1(experiments 5.1.1.1 and 5.1.2.1) were provided to Dr. Michael Braunack of CSIRO for a project that was performing a meta-analysis and developing a model of management, climate and other variables on soil quality and cotton yields across a large number of sites in the cotton industry. A brief report, authored by Dr. Braunack, for the ACRI sites is given in Appendix 3.

5.2.2 Field measurements

Surface soil water content was determined gravimetrically whereas that in depths > 20 cm was measured with neutron moisture meter (CPN-503 DR Hydroprobe®) that had been calibrated *in situ*[5].

Root growth in the surface 10 cm was measured with the core-break method[1]. The live roots in a sub-sample of the cores were separated from the dead material after washing. Washing root

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[1] Nitrate-N was measured only in ACRI's cotton-wheat-vetch experiment (see section 5.1.2.1).

[2] Rayment, G.E., and Higginson, F.R. 1992. *Australian Laboratory Handbook of Soil and Water Methods, 1st edition*. Inkata, Melbourne and Sydney.

[3] McKenzie, N., Coughlan, K., and Cresswell. 2005. *Soil Physical Measurement and Interpretation for Land Evaluation,* 1st edition. CSIRO publishing, Collingwood.

[4] McIntyre, D.S., and Stirk, G.B., 1954. A method for determination of apparent density of soil aggregates. *Aust. J. Agric. Res.* **5**, 291-296.

[5] Greacen, E.L. 1981. S*oil water assessment by the neutron method.* CSIRO publishing, East Melbourne.

samples involved soaking them in warm water containing a solution containing a 2:1 10% sodium hexametaphosphate: 1 M sodium hydroxide for a period of 4-6 hours. Once dispersed, the suspension was washed through a 0.2 mm sieve. The remaining silt and sand material were separated from the root and other organic material by flotation and decantation. The remaining organic material (including roots) were then stained with a 0.1% congo red solution for a period 8 hours (depending on age of crop), followed by washing in absolute alcohol (supermarket grade). The congo red stains the live roots in the sample a bright red colour, whereas the dead organic material remain black. The live roots were separated from the dead material using a forceps under a bright light. Root separation was done by spreading the sample in a shallow white, plastic tray. The trays were filled with ~5 mm of water. Once the live roots were separated from the dead material, they were stored in a 25% alcohol solution until the length was measured using a modified Newman's line interception method or scanned and measured with WINRHIZO® software. The root samples were then oven-dried, weighed and nitrogen and carbon concentration measured by combustion with a LECO CHN 2000 analyser. Relationships were derived between root number, root length and root weight, and the root length and weight in each core estimated. Relative root length (root weight/root length) was also calculated. Root growth in the 0.10 to 1.0 m depth was measured at 10 cm depth intervals with a "Bartz" BTC-2 I-CAP image capture system®. The video camera part of the image capture system was inserted into clear, plastic acrylic minirhizotron tubes (50 mm diameter) installed within each plot, 30^o from the vertical. Measurements of roots were made 4-5 times during the crop growing season, at approximately 3-4 week intervals. Root images were captured in two orientations, left and right side of each tube, at each time of measurement and analysed with RooTracker 2.03® to estimate selected root growth indices. The data for each orientation and over the entire measured profile were summed to assess root growth over a 360^o plane of vision. The indices evaluated were the length and number of live roots at each time of measurement, number and length of roots which died (i.e. disappeared between times of measurement) and net change in root numbers and length. The above, together with the previously-described relative root lengths and root C concentrations were used to calculate several other indices of root growth; viz. (1) Root length per unit area to a depth of 1 m, L_A; (2) Root carbon at end of season, C_{root} = Sum of net changes in root carbon between times of measurement in all depths where, for individual depths and between times of measurement, the net change in root carbon was calculated as: Net change in root length x Relative root length x Root carbon concentration) (3) Root carbon added to the soil during season, C_{lost} = Sum of root carbon added to soil due to root death between times of measurement in all depths where, for individual depths and between times of measurement, root carbon added to soil was calculated as: Length of roots which died x Relative root length x Root carbon concentration; (4) Root carbon which could be *potentially* added to SOC, $C_{total} = C_{root}$ (2) + C_{lost} (3).

Green house gas monitoring was conducted at regular intervals, triggered by key events in the system, such as slashing/incorporation, irrigation and fertiliser application. Emissions were measured in Fields C1, D1 and "Federation Farm" 150mm diameter static chambers, with a 150mm head-space. These were capped for 2 hours prior to atmospheric sampling. A 25mL air sample was taken in an Exetainer vial and analysed by multi-column GHG GC: N_2O, CO_2, CO and CH_4. This methodology is suitable for detecting differences between treatments, but makes emission accounting difficult due to the sporadic nature of the sampling program. Lids were removable to allow semi-permanent installation, and could be fitted with septa for one-off sampling or septa and Tedlar® baffle combination to allow for multiple samplings from a single chamber with Exetainer® sampling tubes and gas-tight syringes. Due to the highly labour-intensive nature of their operation, sampling was limited to emissions associated with events such as tillage, irrigation, laser-levelling and fertiliser application.

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[1] Smit, A.L., Bengough, A.G., van Noordjwijk, M., Pellerin, S., van de Geijin, S.C. (Eds). *Root methods: A Handbook*. Springer-Verlag, Berlin, Heidelberg & New York.

Black root-rot incidence in the rotation experiment in Field D1 was assessed by Dr. K. Kirkby and Mr. P. Lonergan of the Plant Pathology unit at ACRI by sampling two transects in each cotton plot, one at the head ditch end and the other at the tail ditch end. From each plot 160 plants were dug up and the tap root assessed. Severity of the disease was established by rating the percentage length of the tap root with characteristic blackening using a scale of 0-10, where 0 = no blackening, 1 was >0 and ≤10%, 2 was >10% and ≤20%, 3 was >20% and ≤30%, 4 was >30% and ≤40%, 5 was >40% and ≤50%, 6 was >50% and ≤60%, 7 was >60% and ≤70%, 8 was >70% and ≤80%, 9 was >80% and ≤90% and 10 was >90% and ≤100% of the tap root affected.

Agronomic measurements included plant mapping, plant dry weight and crop yields. In all sites multiple locations (3/plot in on-station experiments and 10-15/plot in on-farm sites) of 1 m^2 were sampled. Yield in on-station experiments was assessed by mechanically-picking cotton or harvesting grain from the entire plot. Nitrogen and carbon concentration in vetch dry matter was measured by combustion with a LECO CHN 2000 analyser.

The soil fauna present and their abundance were assessed in two of the cropping systems in the experiment in Field D1 at ACRI; viz. cotton-winter fallow-cotton and cotton-wheat-summer fallow-vetch-cotton; wheat stubble retained as standing stubble. Insects were collected in pitfall traps at on 8 occasions between 7th October 2011 and 22nd April 2012. Pitfall traps were set in 3 clusters of 20 for each treatment. The samples were separated manually according to groups, genera and family.

Cotton fibre quality parameters assessed (by the CSIRO fibre quality laboratory) were fibre length, strength, short fibre index, uniformity, elongation and micronaire. Wheat grain quality parameters were protein concentration, falling numbers and screenings.

5.2.3 Desktop assessment of greenhouse gas emissions associated with farming practices

Greenhouse gas emissions (as carbon dioxide equivalents, CO_2-e) associated with farming operations, herbicide and fuel production and transport were estimated from available sources[1] by relating them to diesel and electricity consumed. Estimates were made for the two long-term experiments at ACRI (sections 5.1.1.1, 5.1.2.1). Nitrous oxide emissions from N fertiliser and legume cover crops were based on the average figure 0f 0.3% of N inputs reported for these sites by Grace (2006)[2].

5.2.4 Life Cycle Analysis of cotton farming systems in the Namoi valley estimated with SIMAPRO (collaborative study with Dr. P. Brock of NSW DPI and Dr. D. Tan and Mr. G. Quigley of the University of Sydney)

A "cradle-to-gate" (farm gate) Life Cycle Analysis was conducted for selected on-farm sites and the long-term experiment in Field C1 using energy costs associated with growing a crop (e.g., fertiliser, crop establishment, and crop maintenance) in dryland (rain-fed) and irrigated scenarios. Data for these analyses were accessed from three co-operating growers in the lower Namoi (one dryland, two irrigated), and a long-term experiment at the Australian Cotton Research Institute (ACRI). The growers were located at 'Breeza Station' (31˚17'46'' S, 150˚27'06'' E, elevation 294 m), 'Rossmar Park' (31˚18'16'' S, 150˚24'30'' E, elevation 293 m), Auscott Narrabri (30˚10'53" S, 149˚40'17'' E, elevation 206 m) and ACRI (30˚12'04'' S, 149˚36'18'' E, elevation

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[1] (i) Chen, G., and Baillie, C. 2007. Development of EnergyCalc – *A tool to assess cotton on-farm energy uses* (NCEA Publication 1002565/1). University of Southern Queensland,Toowoomba, Qld.
(ii) Audsley, E., Stacey, K., Parsons, D.J., and Williams, A.G. 2009. *Estimation of the greenhouse gas emissions from agricultural pesticide manufacture and use*. Cranfield University, Cranfield, UK.
(iii) Scott, F. 2009. Personal Communication.

[2] Grace, P. 2006. *Reducing nitrogen losses from cotton rotation systems*. Final report for project no. GCRC4C, 24 pp. CRDC, Narrabri, NSW.

201 m). Gross margins from the New South Wales Department of Primary Industries (NSW DPI) for irrigated and dryland cotton, and irrigated corn were also used as a ‘district average’ to give a baseline comparison in each crop type. Actual crop history records were obtained by interviewing each farmer face-to-face with a questionnaire and the necessary crop input quantities and information such as crop rotations, machinery use for the crop, products and rates used for the crop in selected fields.

This collated data was analysed using the SimaPro, a software package that can model products and systems from a Life Cycle Assessment (LCA) perspective. SimaPro is a LCA computational tool used to calculate greenhouse gas (GHG) balances and energy efficiency of crop species and it allows analysis of each stage in the production process of a farming system. SimaPro was chosen because of its ability to analyse not only CO2, but other significant GHG such as nitrous oxide (N_2O) and methane. Data was entered and analysed using corresponding values in both SimaPro’s Australasian Life Cycle Inventory (LCI) Database and the Swiss ‘Ecoinvent’ Database. Formulae from the National Inventory Report (NIR) were built into SimaPro and the emission factors were taken from NSW field research data. Approximate fuel use (L/ha) for various implements were estimated from literature and split into pre-farm and on-farm components. The LCI databases were modified by removing CO_2 losses during field application in the manufacturing stage of urea production to avoid double accounting. The information produced was assessed to allow for a number of comparisons in the emission levels of different production systems, crops and practices used in each case study, and was used to identify any emission hotspots in these production systems, resulting in potential opportunities for reducing the carbon footprint of corn farming systems.

5.2.5 Estimating soil organic carbon storage and sequestration

Soil organic carbon (SOC) concentration (%) in each depth interval was converted to carbon content (t/ha) as:

SOC storage = SOC concentration x oven-dried bulk density (Mg/m^3) x depth interval (m).

SOC concentration is usually reported on an oven-dried basis. Soil carbon storage at any one time was determined by summing carbon contents of specified depth intervals in a profile.

SOC sequestration is defined as the rate of change in SOC storage with time, and is usually determined by fitting a linear regression model ($y = mx + c$) between time (in years) and SOC storage measured at intervals of 1-3 years or more (Powlson *et al*., 2011)[1].

5.2.6 Data analyses

In replicated experiments, all data were analysed with analysis of variance appropriate for the specified experimental design. In unreplicated split field experiments, where soil was sampled in paired transects, the results were analysed using univariate analysis of variance with clay content used as a covariate and years as a replicate or as a paired t-test. The paired fields survey of cotton and corn rotations was analysed using univariate analysis of variance with clay content used as a covariate, and each farm as a replicate. The same data set was also analysed with principal component analysis with biplots.

The relationship between management practices such as tillage depth, rotation crop, dry matter inputs, N fertiliser and irrigation amounts, and climatic factors such as temperature, rainfall (in-crop, fallow etc.), on lint yield, soil organic carbon sequestration, N use efficiency (yield/N in fertiliser) and water use efficiency (yield/total water) were evaluated with multiple linear regression analysis using results from past and on-going irrigated experiments on crop rotations and tillage systems conducted between 1993 and 2013 in the Lachlan, Namoi and Macquarie valleys of NSW, and the Darling Downs in Queensland. Analyses were conducted within each

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[1] Powlson, D. S., Whitmore, A. P., Goulding, K. W. T. 2011. Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false. *European J. Soil Sci*. **62**, 42-55.

individual site and among all sites. Details of these sites (when not reported in section 5.1) are summarised in Appendix 4.

The influence of temperature within and between sites was further investigated with non-linear regression analysis using Gaussian models. Daily maximum temperature values for the previously described long-term experimental sites and time periods were obtained from the Patched Point data in the SILO climate database hosted by the Queensland Climate Change Centre of Excellence (http://www.longpaddock.qld.gov.au/silo). Soil organic carbon stocks in the surface 60 cm and average annual maximum temperature for the 12 months prior to sampling were fitted to Gaussian models and standardized residual values determined for all data points using regression analysis and curve-fitting software (SigmaPlot ver. 11.0, Systat Software, Inc., San Jose California USA, www.sigmaplot.com). The models used were either 3-parameter ($y = a*\exp(-0.5*((x-x_0)/b)^\wedge 2)$) or 4-parameter ($y = y_0+a*\exp(-0.5*((x-x_0)/b)^\wedge 2)$) Gaussian curves where y is soil organic carbon stocks (t/ha), x the average annual maximum temperature during the 12 months prior to sampling, and x_0 the optimum average annual maximum temperature (with respect to soil organic carbon stocks). Where data points with standardized residual values > |2| were present, they were excluded and the regression repeated as before. Fit of the data to the models were further tested with analysis of variance, R^2, the Durbin-Watson statistic and the constant variance test (SigmaPlot ver. 11.0, Systat Software, Inc., San Jose California USA, www.sigmaplot.com).

5.2.7 Profitability

Profitability: Financial returns and profitability for each rotation were evaluated for the tillage/rotation (C1) and rotation (D1) experiments at ACRI by comparing cumulative gross margins per hectare and per ML of irrigation water applied. A gross margin is the gross income from an enterprise less the variable costs (costs directly attributed to the enterprise). Fixed costs such as depreciation, permanent labour and overhead costs are not included. Gross margin results were calculated using a cotton price of $450/bale and a seed price of $300/tonne and costing of all operations conducted on each treatment, including fallow management. The wheat price used was ‘Feed’ and ‘ASW’ $195/tonne, ‘AH’ $202/tonne and ‘PH14’ $235/tonne with the current discount system for low protein and bonuses for low screenings included. Where possible, 2011 prices have been used for inputs such as fuel, fertiliser, herbicides (including defoliants) and pesticides. The same output and input prices are used for each season’s results, in order to determine the rotation effects. Alteration of prices from year to year would confuse the rotation effect. Cotton price sensitivity testing was conducted using lint prices ranging from $350 to $550 per bale.

6. Key Results and Discussion

6.1 Cropping systems and soil organic carbon

6.1.1 Soil organic carbon stocks 2011-2013

Soil organic carbon stocks generally ranged between 50 and 70 t/ha in the 0-60 cm depth, although higher values were present in the tillage/rotation experiment at ACRI during 2011 (Table 3). Values in the 0-30 cm depth generally ranged between 30 and 60 t/ha. Carbon in the 0-30 cm depth of a cotton-wheat-sorghum sequence was also less than with cotton-wheat and in spite of the higher amounts of plant material that were retained in the field with the former. These observations are the reverse of those observed during the previous three years.

Significant differences among treatments in the cotton/vetch/wheat rotation experiment at ACRI only occurred during 2012. Differences among treatments in this experiment were inconsistent, and analysis of the long-term (2002-2010) results indicated that significant differences among rotations were negligible, and were related more to climatic factors than management practices[1].

6.1.2 Soil organic carbon storage after sowing corn

Global analysis of samples taken from paired on-farm sites (post-corn vs. post cotton) in the Namoi and Macquarie valleys, MIA, Border Rivers and Darling Downs indicated that more soil carbon was present in the surface 10 cm, but not in the 10-30 cm depth, after corn than after cotton (Table 4). Overall, in the surface 30 cm, soil carbon storage was higher after corn than after cotton (Table 3). The results suggest that once a cotton crop was sown, carbon stocks are likely to decrease. Inclusion of a well-managed corn crop in the rotation may, nonetheless reduce the rate of carbon decline or maintain soil carbon stocks in the surface 30 cm. Mean values of soil properties (including carbon) at the on-farm sites described in section 5.1.1.2 is given in Appendix 4.

Table 3. Effect of cropping system on SOC stocks, 2011-2013. *, ** and *** indicate that treatments differ significantly at $P < 0.05$, $P < 0.01$ and $P < 0.001$, levels, respectively.

Site	**Depth (cm**	**Cropping system**	**Soil organic C storage (t/ha)**		
			2011	**2012**	**2013**
ACRI, Narrabri, NSW (Tillage/rotation experiment)[2]	0-60	Conventional tillage/continuous cotton	81.6	70.3	78.4
		Permanent beds/continuous cotton	85.0	77.2	87.1
		Permanent beds/cotton-wheat (*in situ* mulch)	87.0	77.6	94.5
		P <	ns	0.05	0.05
		SEM	3.17	1.30	3.41
ACRI, Narrabri, NSW (Cotton/vetch/ wheat rotations experiment)	0-60	Continuous cotton	61.1	77.6	77.4
		Cotton-vetch (2002-2012) fb. cotton-oats (from 2013)	62.3	77.0	75.6
		Cotton-wheat (incorporated), cotton phase	62.5	74.1	74.6
		Cotton-wheat (*in situ* mulch)-vetch, cotton phase	67.8	88.4	78.4
		P <	ns	0.05	ns
		SEM	3.36	2.84	2.28
"Federation Farm", Narrabri, NSW	0-60	Permanent beds/cotton-wheat (*in situ mulch*)	66.5	-	60.6
		Permanent beds/cotton-wheat (*incorporated with Aer-way cultivator*)	62.8	-	70.5
		P <	ns	-	ns
		SEM	5.91	-	7.64
"New Haven", Narromine, NSW[3]	0-30	Corn (burnt) fb. cotton-wheat (*in situ* mulch)	45.8	51.8	58.5
		Cotton-wheat (*in situ* mulch)	57.4	57.6	67.8
		t-value (df = 9)	-2.67	-1.11	-2.05
		P <	0.05	ns	ns
Namoi and Macquarie Valleys; MIA; Border Rivers; Darling Downs	0-30	Post-Corn	52.7		
		Post-Cotton	50.3		
		P <	0.001		
		SEM	0.07		
"Merrowie", Hillston NSW[2]	0-30	Treatments not imposed. Only values averaged among all treatment plots are reported	-	35.7	-
			-		-
			-		-
ACRI, Narrabri, NSW (Cotton/wheat/ sorghum rotation experiment)[1]	0-30	Cotton-wheat-sorghum		26.3	
		Cotton-wheat		36.8	
		P <		0.05	
		SEM		0.99	

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[1] Hulugalle, N.R., Weaver, T.B., Finlay, L.A., and Heimoana, V. (2013). Soil organic carbon concentrations and storage in irrigated cotton cropping systems sown on permanent beds in a Vertosol with restricted subsoil drainage. *Crop & Pasture Sci.*, **64**, 799-805.

[2] Does not include treatments that had corn sown in them during 2011 and 2013. See later section for effects of sowing corn

[3] Values adjusted using equivalent soil mass method..

Table 4. Effect of sowing corn on soil carbon concentration in the 0-10 cm and 10-30 cm depths from farms in the Namoi, McIntyre and Macquarie valleys, MIA, Border Rivers and the Darling Downs, 2011-2013

+/- Corn	Depth (cm)	Soil carbon concentration (g/100 g)
Post-Corn	0-10 cm	1.18
Post-Cotton (Control)		1.09
Post-Corn	10-30 cm	0.95
Post-Cotton (Control)		0.94
SEM		0.025*

Table 5. Effect of corn on soil carbon storage (t/ha), Field C1, ACRI, 2012

Historical cropping system	+/- Corn	0-30 cm	0-60 cm	0-120 cm	60-120 cm
Conventional till/continuous cotton	+Corn	37.8	72.7	142.7	70.0
	-Corn (Control)	37.0	68.0	122.9	55.0
Permanent beds/continuous cotton	+Corn	40.7	78.2	146.5	68.2
	-Corn (Control)	41.0	76.2	140.7	64.5
Permanent beds/cotton-wheat	+Corn	41.0	78.5	162.0	83.6
	-Corn (Control)	40.1	76.8	147.8	71.0
SEM					
Historical cropping systems (HCS)		1.28	1.30*	4.23*	3.68*
Corn (C)		1.10	2.52	4.55$^{(-)}$	2.84*
HCS x C		1.90	4.36	7.93	4.91

*, significantly different at 95% level of probability; (-), significantly different at 90% level of probability

In the long-term experiment in Field C1 at ACRI, sowing corn increased carbon during 2012 at depth (60-120 cm), an observation that has not been reported before (Table 5). The increase at depth approximates the carbon in corn roots[2]. Cotton sown after corn had deeper and more extensive root systems than that in control plots. These differences were not observed, however, in the soil sampled from the same plots during 2013 (Table 6). Soil carbon storage had increased by an average of 13% in the surface 60 cm, but decreased by and average of 28% in the 60-120 cm. These changes probably reflect the short-term impact of the shallower depth of the cotton root systems, combined with the decomposition and/or leaching of carbon in the 60-120 cm. In summary, under irrigation it may be that the carbon added to the soil by the corn roots may be highly labile and thus, not persist for more than a single season. Longer-term studies may clarify this issue.

Table 6. Effect of corn on soil carbon storage (t/ha), Field C1, ACRI, 2013

Historical cropping system	+/- Corn	0-30 cm	0-60 cm	0-120 cm	60-120 cm
Conventional till/continuous cotton	+Corn	49.8	85.6	137.4	47.1
	-Corn (Control)	45.3	78.4	125.6	51.9
Permanent beds/continuous cotton	+Corn	47.4	83.0	132.1	49.1
	-Corn (Control)	51.7	87.2	131.2	44.1
Permanent beds/cotton-wheat	+Corn	49.4	85.2	133.4	47.9
	-Corn (Control)	52.9	94.5	153.4	58.9
SEM					
Historical cropping systems (HCS)		2.43	3.73	7.84	4.52
Corn (C)		1.25	1.17	2.35	2.44
HCS x C		2.17	2.03**	4.08*	4.23

*, significantly different at 95% level of probability; **, significantly different at the 99% level of probability.

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[1] Data analysed by considering each year as a replicate. Values are from soil sampled before sowing cotton.

[2] Hulugalle, N.R., Weaver, T.B., and Finlay, L.A. (2010). Carbon inputs by irrigated corn roots to a Vertisol. *Plant Root*, **4**, 18-21.

6.1.3 Soil organic carbon sequestration 1993-2013

The initial analysis conducted during the previous project suggested that SOC sequestration rates were, generally, negative for extended periods in many sites (Table 7). In other words, there was a net loss of carbon each year. In some sites such as Federation Farm and "Glenarvon", the low R^2 values suggest that SOC sequestration rates, although negative, were effectively similar to a situation where there was no net change with time (i.e. the line was horizontal). Re-analysis of the results, including two previously unanalysed dryland sites (Warra, Emerald) indicated that in most sites there was an initial rapid decrease in SOC sequestration followed by a stabilisation or an increase (i.e. a reduction of the slope or a positive slope). In most, this change was associated with implementation of soil conservation measures (e.g. replacement of conventional management practices with soil conserving practices such as no-tillage, or replacing saline irrigation water with good quality water). One exception to the general pattern was the sequestration rates in Field C1, at ACRI. This experiment has been on-going since 1985 but did not show any stabilisation. This may be partly due to the laser levelling and bed-realignment, both of which involved intensive soil disturbance, that occurred in all plots. Another exception was in Field D1 where conservation farming practices (minimum tillage, stubble retention, cover crops) had been implemented since the start of the experiment. In this site, an initially flat relationship was followed by an increase of 2.59 t/ha/year in carbon storage from 2007 to 2013. This increase may be reflection of the high rainfall and good growth conditions that prevailed from 2009 to 2012, and, hence, these results should be viewed with some caution. In summary, in most sites the carbon sequestration process appears to be a two stage process; viz. an initial rapid decrease followed by a reduction in the rate of decrease or an increase in sequestration. This observation requires further research and evaluation for more sites distributed across a range of climates and soil qualities.

Table 7. SOC sequestration rates (t C/ha/year) in the 0-60 cm depth in the Macquarie and Namoi valleys of New South Wales, and Darling Downs and Central Highlands of Qld. A single average value is given for individual sites. Significant differences among treatments occurred only in Field C1 at ACRI, Narrabri. Only sites where measurements were made for 6 years or more are included in this table.

Site	**Years**	**SOC sequestration rate**	**R^2**
Field C1, ACRI, Narrabri, NSW (Tillage/rotation experiment)	1993-2013	-0.88	0.21***
	1993-2000	-1.54	0.34**
	2000-2013	-1.02	0.27***
Field D1, ACRI, Narrabri, NSW (Cotton/vetch/wheat rotations experiment)	2002-2013	1.08	0.15***
	2002-2007	0.75	0.06ns
	2007-2013	2.59	0.22***
Field D1, ACRI, Narrabri, NSW NSW (Cotton/wheat/ sorghum rotation experiment)	2007-2013	0.10	0.05ns
"Federation Farm", Narrabri, NSW	2000-2013	-0.22	0.004ns
	2000-2009	-1.58	0.21***
	2009-2013	3.91	0.32*
"Beechworth", Merah North, NSW	1993-2004	-0.60	0.04ns
	1993-1999	-4.67	0.55***
	1999-2004	2.10	0.23**
"Glenarvon", Wee Waa, NSW	1993-2001	-1.60	0.04ns
"Auscott", Warren, NSW	1993-2009	-1.74	0.16***
	1993-1998	-5.24	0.37***
	1998-2009	0.04	0.01ns
"Prospect", Warra, Qld	1996-2004	-2.28	0.16***
	1996-1998	-9.58	0.18***
	1998-2004	-2.13	0.13***
"Elsden Farms", Emerald, Qld	1996-2002	-4.30	0.32***
	1996-1999	-10.04	0.54***
	1999-2002	4.42	0.39***

6.1.4 Temperature and soil organic carbon

Analysis of environmental and management data for the NSW rotation sites indicated that annual maximum ambient temperature influenced soil carbon storage. These data, together with the sites in Queensland (Emerald, Warra) (Table 5) were re-analysed to ascertain the influence of ambient temperature on soil carbon storage.

Average ambient temperatures in the trial sites

One hundred year averages showed that average maximum (T_{max}) and minimum (T_{min}) temperatures were in the order of the Macquarie valley (Site 4) < the Namoi valley (Sites 1, 2, 3, 5) < the Darling Downs (Site 6) << Queensland Central Highlands (Site 7) (Table 8). Similar trends were present during the periods between 1993 and 2010 when soil was sampled from the experimental sites. The decrease in both T_{max} and T_{min} with increasing distance on moving south from the Equator and the Tropic of Capricorn, which is located just north of Emerald (Site 7), is caused by factors such as geographical variations in the amount of solar energy that reaches the surface, rainfall distribution, and ocean and atmospheric circulation patterns.

Table 8. Experimental sites that were included in the analysis. All Narrabri sites, Warren and Merah North were irrigated; Warra and Emerald were not. Narrabri site 3 was irrigated with treated sewage effluent. T_{max} and T_{min}, average annual maximum and minimum temperatures (±standard deviation), respectively, during the period of study. Values in parentheses for sites 1, 2, 3 and 5 are the 100-year averages (±standard deviation) for the town of Wee Waa, which lies within a radius of 15 km of these sites.

Site	Location	T_{max} (°C)	T_{min} (°C)	Management practices	Soil type
1	Narrabri (ACRI, Field C1), NSW (30°11'S, 149°36'E)	26.9 ± 6.7 (26.8 ± 6.1)	12.1 ± 6.7 (11.6 ± 5.8)	Crop rotations, tillage systems, stubble management	Grey, self-mulching Vertosol; very fine
2	Narrabri (ACRI, Field D1), NSW (30°11'S, 149°36'E)	27.0 ± 6.8 (26.8 ± 6.1)	12.2 ± 6.9 (11.6 ± 5.8)	Crop rotations, stubble management	Grey, self-mulching Vertosol; very fine
3	Narrabri, NSW (30°13'S, 149°43'E)	27.0 ± (26.8 ± 6.1)	12.1 ± 6.9 (11.6 ± 5.8)	Stubble management, Gypsum application	Grey, self-mulching Vertosol; medium fine
4	Warren, NSW (31°47'S, 147 °46'E)	25.5 ± 7.4 (25.5 ± 6.6)	11.6 ± 6.7 (11.0 ± 5.7)	Crop rotations	Grey, self-mulching Vertosol; medium fine
5	Merah North, NSW (30°11'S, 149°18'E)	27.0 ± 6.7 (26.8 ± 6.1)	12.0 ± 6.7 (11.6 ± 5.8)	Crop rotations	Grey, self-mulching Vertosol; very fine
6	Warra, Qld (26°56'S, 150°50'E)	27.3 ± 4.7 (26.7 ± 4.9)	12.4 ± 5.5 (12.0 ± 5.5)	Crop rotations	Grey, self-mulching Vertosol; medium fine
7	Emerald, Qld (23°30'S, 148°08'E)	29.9 ± 4.2 (29.6 ± 4.5)	16.4 ± 4.9 (15.4 ± 5.2)	Crop rotations, bed widths, stubble management	Black, self-mulching Vertosol; very fine

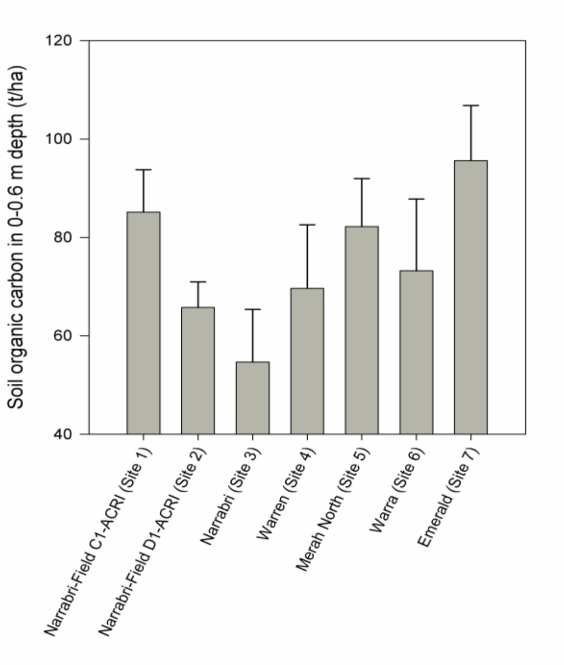


Fig. 1. Mean soil organic carbon storage in the 0-0.6 m depth of the seven experimental sites.

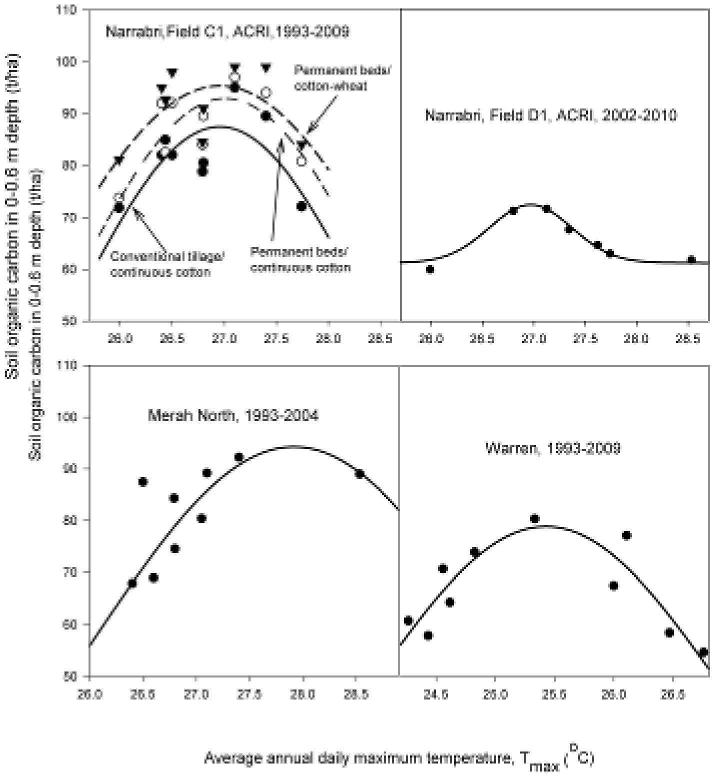


Fig. 2. Variation of soil organic carbon storage in the 0-0.6 m depth with average annual daily maximum temperature in Fields C1 (Site 1) and D1 (Site 2) at the Australian Cotton Research Institute (ACRI), Narrabri; Warren (Site 4) and Merah North (Site 5). Field C1: ●, Conventional tillage/continuous cotton; ○, Permanent beds/ continuous cotton; ▼, Permanent beds/cotton-wheat.

Soil carbon storage

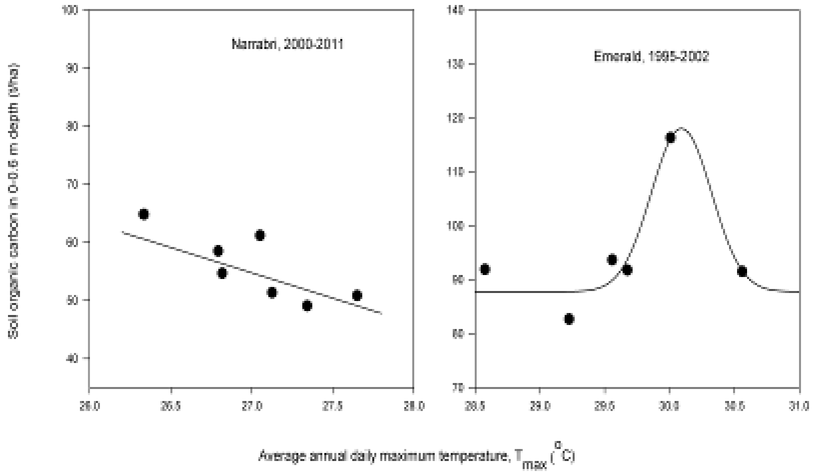
Average soil organic carbon storage in the 0-0.6 m depth was highest in the Black Vertosol at Emerald (Site 7) and lowest in the Grey Vertosol that was irrigated with treated sewage effluent at Narrabri (Site 3) (Fig. 1). In other sites values were generally comparable and ranged from 65 to

85 t C/ha. Variations in SOC storage among all sites were significantly ($P < 0.05$) related to soil parameters such as clay concentration ($R^2 = 0.51^{**}$), clay activity ($cmol_c$/kg clay, $R^2 = 0.56^{**}$) and CEC ($cmol_c$/kg soil, $R^2 = 0.56^{**}$). Climatic parameters such as T_{max} and rainfall in rainfed sites (Sites 6 and 7) but not in irrigated sites (Sites 1-5) were also related to SOC storage. As rainfall and T_{max} were highly correlated ($R^2 = 0.80^{***}$) at Warra (Site 6), it was not possible to separate the role of these individual parameters on SOC storage, and further analyses were discontinued. Water inputs (irrigation and rainfall) and T_{max} were not correlated in all other sites.

Soil carbon storage and its relationship to average annual ambient temperature

In most sites, 3-parameter ($y = a*\text{exp}(-0.5*((x-x_0)/b)^\wedge 2)$) or 4-parameter ($y = y_0+a*\text{exp}(-0.5*((x-x_0)/b)^\wedge 2)$) Gaussian curves where y is soil organic carbon stocks (t/ha), x the average annual maximum temperature during the 12 months prior to sampling, and x_0 the optimum average annual maximum temperature (with respect to soil organic carbon stocks) best described the data (Table 9, Figs. 2 and 3). The exception was the Narrabri site that was irrigated with treated sewage effluent (Site 3), where the relationship between soil organic carbon and T_{max} was linear (Fig. 3). Differences among experimental treatments occurred only in Field C1 at ACRI, Narrabri (Site 1), where SOC storage was highest with cotton-wheat sown on permanent beds and lowest with conventionally-tilled continuous cotton (Fig. 2). At all other locations, differences among treatments were absent, and values of SOC were pooled among treatments and a single curve derived.

Fig. 3. Variation of soil organic carbon storage in the 0-0.6 m depth with average annual daily maximum temperature in



As mentioned above, most of the data fit Gaussian models or bell-shaped curves, typical of substrate decomposition by micro-organisms[1]. In our studies the substrate was the crop residues and the product, stored soil organic carbon. These curves also indicate that carbon storage occurs at peak rates only for a very limited temperature range at any one site. Figs. 2 and 3 indicate that the optimum values for carbon storage, T_{opt} (T_{max} at which carbon storage was highest) appears to be related to latitude; *viz*. values increased with decreasing latitude or as one approached the equator (Table 10). T_{opt} for the Macquarie valley, NSW (Site 4) was 25.5 °C, averaged 27.2 °C in Namoi valley, NSW (Sites 1, 2, 5) and was 30.1 °C in the Central Highlands of Queensland. These very specific temperature-related peaks are associated with peak activity of different microbial populations adapted to the different geographic locations; *viz*. the Macquarie and Namoi valleys of NSW, and the Central Highlands of Queensland; which in turn may be associated with the variations in climate and soil conditions in each location. Table 8 indicates that SOC storage was highest (117 t C/ha) in the Central Highlands of Queensland (Site 7, a fertile black Vertosol with a high degree of soil structural stability[2]) and averaged 87 t C/ha among the other sites reported in Table 10 (all grey Vertosols), ranging from 72.4 t C/ha in Site 2 to 94 t C/ha in Site 5. The relatively high value in site 5, in spite of its initially sodic nature, may be a consequence of improved aggregation

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[1] Gendugov V, Glazunov G, Evdokimova M (2011) Macrokinetics of microbial growth and decline in soil. *Microbiology* **80**, 514-518.

[2] Hulugalle NR, Rohde KW, Yule DF (2002b) Cropping systems and bed width effects on runoff, erosion and soil properties in a rainfed Vertisol. *Land Degradation & Development* **13**, 363-374.

resulting from regular gypsum application, salinization due to declining irrigation water quality and latterly, elimination of the summer fallow[1]. Variation among sites was related primarily to clay activity ($R^2 = 0.78^*$), although the influence of other factors such as length of growing season, nutrient inputs, tillage intensity cannot be excluded. The relatively low value in Site 2 (72 t C/ha) in comparison with the other grey Vertosols (Table 10) may be related to the low ESI (< 0.05) in the sub-surface (> 0.30 m)[2], and consequently, low structural stability, which would have had a detrimental effect on soil organic carbon storage. Low structural stability may also be the reason behind the absence of a Gaussian relationship between soil organic carbon and T_{max} at Site 3. The high SAR values of irrigation water resulted in decreases in profile ESI such that it did not exceed 0.05 in the 0-1.8 m depth by 2011[3]. Other factors that may have contributed to the absence of a Gaussian relationship include the high nutrient loads, high alkalinity ($pH_w \geq 9$), and moderate to high chloride concentration of the effluent, and overstimulation of microbial activity.

In summary, variations in carbon storage of Vertosols sown with cotton-based farming systems with average ambient maximum temperature were described by Gaussian models or bell-shaped curves that are characteristic of microbial decomposition. Carbon storage occurred at peak rates only for a very limited temperature range at any one site, with these temperatures increasing with decreasing distance from the equator. These findings suggest that the decrease or absence of change in soil carbon storage with time reported in many Australian studies of annual cropping systems may be due to carbon storage occurring within a limited temperature range, whereas intra-seasonal average maximum temperatures can range widely. Further research needs to be conducted under field conditions to confirm these observations. In particular, the impact of short-term fluctuations such as heat wave events on both short- and long-term soil carbon storage is a subject that is worthy of more detailed study.

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[1] Hulugalle NR, Entwistle PC, Weaver TB, Scott F, Finlay LA (2002a) Cotton-based rotation systems on a sodic Vertosol under irrigation: effects on soil quality and profitability. *Australian Journal of Experimental Agriculture* **42,** 341-349.
Hulugalle NR, Weaver TB, Finlay LA (2006) Residual effects of cotton-based crop rotations on soil properties of irrigated Vertosols in central-western and north-western New South Wales. *Australian Journal of Soil Research* **44**, 467-477.

[2] Hulugalle NR, Weaver TB, Finlay LA, Lonergan P (2012). Soil properties, black root-rot incidence, yield and greenhouse gas emissions in irrigated cotton cropping systems sown in a Vertosol with subsoil sodicity. *Soil Research* **50**, 278-292.

[3] Hulugalle NR, Weaver T, Kimber S, Powell J, Scott F (2011) Maintaining profitability and soil quality in cotton farming systems III. Final Report to Cotton Catchment Communities Co-operative Research Centre on Project No. 1.04.16.

Table 9. Model parameters and regression statistics for the experimental sites. SE, standard error; n, observations; R^2, regression coefficient; SEE, standard error of estimate; SOC, soil organic carbon storage in the 0-0.6 m depth; T_{max}, average maximum temperature; T_{opt}, optimum T_{max}, temperature at which carbon storage peaks; SOC_0, initial soil organic carbon storage in the 0-0.6 m depth (intercept); *, **, ***, significant at 95%, 99% and 99.9% levels of probability

Site	Location	Best-fit model	Model coefficients				Regression statistics		
			a ± SE	b ± SE	T_{opt}	SOC_0	R^2	n	SEE
1	Narrabri (ACRI, Field C1), NSW								
	- Conventional tillage/continuous cotton	$SOC = a*\exp(-0.5*((T_{max}-T_{opt})/b)^2)$	$87.43^{***} \pm 2.40$	$1.40^{***} \pm 0.18$	$27.0^{***} \pm 0.07$	-	0.66^{**}	12	5.34
	- Permanent beds/continuous cotton	$SOC = a*\exp(-0.5*((T_{max}-T_{opt})/b)^2)$	$92.90^{***} \pm 2.08$	$1.48^{***} \pm 0.17$	$27.0^{***} \pm 0.07$	-	0.72^{**}	12	4.62
	- Permanent beds/cotton-wheat	$SOC = a*\exp(-0.5*((T_{max}-T_{opt})/b)^2)$	$95.34^{***} \pm 2.48$	$1.71^{***} \pm 0.17$	$27.0^{***} \pm 0.10$	-	0.51^{*}	12	5.62
	All treatments	$SOC = a*\exp(-0.5*((T_{max}-T_{opt})/b)^2)$	$91.87^{***} \pm 1.64$	$1.52^{***} \pm 0.15$	$27.0^{***} \pm 0.06$	-	0.49^{***}	36	6.36
2	Narrabri (ACRI, Field D1), NSW	$SOC = SOC_0 + a*\exp(-0.5*((T_{max}-T_{opt})/b)^2)$	$11.20^{***} \pm 1.35$	$0.40^{***} \pm 0.09$	$27.0^{***} \pm 0.07$	$61.2^{***} \pm 1.14$	0.66^{***}	41	3.41
3	Narrabri, NSW	$SOC = SOC_0 + a*T_{max}$	$-11.31^{**} \pm 3.79$	-	-	$361.2^{***} \pm 102.4$	0.18^{**}	42	9.64
4	Warren, NSW	$SOC = a*\exp(-0.5*((T_{max}-T_{opt})/b)^2)$	$78.92^{***} \pm 1.08$	$1.49^{***} \pm 0.05$	$25.4^{***} \pm 0.02$	-	0.75^{***}	70	4.38
5	Merah North, NSW	$SOC = a*\exp(-0.5*((T_{max}-T_{opt})/b)^2)$	$94.26^{***} \pm 1.72$	$1.88^{***} \pm 0.15$	$27.9^{***} \pm 0.09$	-	0.65^{***}	63	5.90
7	Emerald, Qld	$SOC = SOC_0 + a*\exp(-0.5*((T_{max}-T_{opt})/b)^2)$	$30.23^{***} \pm 3.24$	$0.23^{***} \pm 0.03$	$30.1^{***} \pm 0.04$	$87.8^{***} \pm 1.37$	0.73^{***}	50	5.96

Table 10. Optimum T_{max}, temperature at which carbon storage peaks (T_{opt}) and maximum soil organic carbon (SOC_{max}) storage in the 0-0.6 m depth for the experimental sites at Narrabri, Warren, Merah North and Emerald estimated from the curves shown in Figures 2 and 3. Values for site 1 were derived by pooling results for all three cropping systems.

Site	Location	Latitude	T_{opt} (°C)	SOC_{max} (t C/ha)
1	Narrabri (ACRI, Field C1), NSW	30°11'S	27.0	92
2	Narrabri (ACRI, Field D1), NSW	30°11'S	27.0	72
4	Warren, NSW	31°47'S	25.4	79
5	Merah North, NSW	30°11'S	27.9	94
7	Emerald, Qld	23°30'S	30.1	117

6.1.5 Management inputs and soil organic carbon stocks

Within site multiple linear regression of management and climatic variables with soil organic carbon stocks for the individual sites produced somewhat variable results (Table 11). SOC storage in Field D1 at ACRI was positively (but weakly) related to annual average minimum and maximum temperatures. In Field C1 the number of tillage operations irrespective of tillage depth had a negative effect on SOC whereas at “Glenarvon” and “Beechworth” it was positive. This may be due to the fact that in the latter two sites “deep tillage” was primarily associated with pupae-busting and rarely exceeded 15 cm but in Field C1 it was more aggressive and associated with chisel- and disc-ploughing, listering and preparation of land for laser-levelling. The number of shallow tillage (< 10 cm depth) operations had negative effects on SOC at Fild C1 and “Auscott-Warren”. Unlike in previous models, increasing N fertiliser rates no significant effect on SOC in any of the sites monitored. Dry matter inputs had a negative effect on SOC at C1 and “Beechworth”. Average daily maximum temperature had a positive effect on SOC at Fields C1 and D1, “Auscott-Warren” and “Beechworth” but had no effect on SOC at “Glenarvon” and “Prospect”. In the rainfed site at Warra, water inputs (i.e. rain) was the sole factor that was positively related to carbon storage.

Table 11. Results of multiple linear regression analyses of management and climatic variables on SOC sequestration. Max till, number of tillage operations > 10 cm deep; Min till, number of tillage operations < 10 cm deep; N, N fertiliser applied (kg N/ha); Water, total water inputs, irrigation and rainfall (mm); T_{max}, annual average daily maximum temperature (^oC); T_{min}, annual average daily minimum temperature (^oC); DM, total plant dry matter (t/ha); VIF, variance inflation factor. . Interaction terms, when significant, had only a small effect on the fit of the data, and were thus, dropped from the models.

Site	Variable	Coefficient	VIF	P <	R^2	n
Field C1, ACRI, Narrabri, NSW	Max till	-2.56	1.2	0.001	0.50^{***}	67
	Min till	-3.46	1.2	0.001		
	T_{max}	3.40	1.1	0.01		
	T_{min}	-3.58	1.1	0.05		
	DM	-0.61	1.2	0.05		
Field D1, ACRI, Narrabri, NSW	T_{max}	5.62	1.1	0.05	0.10*	72
	T_{min}	-11.14	1.1	0.05		
“Glenarvon”, Wee Waa, NSW	Max till	2.07	1.1	0.01	0.60^{**}	32
	Min till	2.77	1.6	0.001		
	N	-0.039	1.6	0.05		
“Beechworth”, Merah North, NSW	Max till	10.86	1.3	0.001	0.68^{***}	72
	T_{max}	6.63	1.2	0.001		
	T_{min}	3.98	1.1	0.05		
	DM	-0.57	1.2	0.001		
	N	0.024	1.2	0.01		
“Auscott-Warren”, Warren, NSW	T_{max}	4.46	1.3	0.001	0.52^{**}	56
	Min till	-2.50	1.2	0.001		
	T_{min}	5.71	1.2	0.05		
“Prospect”, Warra Qld.	Water	0.034	1.0	0.001	0.36^{***}	50
Pooled results[1] for - all sites	Max till	4.11	1.0	0.001	0.15^{***}	353
	T_{max}	2.82	1.0	0.001		

Average daily minimum temperature was positively related to SOC at “Auscott-Warren” and “Beechworth”, but had a negative effect at Field C1 and D1. The variations in SOC stocks in Field D1 were solely explained (but weakly) by annual temperature variables (Table 9). Presumably a

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[1] Fields C1 and D1, ACRI, Narrabri; “Glenarvon”, Wee Waa; “Auscott-Warren”, Warren, NSW; “Prospect”, Warra, Qld., “Merrowie”, Hillston, NSW. The Emerald site was excluded as insufficient data was available on management practices.

non-linear approach may have had more success, although model complexity may have been significantly enhanced.

Pooling of results for all sites listed in Table 11 and “Merrowie”, Hillston, NSW indicated that average daily maximum temperature and the number of tillage operations greater then 10 cm deep increased SOC stocks in the 0-60 cm (Table 11). The positive impact of tillage > 10 cm deep is at variance with the widely-held belief that tillage results in depletion of SOC stocks. It should be noted that these claims have been made with respect to carbon concentrations in shallow depths whereas the present study was based on SOC stocks in the 0-60 cm depth. In addition many of the tillage operations conducted in this study, did not include inversion tillage, did not exceed 20 cm, and were mainly associated with pupae-busting and thus conducted under dry conditions after picking cotton. The clods formed by tillage were coarse, and thus aggregate disruption was minimal. Examples of such tillage practices were cultivation with the Aer-way cultivator, “centre-busting” or “go-devils” (disc-hiller). The end result is an aeration of the soil after the compactive effects of trafficking associated with picking (Fig. 4). In contrast, if an implement such as a rotary-harrow had been used significant disruption of soil aggregates would have been likely. The relationship to average maximum ambient temperature was similar to that observed in earlier versions of the model, and was assessed at depth in a previous section (see section 6.1.4).

Fig. 4. Aer-way cultivator and associated land preparation at “Federation Farm”.

6.1.6 Carbon inputs into soil

The major sources of carbon inputs into soil in agricultural systems are plant materials, *viz*. above and below-ground residues, root exudates etc. However, much of the carbon in crop residues is returned to the atmosphere as carbon dioxide through microbial respiration. The literature suggests that the proportion of carbon in crop residues that is ultimately sequestered in soil can range from 1-20%, although most authors concur that the values are likely to be at the lower end of this range. In this report we have used a value of 5% to estimate the amounts of carbon that can potentially be sequestered in soil. This assessment does not account for the subsequent losses of carbon due to microbial decomposition, soil erosion and runoff.

Cotton and rotation crop above-ground residues for the period 2011-14 are summarised in Tables 12, 13 and 14. Assuming a 5% sequestration rate[1], values of carbon sequestered from above-ground inputs were estimated to range from 0.07 t C/ha/year for continuous cotton to 0.3 t C/ha/year for cotton-wheat-vetch. The amounts of sequestered carbon estimated for the cotton-wheat-vetch rotation and C_4 crops such as corn and sorghum using a 5% sequestration rate are similar to those reported for Vertosols under annual cropping systems in Texas, USA (Potter, 2010[2]). In spite of this higher value, however, significant differences among SOC stocks in this

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[1] Hulugalle NR, Weaver T, Kimber S, Powell J, Scott F (2011) Maintaining profitability and soil quality in cotton farming systems III. Final Report to Cotton Catchment Communities Co-operative Research Centre on Project No. 1.04.16.

[2] Potter, K.N. (2010). Building soil carbon content of Texas Vertisols. In: *Soil Solutions for a Changing World, Eds. R. J. Gilkes and N. Prakongkep, Proc. 19th World Congress of Soil Science, 1 – 6 August 2010, Brisbane, Australia [DVD]*. http://www.iuss.org/19th%20WCSS/symposium/pdf/0222.pdf

experiment (in Field D1) were absent among cropping systems. This implies that even though higher amounts of carbon are potentially available for sequestration with the cotton-wheat-vetch sequence, the high N concentration, and thus, low C/N ratios of both above- (12.9) and below-ground (18.7) vetch materials results in enhanced microbial decomposition of soil organic matter resulting from vetch residues. This casts doubt on the efficacy of leguminous crops in soil carbon sequestration in environments where microbial activity is high such as in irrigated summer-cropping systems. A further cause of SOC losses from a field are those associated with erosion and as dissolved carbon in runoff water. No long-term results are available for cotton soils under furrow irrigation but data from Canada suggests that up to 70% of SOC losses are due to erosion and only 30% were caused by microbial decomposition. Extrapolating from published data of SOC concentration in eroded sediments and sediment concentration in runoff water[1], for a typical cotton season estimated values of SOC lost with erosion ranged from 0.4 to 1.2 t C/ha. These values, for the most part, are greater than the sequestered values estimated from carbon inputs reported in Tables 10-12. It is not surprising, therefore, that net long-term carbon sequestration measured in this study (Table 7) was either negative or neutral.

In comparison with C_3 crops, the estimated potential C sequestration values of the C_4 crops corn and sorghum were much higher. Above-ground sequestration rates for corn-cotton rotations in Field C1 averaged 0.14 t C/ha/year and for cotton-sorghum 0.33. Below-ground carbon sequestration rates were A previous report[2] indicated that corn roots could contribute 0.4 t/ha/year to SOC stocks and cotton 0.06 t C/ha/year. Above- and below-ground carbon sequestration rates by cotton-corn rotations are, therefore of the order of 0.6 t C/ha/year. Sorghum roots contributed less carbon with conventional tillage than with no-tillage ($P < 0.05$) in a wet year but not in a dry year (Fig. 5). Average sequestration rates for 2011-2013 period were of the order of 0.7 t C/ha/year, and concurs with previous observations. A large proportion of the carbon inputs from sorghum roots came from depths > 60 cm. Averaged between both treatments, during flowering and grain filling, 65% of the total root mass was located in the 60-1.0 m depth (Fig. 5). This pattern of root distribution is unusual in irrigated soils where the majority of roots are located in the surface regions. In total the estimated carbon sequestration in a cotton-sorghum rotation is of the order of 1.1 t C/ha/year. These values are similar to those reported by Potter et al. (2010)[1] for pastures in Vertosols of Texas. Further discussion of sorghum root growth and proliferation in the subsoils can be seen in section 6.6.2.1.

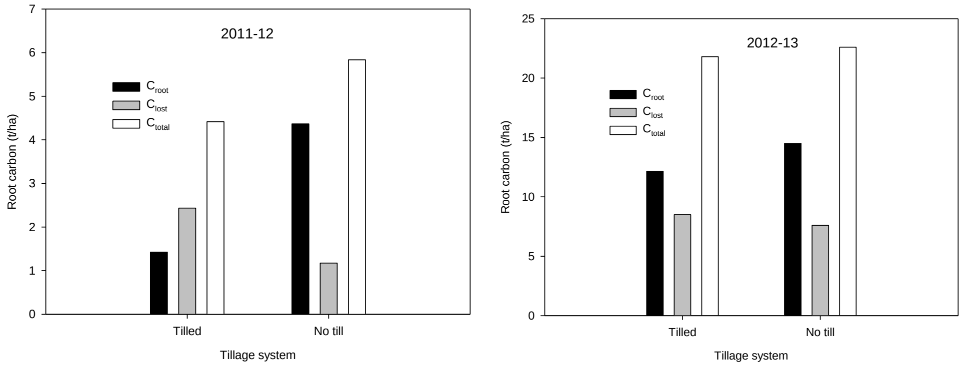

Fig. 5. Effect of tillage system on sorghum root C indices during the 2011-12 and 2012-13 seasons . C_{root}, root carbon at end of season; C_{lost}, root carbon added to the soil during season; C_{total}, root carbon which could be potentially added to soil organic carbon stocks = $C_{root} + C_{lost}$.

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[1] (a) Carroll C. *et al* (1999). A simulation study of erosion in the Emerald Irrigation Area. *Aust. J. Soil Res*. **37**, 479-494; (b) Silburn, D.M. and Glanville, S.F. (2002). Management practices for control of runoff losses from cotton furrows under storm rainfall. I. Runoff and sediment on a black Vertosol. *Aust. J. Soil Res*. **40**, 1-20. (c) Silburn, D. M., *et a*l. (2009). Management practices for control of runoff losses from cotton furrows under storm rainfall.III.Cover and wheel traffic effects on nutrients (N and P) in runoff from a black Vertosol. *Aust. J. Soil Res*. **47,** 221-233.

[2] Hulugalle NR, Weaver T, Kimber S, Powell J, Scott F (2011) Maintaining profitability and soil quality in cotton farming systems III. Final Report to Cotton Catchment Communities Co-operative Research Centre on Project No. 1.04.16.

Table 12. Dry matter production of wheat and cotton in tillage/rotation experiment, Field C1, ACRI. DM, dry matter. Values in parentheses are $\log_e$ transformed values. *, ** and *** indicate that treatments differ significantly at $P < 0.05$, $P < 0.01$ and $P < 0.001$, levels, respectively. 40% of plant dry matter was assumed to consist of carbon. All values are in t/ha.

+/- Corn	**Rotation**	**Tillage system**	**2011-12**					**2012-13**		
			Wheat[1]	**Cotton**	**Corn**	**Total DM**	**Total carbon**	**Cotton**	**Total DM**	**Total carbon**
+Corn	Cotton-cotton	Conventional	-	-	6.2	6.2	2.5	4.3	4.3	1.7
	Cotton-cotton	Permanent beds	-	-	7.4	7.4	3.0	4.7	4.7	1.9
	Cotton-wheat	Permanent beds	0.3	-	7.3	7.6	3.0	4.3	4.3	1.7
-Corn (control	Cotton-cotton	Conventional	-	3.1	-	3.1	1.2	3.5	3.5	1.4
	Cotton-cotton	Permanent beds	-	3.6	-	3.6	1.4	4.7	4.7	1.9
	Cotton-wheat	Permanent beds	0.3	-	-	0.3	0.12	5.2	5.2	2.1

+/- Corn	**Rotation**	**Tillage system**	**2013-14**					**2011-2014**				
			Wheat	**Cotton**	**Corn**	**Total DM**	**Total carbon**	**Wheat**	**Cotton**	**Corn**	**Total DM**	**Total carbon**
+Corn	Cotton-cotton	Conventional	-	-	8.7	8.7	3.5		4.3	14.9	19.2	7.7
	Cotton-cotton	Permanent beds	-	-	8.7	8.7	3.5		4.7	16.1	20.8	8.3
	Cotton-wheat	Permanent beds	1.5	-	10.0	11.5	4.6	1.8	4.3	17.3	23.4	9.4
-Corn (control	Cotton-cotton	Conventional	-	3.6	-	3.6	1.4		10.2	-	10.2	4.1
	Cotton-cotton	Permanent beds	-	3.7	-	3.7	1.5		12.0	-	12.0	4.8
	Cotton-wheat	Permanent beds	1.6	-	-	1.6	0.6	1.9	5.2	-	7.1	2.8

SEM:

Parameter	**Historical Cropping systems (HCS)**			**+/- Corn (C)**			**HCS x C**		
	2011-12	**2012-13**	**2013-14**	**2011-12**	**2012-13**	**2013-14**	**2011-12**	**2012-13**	**2013-14**
Cotton DM	0.24	0.18*	0.19	-	0.16	-	-	0.27*	-
Corn DM	0.32*	-	0.48	-	-	--	-	-	-

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[1] Wheat was sown after laser levelling. As growth was very poor, the crop was sprayed out.

Table 13. Dry matter production (t/ha) of vetch, wheat and cotton in rotation experiment, Field D1, ACRI. Wheat dry matter yields are those from previous winter; thus for 2011-12 season, wheat dry matter yields shown are from 2010 winter. DM, dry matter. *, ** and *** indicate that treatments differ significantly at $P < 0.05$, $P < 0.01$ and $P < 0.001$, levels, respectively. 40% of plant dry matter was assumed to consist of carbon. V, vetch, W, wheat, Cot, cotton, O, Oats

Rotation	**Rotation stul management**	**2011-12**					**2012-13**				
		V	**W**	**Cot**	**Total DM**	**Total carbon**	**V**	**W[1]**	**Cot**	**Total DM**	**Total carbon**
Cotton-vetch	Mulched	0.2	-	4.1	4.3	1.7	0.3	-	3.6	3.9	1.6
Cotton-cotton	-	-	-	3.3	3.3	1.3	-	-	3.7	3.7	1.5
Cotton-wheat	Incorporated	-	4.0	3.6	7.6	3.0	-	10.2	3.6	13.8	5.5
Cotton-wheat-vetch	Mulched	4.0	4.0	4.6	12.6	5.0	2.6	11.4	3.9	17.9	7.2
SEM		0.14**	0.19	0.29*			0.12***	0.51	0.23		

Rotation	**Rotation stubble management**	**2013-14**						**2011-14**					
		V	**O**	**W**	**Cot**	**Total DM**	**Total carbon**	**V**	**O**	**W**	**Cot**	**Total DM**	**Total carbon**
Cotton-vetch[2]	Mulched	-	2.7	-	3.1	5.8	2.3	0.5	2.7	-	10.8	14.0	5.6
Cotton-cotton	-	-	-	-	3.3	3.3	1.3	-	-		10.2	10.2	4.1
Cotton-wheat	Incorporated	-	-	3.4	3.8	7.2	2.9	-	-	17.6	11.0	28.6	11.4
Cotton-wheat-vetch	Mulched	4.8	-	4.1	3.9	12.8	5.1	11.4	-	19.5	12.4	43.3	17.3
SEM		-	-	0.19*	0.21*								

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[1] Due to a calibration error by ACRI farm staff, wheat was sown at a rate of 240 kg/ha and not the recommended sowing rate of 60 kg/ha. Hence, the exceptionally high biomass

[2] Vetch in the cotton-vetch rotation was replaced with oats during the 2013 winter

Table 14. Dry matter production of rotation crops and cotton in experiments at “Federation Farm”, Narrabri; “New Haven”, Narromine; “Merrowie”, Hillston; and the cotton-wheat-sorghum rotation experiment, Field D1, ACRI, Narrabri. DM, dry matter. *, ** and *** indicate that treatments differ significantly at $P < 0.05$, $P < 0.01$ and $P < 0.001$, levels, respectively. 40% of plant dry matter was assumed to consist of carbon.

Site	**Cropping system**	**2011-12**				**2012-13**				**2013-14**			
		Rotation	**Cotton**	**Total D**	**Carbon**	**Rotation**	**Cotton**	**Total DM**	**Carbon**	**Rotation**	**Cotton**	**Total DM**	**Carbon**
“Federation Farm Narrabri[1]	Stubble incorporated	-	4.8	4.8	1.9	1.3	1.7	3.0	1.2	0.8	5.9	6.7	2.7
	Stubble retained as *in situ* mulch)	-	4.7	4.7	1.9	1.3	1.7	3.0	1.2	0.8	5.8	6.6	2.6
	SEM	-	0.18			-	-	-			0.37		
“Merrowie”, Hillston[2]	Cotton-wheat	2.4	-	2.4	1.0	Experiment terminated							
	Cotton-wheat-sorghum	2.3	-	2.3	0.9								
	SEM	0.10	-										
“New Haven”, Narromine	Corn (burnt) fb. Cotton-wheat	-	7.9	7.9	3.2	NA[3]	-	?	?	-			
	Cotton-wheat (*in situ* mulch)	-	8.3	8.3	3.3	-	9.0	9.0	3.6	-	-	-	-
	t-value	-	-0.79										
Field D1, ACRI, Narrabri	Cotton-wheat-sorghum[4] (*in situ* mulch)	10.3	3.3	13.6	5.4	14.4	4.6	19.0	7.6	13.6	4.5	18.1	7.2
	Cotton-wheat (*in situ* mulch)	3.5	4.3	7.8	3.1	11.7	3.8	15.5	1.4	3.0	3.4	6.4	2.6
	t-value	-8.04*	1.97			-4.43*	0.69			10.53**	3.15		

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[1] During the 2012-13 season, chickpea was sown in replicates 1 and 2 and replicate 3 was fallowed. During the 2013-14 season, replicates 1 and 2 were fallowed in winter and cotton was sown during the summer, and wheat was sown in replicate 3 during winter and fallowed in summer. Dry matter production was estimated from grain yields using harvest indices and a weighted mean calculated for all plots.

[2] Rotation crop sown during 2011-12 was wheat. Sorghum was not sown by the collaborator during the 2011-12 summer as required by the experimental plan. Experiment terminated in 2012.

[3] Samples not taken for wheat dry matter

[4] Forage sorghum was sown during 2008-09, and grain sorghum, thereafter. The experiment was designed such that both cotton and rotation phases were sown every year.

6.2 Greenhouse gas emissions

6.2.1 Greenhouse gas emissions associated with farming practices

A significant cause of greenhouse gas emissions in agriculture is claimed to be that produced by burning fossil fuel during various farming operations. Few long-term results exist, however, for Australian cotton farming systems. This section presents emissions estimated from fuel and electricity use (presented as carbon dioxide equivalents, CO_2-e) from the experiments described in sections 5.1.1.1 and 5.1.2.1. Treatments included tillage systems, stubble retention and, summer and winter rotation crops such as corn, wheat and vetch.

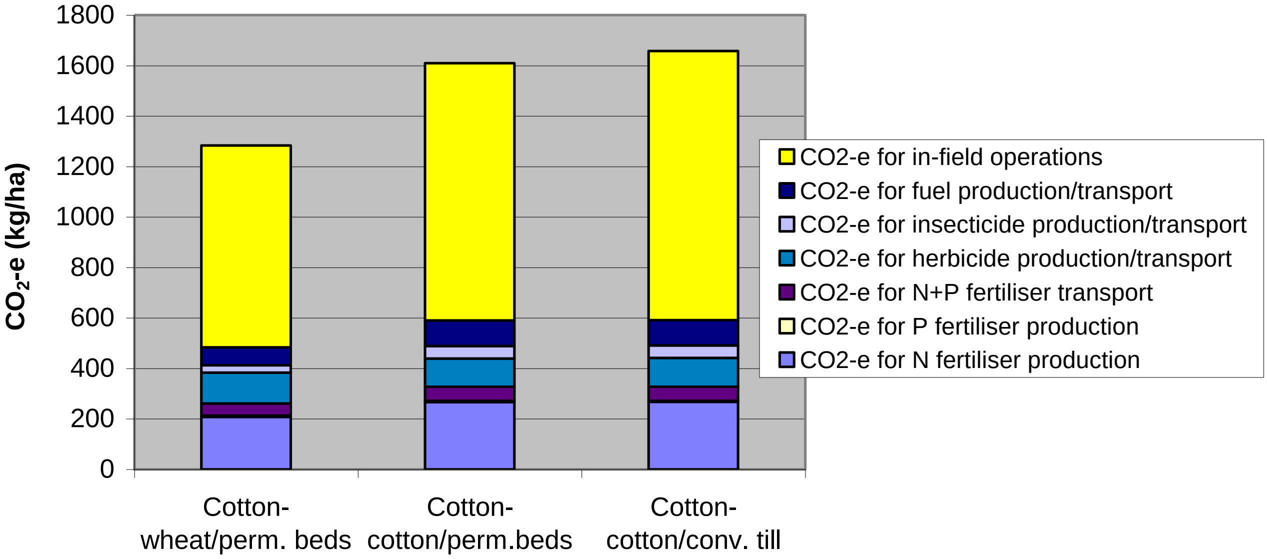

Fig. 6. Effect of tillage and cropping system on average greenhouse gas emissions (1998-2013), measured as carbon dioxide equivalent (CO_2-e), Field C1, ACRI, Narrabri. Excludes plots sown with corn in 2011.

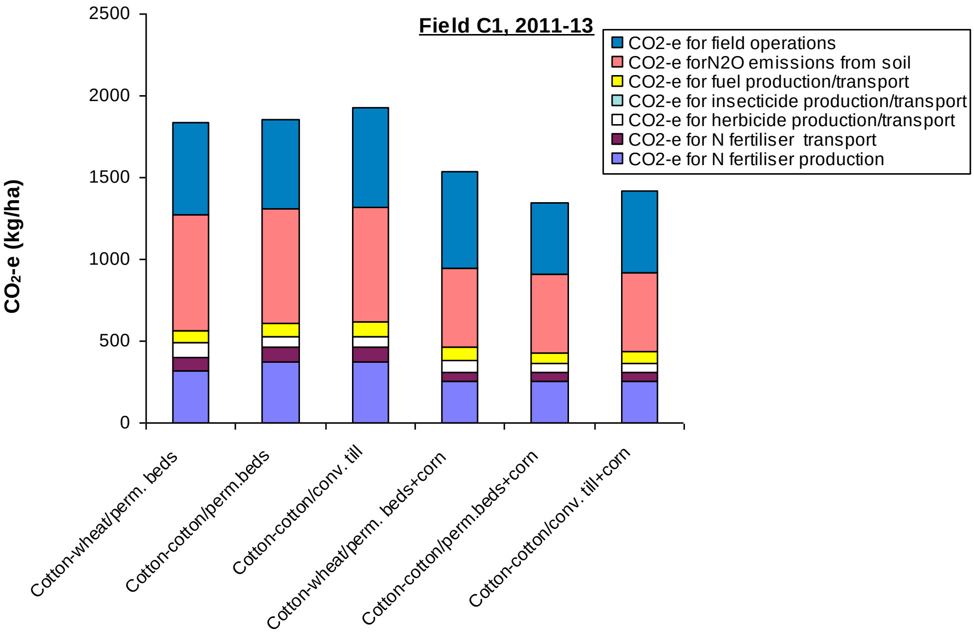

Fig. 7. Effect of including a corn rotation crop on average greenhouse gas emissions (2011-2013), measured as carbon dioxide equivalent (CO_2-e), Field C1, ACRI, Narrabri.

The key findings from these estimates are summarised as follows:

- Reducing tillage reduced in-field emissions whereas continuous cotton increased them. High emissions occurred when cotton was sown every year (i.e. summer cotton-winter fallow or rotation crop-summer cotton) (Figs. 6-7). Within such cropping systems, sowing cotton onto permanent beds resulted in the least amount of emissions, with increases taking place when conventional tillage was practiced or a vetch rotation crop was sown. Relative to permanent beds, conventional tillage produced about 3 times more CO_2-e (i.e. 3 times more diesel is consumed) during land preparation. Furthermore, sowing a vetch or any other rotation crop into dry soil immediately after cotton and when rainfall is insufficient for seed germination required irrigation, which produces emissions.

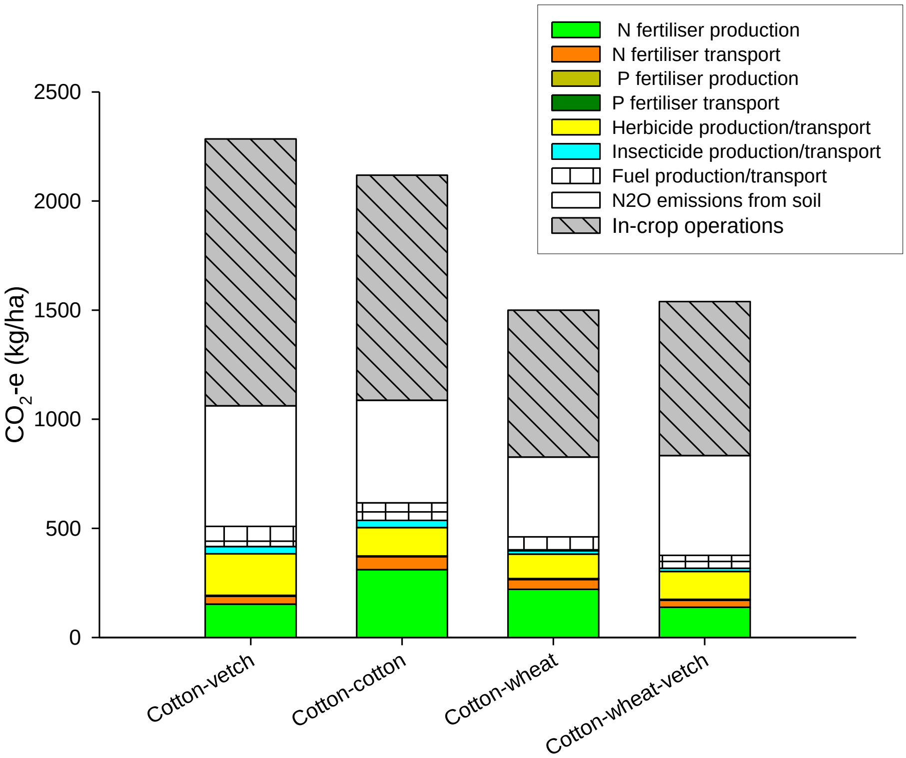

Fig. 8. Effect of tillage and cropping system on average greenhouse gas emissions (2002-2013), measured as carbon dioxide equivalent (CO_2-e), Field D1, ACRI, Narrabri

- Emissions were reduced when wheat or corn was part of the rotation. Including vetch in a cotton-wheat rotation did not increase CO_2-e emissions appreciably because the former was grown mainly as a dryland crop with water used coming from stored soil water and in-crop rainfall.

- Partial life cycle analysis showed that most CO_2-e was produced by in-field activities and soil emissions (Figs. 6-8). Significant amounts of CO_2-e were also emitted during production of N fertiliser used in the field, herbicide production and transport to the field and fuel production and transport to the field. Partial substitution of mineral N fertiliser by legumes such as vetch was able to reduce emissions associated with N fertiliser production and transport by 48% when cotton was sown every year and 36% in a cotton-wheat rotation system. This is equivalent to a reduction of 90 and 47 kg CO_2-e/ha/year, respectively. These values are less than those reported in previous reports because vetch growth was poorer during the 2011-2013 period. When nitrous oxide emissions from soil due to both fertiliser and leguminous N are accounted for, however, there was no difference between the systems.

- Emissions per bales of cotton lint produced and per unit of energy produced in a cropping system were reduced by permanent beds and by inclusion of a wheat crop in the rotation. Further reductions occurred with the inclusion of a corn crop in the rotation (Table 15). Energy efficiency can be greatly improved by including crops that produce energy (e.g. grains, oilseeds etc.) in cotton-based farming systems.

Table 15. Emissions per unit of cotton production and energy produced in cotton cropping systems

Field	Period	Cropping system	kg CO_2-e/bale of cotton lint produced	g CO_2-e/MJ of product[1]
C1	1998-2013	Conventional tillage/continuous cotton	293	43
		Permanent beds/continuous cotton	275	40
		Permanent beds/cotton-wheat	197	31
	2011-2013	Conventional tillage/continuous cotton	266	33
		Permanent beds/continuous cotton	230	36
		Permanent beds/cotton-wheat	178	39
	2011-2013	Conventional tillage/continuous cotton + corn	144	21
		Permanent beds/continuous cotton + corn	133	18
		Permanent beds/cotton-wheat + corn	144	25
D1	2002-2013	Cotton-vetch	265	44
		Cotton-cotton	248	41
		Cotton-wheat, wheat stubble incorporated	149	15
		Cotton-wheat-vetch, standing wheat stubble	162	15

- Groundwater pumping can be a major contributor to greenhouse gas emissions. Emissions produced during irrigation with river water are relatively small whereas those produced by pumping groundwater are large; about 6 times higher, in fact. Energy use and emissions are high when pumping depths are high. These results were presented in the 2008-2011 report

In summary, reduction in in-field CO_2-e production occurred when management practices such as reduced or minimum tillage, permanent beds, corn and wheat rotation crops were used in comparison with sowing cotton every year after conventional tillage. The inclusion of wheat was able to reduce emissions because it included a stubble-mulched fallow which facilitated harvesting of rain water, thereby reducing the number of irrigations. Past research has also shown that these are the very same practices which can improve soil health, cotton yield and fibre quality. Substitution of mineral N fertiliser with a leguminous crop was not able to reduce the carbon footprint of cotton-based rotation systems because of the additional emissions associated with growing it.

6.2.2 Life cycle analysis of cotton farming systems in the Namoi valley estimated with SIMAPRO (collaborative study with Dr. P. Brock of NSW DPI, and Dr. D. Tan and Mr. G. Quigley of the University of Sydney)

The greenhouse gas emissions from the production of 1 tonne of “seed cotton” (cotton lint and seed) on-farm were calculated (see example for ACRI in Fig. 9) and tabulated for the different enterprises (Table 16).

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[1] Cottonseed, cotton lint, wheat grain and corn grain

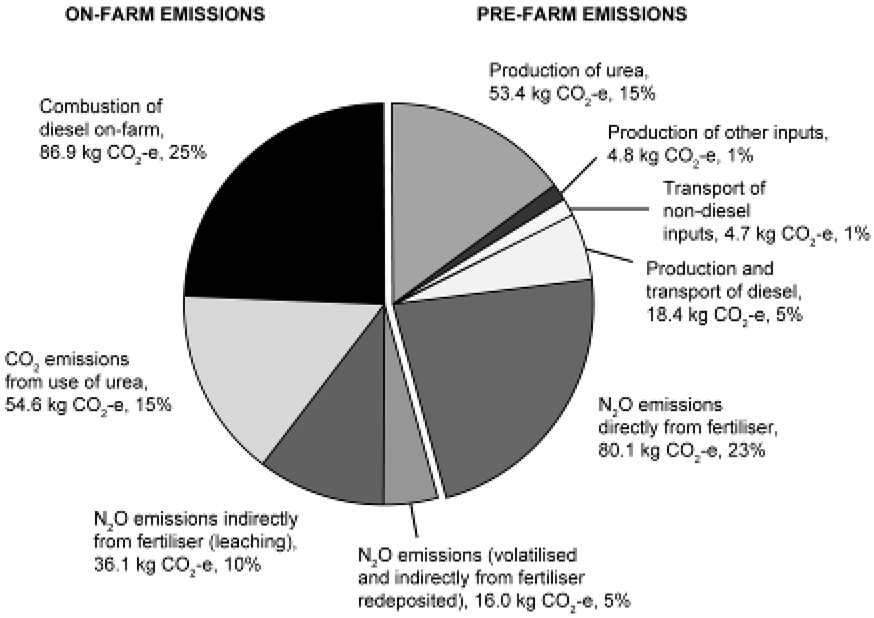

Fig. 9. Greenhouse gas emissions (kg CO_2-e) from the production of 1 tonne of "seed cotton" (cotton lint and seed) at ACRI, Narrabri, NSW, Australia.

Table 16. Total greenhouse gas emissions and yield from each farm and scenario.

Farm and scenario	Total emissions per tonne of produce (kg CO_2-e)	Yield (t/ha)
NSW DPI gross margin (irrigated cotton)	468	5.3
ACRI (irrigated cotton)	355	5.3
Breeza Station (irrigated cotton)	217	6.8
NSW DPI gross margin (dryland cotton)	300	2.4
Rossmar Park (dryland cotton)	385	3.4
NSW DPI gross margin (irrigated corn)	334	10
ACRI (irrigated corn)	308	10
Auscott Narrabri (irrigated corn)	335	10

For both dryland and irrigated cotton, GHG emissions averaged 345 kg CO_2-e per tonne cotton as lint and seed. Emissions from dryland and irrigated cotton were similar because although the dryland crop had no emissions from irrigation, the yields were also nearly half that of the irrigated yield. There is a strong relationship between inputs and yields i.e., more input is divided by a higher yield so that the LCAs equal out to some extent. Breeza Station had the lowest emissions (216 kg CO_2-e per tonne) because it had the highest irrigated cotton yields (6.83 tonnes) with similar agricultural inputs, giving it higher efficiencies.

The greenhouse gas emissions from the production of tonne kg of corn on-farm averaged around 325 kg CO_2-e per tonne corn. The emissions profile for irrigated cotton grown in rotation included N_2O directly from fertilisers (35.3%), production of fertilisers (14%), CO_2 emissions from the use of nitrogenous fertilisers (11.6%), N_2O emissions indirectly via leaching (7.2%), N_2O emissions via volatilisation and indirectly from fertiliser re-deposition (3.8%), CO_2 emissions from on-farm combustion (7.8%) and irrigation (9.2%). Emissions from water pumping accounted for only 10% of emissions, and total diesel fuel use (including for water pumping) accounted for 25% of emissions for irrigated cotton. The emissions profiles were dominated by the production and use of synthetic nitrogenous fertilisers, at 72% for cotton and 65% for corn. The alkaline grey Vertosols on which cotton and corn is predominately grown, tend to use nitrogen fertiliser inefficiently, due largely to nitrogen loss (commonly 50 - 100 kg N/ha) through denitrification. The high water holding capacity soil is ideal for growing cotton and corn, but it is also ideal for denitrification and its associated losses of N_2O.

The two main contributors of GHG emissions in a typical U.S cotton field were irrigation, approximately 31% (175 kg CO_2-e/ha), and N_2O emissions from the soil approximately 22% (120 kg CO_2-e/ha). The energy stored in the cotton seeds was approximately equivalent to 2250 kg CO_2-e/ton of lint, which was claimed to be larger than the 1800 kg CO_2-e/ton of lint emissions due to production, growing and ginning. If this was taken into account in this assessment, the oil which was produced from the cotton seed could potentially give the cotton lifecycle a positive energy balance.

In summary, greenhouse gas emissions from the production of 1 tonne of "seed cotton" (cotton lint and seed) on-farm average 345 kg CO_2-e from both irrigated and dryland cotton crops, and from the production of 1 tonne of irrigated corn was 325 kg CO_2-e. The emissions are dominated by the production and use of nitrogenous fertilisers.

6.2.3 Greenhouse gas emissions from soil

Green house gas samples were taken from 150mm diameter static chambers (0.24 m^2) over a two hour incubation period with monitoring conducted at regular intervals, triggered by key events in the system such as slashing/incorporation, irrigation and fertiliser application (Figs. 10-11). However, fertiliser application combined with high soil moisture is seen as the dominant driver of nitrous oxide generation. For example, application of fertiliser in Field C1 on 12th December 2012 resulted in a significant nitrous oxide flux, when measured at the irrigation of 18th December 2012. Methane was not detected in significant quantities in any of the sampling events, and so results are not included.

Carbon dioxide was once again the dominant greenhouse gas generated in the system. Nitrous oxide flux was quite low, and extremely variable. This is acknowledged as a problem in the field[1]. A significantly increased sampling campaign is required to obtain a clear picture of total greenhouse gas emissions for these systems.

It should be noted that the static chamber method of greenhouse gas measurement is suitable for the comparison of treatments, but is not appropriate for quantifying total emissions. Inherent variability in greenhouse gas generation, in particular nitrous oxide, remains problematic, but this is real variability and cannot be avoided. The research team at Wollongbar are currently using an automated sampling and analysis system.

A lack of temporal replication, typical of manual green house gas sampling techniques makes interpretation of results difficult. Previous laboratory work by the author has shown that spikes in emissions, particularly of N_2O, (but also CO_2, such as during urea hydrolysis) can be very rapid, and brief. As such, these events can easily be missed with this sampling regime.

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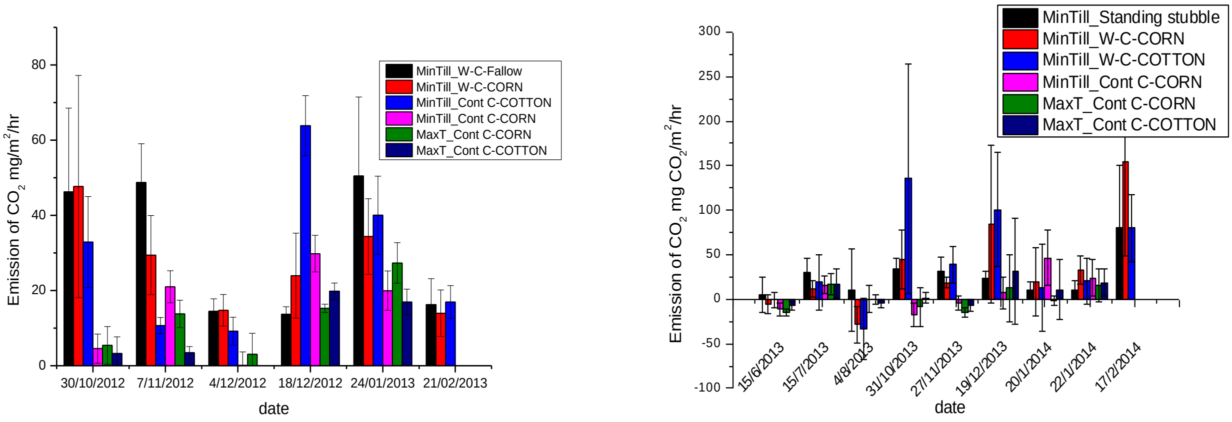
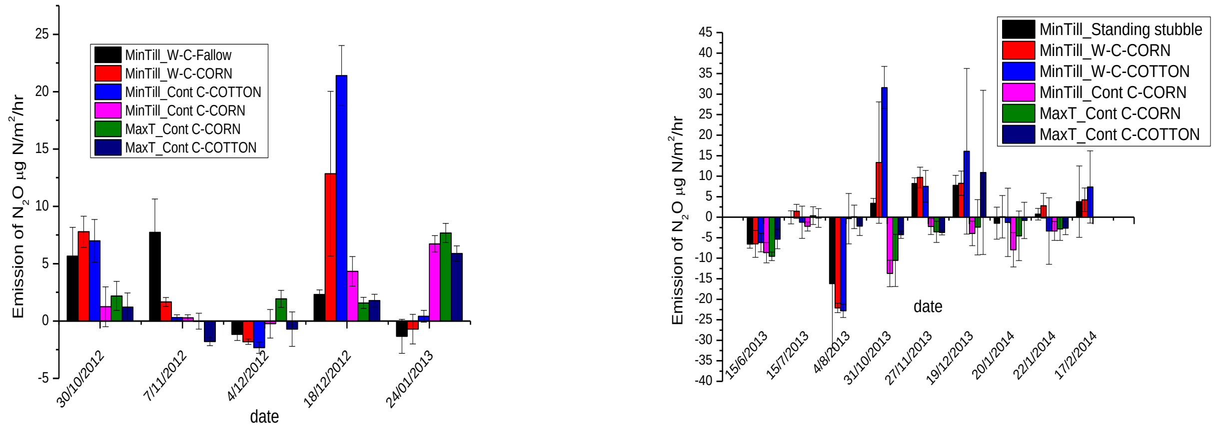
[1] S.G. Morris , S.W.L. Kimber , P. Grace , L. Van Zwieten (2013) Improving the statistical preparation for measuring soil N2O flux by closed chamber Science of the Total Environment 465 , 166–172



(a) Carbon dioxide emissions, 2012-13. All treatments under cotton

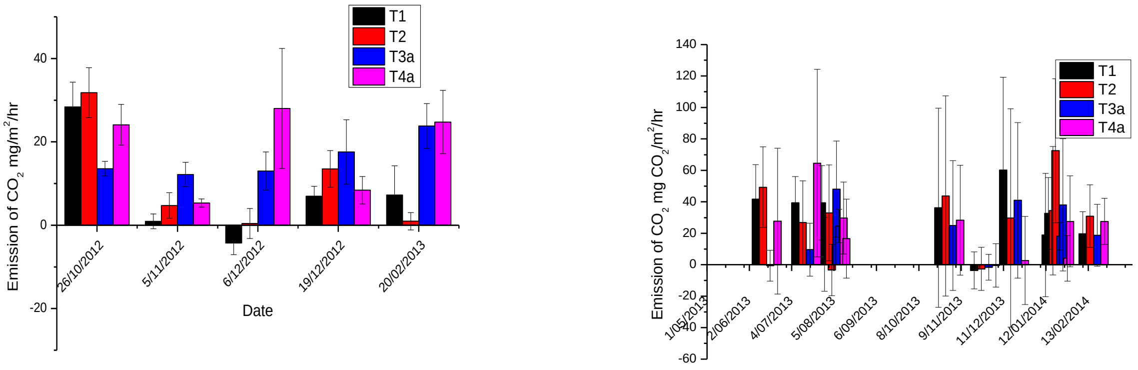
(b) Carbon dioxide emissions under corn and cotton 2013-14



(c) Nitrous oxide emissions, 2012-13. All treatments under cotton

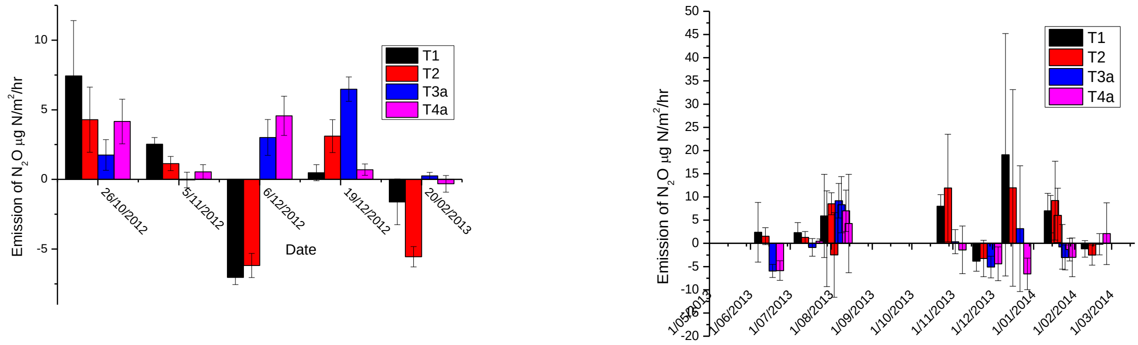
(d) Nitrous oxide emissions under corn and cotton 2013-14

Fig. 10. Carbon dioxide and nitrous oxide emissions in Field C1, ACRI, 2012-13 and 2013-14 growing seasons



(a) Carbon dioxide emissions, 2012-13 season

(b) Carbon dioxide emissions 2013-14 season



(c) Nitrous oxide emissions, 2012-13 season

(d) Nitrous oxide emissions 2013-14 season

Fig. 11. Carbon dioxide and nitrous oxide emissions in Field D1, ACRI, 2012-13 and 2013-14 growing seasons. T1, Cotton-vetch-cotton (2012-13) fb. Cotton-oats-cotton (2013-14); T1, Cotton-winter fallow-cotton; T3. Cotton-wheat, wheat stubble incorporated; T4, Cotton-wheat-vetch, standing wheat stubble

6.3 Cropping systems and soil quality

"Soil quality" in this section refers primarily to soil physical and chemical properties including soil carbon concentration. A limited number of measurements were conducted on soil biology by various collaborators.

6.3.1 Managing rotation crop stubble in irrigated cotton systems

Results in this section relate to the cotton-wheat and cotton-vetch cropping systems experiment in Field D1 at ACRI (experiment 5.1.2.1), gypsum x standing wheat stubble experiment at "Federation Farm", near Narrabri (Experiment 5.1.2.2), and the comparison of cotton-corn (stubble burnt/incorporated) with cotton-wheat (standing wheat stubble/no-tillage "New Haven", Narromine (Experiment 5.1.2.3).

At "New Haven", Narromine (Table 15), significant differences were absent between the plots sown with corn and wheat in 2008. The absence of differences between the rotations differs from most other sites reported in this report, and may be related to the burning of the corn residues in 2008.

Except for nitrate-N, and SOC and exchangeable K concentrations, values of other soil chemical properties generally increased with depth but were affected by factors such as presence of a crop and length of fallow (Tables 17, 19-24). Key points were:

- Nitrate-N was influenced by fertiliser application (before cotton) and the presence of vetch (i.e. a legume) or wheat in the rotations. Hence, surface concentrations of nitrate-N were higher where N fertiliser was applied (cotton in cotton-wheat, cotton-cotton) and where legume had been sown. Between cotton-vetch and cotton-wheat-vetch, N values were lower in the latter, and may have been due to a ~4.5 month fallow in the latter, which may have facilitated N leaching and volatilisation. Lowest values occurred in the surface where a wheat crop was present. At depth, values were higher in rotations that include wheat and where sampling was preceded by a fallow. This highest nitrate-N values at depth and to a deeper depth were observed in the cotton plots in the cotton-wheat rotation, which had been preceded by a 11 month fallow. This treatment was also noted to have the highest drainage[1].

  The responses during 2013-14 were somewhat anomalous as the higher values observed with legumes were absent during this year. This may be related two factors: the dry winter and spring may have resulted in little decomposition of vetch crop residues, hence limiting nitrate-N concentrations in the soil; and the drought-affected wheat may have ensured that N fertiliser uptake was restricted by the wheat, thus resulting in relatively higher concentrations of nitrate-N. In addition, the absence of spring and low winter rainfall may have resulted in very low leaching of salts and nutrients, thus contracting with results obtained in wet years.

- Evidence of leaching was present also with respect to electrical conductivity, Cl and ESP profiles, and similar trends to the nitrates were observed in the subsoil. These differences were more pronounced in years with above average rainfall. Treatments such as conventional tillage, which has lower drainage rates because of fewer preferential flow systems, tended to have higher Cl, ESP and $EC_{1:5}$ than in minimum-tilled treatments.

- SOC concentration in beds was higher with minimum tillage than with conventional tillage.

- As noted in a previous chapter, in a year when rainfall was average or wet surface SOC concentrations tended to be were highest where a wheat crop was followed by vetch. In other words, decreasing length of fallow was strongly related to increases in SOC concentrations in

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[1] Hulugalle, N.R., Weaver, T.B., and Finlay, L.A. (2012). Soil water storage, drainage and leaching in four irrigated cotton-based cropping systems sown in a Vertisol with subsoil sodicity. *Soil Research*, **50**, 652-663.

the surface. It should be noted that variations in climate appeared to have a large influence whether increases in SOC were statistically significant. Differences among rotations in other depths were not significant. In a very dry year, there were no differences among cropping systems. Presumably this was due to a combination of reduced crop growth and low decomposition rates of the crop residues.

- Incorporation of wheat stubble with an Aer-way cultivator at "Federation Farm" did not result in any significant differences in soil properties relative to standing wheat stubble. This confirms previous observations at this site and suggests that soil quality can be maintained in Vertosols with shallow cultivation. Presumably, the strong shrink-swell capability inherent in Vertosols and thus, rapid stabilisation of surface aggregates, contributes to such a response. Use of an implement such as an Aer-way cultivator to incorporate wheat stubble offers some advantages over that of standing wheat stubble with respect to farm operations such as weed management (i.e. managing resistance to herbicides) and fertiliser application (i.e. reducing volatilisation losses).

6.3.2 Including corn in the rotation

Results in this section relate to the on-farm sampling conducted on paired sites (corn vs. cotton) (Experiment 5.1.1.2), split-field experiment at Narromine (Experiment 5.1.2.3) and the tillage rotation experiment at ACRI (Experiment 5.1.1.1).

As noted in the previous section, significant differences were absent at "New Haven", Narromine, between the plots sown with corn and wheat in 2008. The absence of differences between the rotations differs from most other sites reported in this report, and may be related to the burning of the corn residues in 2008 (Table 17).

Soil organic carbon concentration was higher in the surface 10 cm after corn than after cotton (Table 18) in the on-farm paired sites study (experiment 5.1.1.2). Exchangeable cation (Ca, Mg, K and Na) concentrations and $EC_{1:5}$ were, however, higher after cotton than after corn. Presumably this reflects the greater biomass and grain production, and consequently, greater nutrient uptake by the corn in comparison with the cotton. A summary of the soil properties in the individual farms that were sampled are reported in Appendix 5.

Prior to sowing the corn rotation crops in 2011 in the tillage rotation experiment in Field C1 at ACRI, $EC_{1:5}$, soil organic carbon, ESI and exchangeable K were higher and exchangeable Na and ESP lower in the cotton-wheat wheat rotation than in the conventionally-tilled continuous cotton in the 0-15 cm depth (Table 19). The higher $EC_{1:5}$ was probably caused by higher nutrient levels under the cotton-wheat rotation rather than higher salinity. Exchangeable Na, ESP and $EC_{1:5}$ were lowest in all depths under the cotton-wheat. This is a reflection of the higher drainage and leaching that occurs in this system, and has been documented in previous studies conducted at this site. Soil properties measured after the corn crop and before the following cotton (October 2012) indicated that minimum tilled cotton-wheat rotation had a beneficial effect on EC1:5, SOC, exchangeable Ca, Mg and Na, and Na-related sodicity indices with strong interactions with depth interval (Table 20). Corn also improved exchangeable Ca, K and had beneficial effects on sodicity with significant variations in the intensity of these changes with depth. It should be noted that these differences were relatively small and the consequent impact on soil behaviour is likely to be minimal in the short-term. Longer-term impacts may, however, be more discernible.

Table 17. Average soil properties in the 0-10 cm and 10-30 cm depths under cotton-wheat (*in situ* mulch) and cotton-corn (burnt) rotations, “New Haven”, Narromine, 20011, 2012 and 2013. Significant differences among treatments were not present.

Rotation crop	Depth (cm)	pH	EC$_{1:5}$ (ds/m)	Soil organ C (g/100g	Exch. Ca (cmol$_c$/kg)	Exch. Mg (cmol$_c$/kg)	Exch. K (cmol$_c$/kg)	Exch. Na (cmol$_c$/kg)	ESP	ESI
Cotton-Corn	0-10	6.8	0.18	1.14	16.3	6.7	2.0	0.8	3.1	0.07
(burnt)	10-30	6.9	0.23	0.94	17.2	7.6	1.5	1.4	4.9	0.05
Cotton-wheat	0-10	7.1	0.19	1.41	18.0	6.1	2.2	0.6	2.3	0.08
(standing stubble)	10-30	7.1	0.25	1.31	17.5	6.1	1.8	0.9	3.3	0.09
SEM	0-10	0.24	0.033	0.089	0.52	0.46	0.29	0.22	0.90	0.03
	10-30	0.27	0.14	0.19	0.69	1.03	0.37	0.20	0.75	0.06

Table 18. Effect of corn rotation crop and sampling depth on soil properties. Sampled during September 2011, 2012 and 2013 from adjacent or split fields sown with corn or cotton on cotton farms located in the Namoi and Macquarie valleys, MIA, Border rivers and Darling Downs. SED, standard error of the difference between means; n.s., non-significant, ESP, exchangeable sodium percentage, ESI, electrochemical stability index.

Rotation crop	Depth (cm)	pH (0.01 M CaCl$_2$)	EC$_{1:5}$ (ds/m)	Soil organic C (g/100g)	Bulk density (Mg/m^3)	Exch. Ca (cmol$_c$/kg)	Exch. Mg (cmol$_c$/kg)	Exch. K (cmol$_c$/kg)	Exch. Na (cmol$_c$/kg)	ESP	ESI
Corn	0-10	6.6	0.36	1.18	1.55	17.1	10.4	1.28	0.73	2.5	0.08
	10-30	6.5	0.36	0.95	1.81	17.5	10.9	0.82	1.19	3.7	0.05
Cotton	0-10	6.6	0.40	1.09	1.54	19.0	10.7	1.36	0.89	2.7	0.09
	10-30	6.6	0.38	0.93	1.81	18.8	11.1	0.98	1.33	3.9	0.06
SED			0.010	0.025	0.014	0.46	0.17	0.035	0.066	0.15	0.008
P<											
Rotation crops (R)		n.s.	0.001	0.01	n.s.	0.001	0.05	0.001	0.01	n.s.	n.s.
Depth (D)		0.01	n.s.	0.001	0.001	n.s.	0.001	0.001	0.001	0.001	0.001
R x D		n.s.	n.s.	0.05	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

Table 19. Effect of historical tillage/rotation combinations, on soil chemical properties, Field C1, ACRI, Narrabri, October 2011. *, ** and *** indicate that means differed significantly at $P < 0.05$, $P < 0.01$ and $P < 0.001$, respectively. $EC_{1:5}$, electrical conductivity of 1:5 soil: water suspension; SOC, soil organic carbon, ESP, exchangeable sodium percentage; ESI, electrochemical stability index; pH was measured in a 1:5 soil: 0.01M $CaCl_2$ suspension. N.B. Corn sown during 2011-12 season.

Depth (cm)	**Historical tillage and rotation**	**pH ($CaCl_2$)**	**$EC_{1:5}$ (dS/m)**	**SOC (g/100g)**	**Exchangeable cations (cmol/kg)**				**ESP**	**ESI**
					Ca	**Mg**	**K**	**Na**		
0-15	Conventional till/continuous cotton	7.0	0.10	0.89	23.0	11.3	1.7	0.8	2.1	0.05
	Minimum tillage/continuous cotton	6.9	0.12	1.02	21.4	8.8	1.8	0.6	1.8	0.07
	Minimum tillage/cotton-wheat	6.9	0.18	1.08	21.8	9.2	1.9	0.5	1.5	0.13
15-30	Conventional till/continuous cotton	7.1	0.15	0.81	22.4	12.0	1.4	1.0	2.7	0.05
	Minimum tillage/continuous cotton	7.0	0.13	0.76	21.5	10.5	1.3	0.8	2.4	0.05
	Minimum tillage/cotton-wheat	7.1	0.10	0.78	22.0	10.3	1.3	0.6	1.9	0.06
30-45	Conventional till/continuous cotton	7.1	0.12	0.65	21.9	13.1	1.0	1.7	4.5	0.03
	Minimum tillage/continuous cotton	7.1	0.14	0.62	21.1	12.0	0.9	1.3	3.6	0.04
	Minimum tillage/cotton-wheat	7.1	0.09	0.63	21.9	12.6	0.9	0.9	2.6	0.04
45-60	Conventional till/continuous cotton	7.2	0.14	0.63	21.0	13.7	0.9	2.4	6.3	0.02
	Minimum tillage/continuous cotton	7.2	0.15	0.62	20.5	12.7	0.8	1.9	5.3	0.03
	Minimum tillage/cotton-wheat	7.1	0.09	0.68	21.9	13.3	0.9	1.3	3.6	0.03
60-120	Conventional till/continuous cotton	7.2	0.19	0.56	19.9	14.1	0.9	3.1	8.1	0.03
	Minimum tillage/continuous cotton	7.2	0.25	0.46	18.2	14.8	0.8	2.7	7.2	0.04
	Minimum tillage/cotton-wheat	7.2	0.14	0.51	19.7	14.4	0.9	2.2	6.0	0.02
	SEM									
	Historical tillage/rotation (H)	0.03	0.004*	0.029	0.26	0.37	0.06	0.04*	0.05**	0.005
	Depth (D)	0.02***	0.007***	0.021***	0.19***	0.34***	0.02***	0.09***	0.23***	0.005***
	H x D	0.03	0.013***	0.036*	0.34	0.59	0.04*	0.16	0.40	0.008***

Table 20. Effect of historical tillage/rotation combinations, on soil chemical properties, Field C1, ACRI, Narrabri, October 2012. *, ** and *** indicate that means differed significantly at $P < 0.05$, $P < 0.01$ and $P < 0.001$, respectively. $EC_{1:5}$, electrical conductivity of 1:5 soil: water suspension; SOC, soil organic carbon, ESP, exchangeable sodium percentage; ESI, electrochemical stability index; pH was measured in a 1:5 soil: 0.01M $CaCl_2$ suspension. N.B. Corn sown during 2011-12 season.

Depth (cm)	**Historical tillage and rotation**	**+/- corn**	**pH ($CaCl_2$)**	**$EC_{1:5}$ (dS/m)**	**SOC (g/100g)**	**Exchangeable cations (cmol/kg)**				**ESP**	**ESI**
						Ca	**Mg**	**K**	**Na**		
0-15	Conventional till/continuous cotton	+corn	7.2	0.10	0.80	23.2	8.4	2.7	0.5	1.3	0.08
	Minimum tillage/continuous cotton		6.8	0.11	0.91	23.7	11.5	2.5	0.9	1.8	0.07
	Minimum tillage/cotton-wheat		6.8	0.10	0.95	22.8	12.0	2.4	1.2	1.8	0.06
	Conventional till/continuous cotton	-corn	7.1	0.12	0.83	23.1	8.2	2.3	1.6	1.4	0.09
	Minimum tillage/continuous cotton		6.8	0.12	0.97	22.5	9.7	2.4	2.5	1.6	0.08
	Minimum tillage/cotton-wheat		6.8	0.14	0.95	20.0	9.0	2.6	0.5	1.5	0.10
15-30	Conventional till/continuous cotton	+corn	7.4	0.12	0.70	23.9	9.7	1.5	0.7	2.1	0.06
	Minimum tillage/continuous cotton		7.1	0.12	0.72	24.9	12.0	1.7	1.1	3.0	0.04
	Minimum tillage/cotton-wheat		7.3	0.10	0.73	22.4	12.4	1.3	1.3	3.8	0.03
	Conventional till/continuous cotton	-corn	7.4	0.13	0.63	23.4	9.2	1.5	2.1	2.6	0.05
	Minimum tillage/continuous cotton		7.2	0.12	0.70	22.7	10.6	1.5	0.6	2.9	0.04
	Minimum tillage/cotton-wheat		7.4	0.11	0.67	20.9	10.1	1.3	1.1	2.6	0.04
30-45	Conventional till/continuous cotton	+corn	7.6	0.10	0.60	23.6	10.9	1.1	1.6	2.9	0.04
	Minimum tillage/continuous cotton		7.7	0.10	0.65	24.0	13.7	1.3	1.9	4.6	0.02
	Minimum tillage/cotton-wheat		7.6	0.09	0.65	22.6	13.2	1.1	2.4	5.8	0.02
	Conventional till/continuous cotton	-corn	7.6	0.11	0.54	23.0	10.4	1.2	0.7	3.4	0.04
	Minimum tillage/continuous cotton		7.3	0.10	0.60	22.2	11.2	1.0	1.2	4.3	0.02
	Minimum tillage/cotton-wheat		7.6	0.09	0.66	24.0	13.8	1.2	1.9	3.6	0.03
45-60	Conventional till/continuous cotton	+corn	7.6	0.13	0.63	23.6	11.9	1.1	2.4	3.5	0.04
	Minimum tillage/continuous cotton		7.6	0.14	0.66	22.4	14.0	1.2	3.5	6.0	0.03
	Minimum tillage/cotton-wheat		7.6	0.11	0.67	19.9	13.2	1.1	0.5	8.8	0.01
	Conventional till/continuous cotton	-corn	7.7	0.14	0.55	22.4	11.1	1.2	0.9	4.4	0.03
	Minimum tillage/continuous cotton		7.6	0.13	0.66	21.2	12.8	1.1	1.4	5.2	0.02
	Minimum tillage/cotton-wheat		7.7	0.12	0.63	20.0	11.9	0.9	1.8	5.1	0.03
60-120	Conventional till/continuous cotton	+corn	7.6	0.21	0.60	19.9	13.6	1.1	2.4	5.6	0.04

Minimum tillage/continuous cotton		7.4	0.23	0.67	20.9	14.5	1.3	0.7	8.7	0.03
Minimum tillage/cotton-wheat		7.6	0.16	0.72	18.4	14.0	1.1	1.4	10.5	0.02
Conventional till/continuous cotton	-corn	7.7	0.26	0.47	20.6	12.8	1.1	2.3	6.8	0.04
Minimum tillage/continuous cotton		7.6	0.27	0.56	20.3	12.8	1.2	3.3	6.6	0.04
Minimum tillage/cotton-wheat		7.6	0.17	0.60	17.8	12.8	0.9	3.9	7.2	0.02
SEM										
Historical tillage/rotation (H)		0.06	0.005*	0.015*	0.42*	0.31*	0.05	0.11*	0.23**	0.002**
+/-corn (C)		0.02	0.006	0.018	0.29	0.24**	0.03	0.12*	0.29	0.002*
H x C		0.03	0.010	0.031	0.50	0.42	0.07	0.20*	0.50	0.004
Depth (D)		0.03***	0.005***	0.014***	0.27***	0.23***	0.03***	0.06***	0.14***	0.002***
H x D		0.06	0.009**	0.025	0.47*	0.40*	0.07	0.10**	0.24***	0.003
C x D		0.05	0.007	0.020	0.39	0.33	0.05	0.08**	0.20**	0.003**
H x C x D		0.08	0.013	0.035	0.68	0.56	0.08**	0.14***	0.35**	0.005

Table 21. Soil properties under cotton/vetch/wheat rotations, Field D1, ACRI, October 2011. Cotton stubble was incorporated but rotation stubble was managed as indicated in table. Sampled at time of sowing cotton. *, ** and *** indicate that means differed significantly at $P < 0.05$, $P < 0.01$ and $P < 0.001$, respectively. EC$_{1:5}$, electrical conductivity of 1:5 soil: water suspension; SOC, soil organic carbon, ESP, exchangeable sodium percentage. pH was measured in a 1:5 soil: 0.01M CaCl$_2$ suspension.

Depth (cm)	**Rotation**	**Rotation stubble management**	**pH (CaCl$_2$)**	**EC$_{1:5}$ (dS/m)**	**SOC (g/100g)**	**Nitrate-N (mg/kg)**
0-10	Cotton-vetch	*In situ mulch*	6.9	0.12	1.18	6.2
	Continuous cotton		7.3	0.14	1.01	3.9
	Cotton-wheat (incorporated), cotton phase	Incorporated	7.1	0.09	1.03	2.3
	Cotton-wheat (incorporated), rotation phase	Incorporated	7.0	0.10	1.09	0.8
	Cotton-wheat (*in situ* mulch)-vetch, cotton phase	*In situ mulch*	6.8	0.10	1.09	13.8
	Cotton-wheat (*in situ* mulch)-vetch, rotation phase	*In situ mulch*	7.0	0.11	1.21	2.1
10-30	Cotton-vetch	*In situ mulch*	7.3	0.13	0.53	4.4
	Continuous cotton		7.1	0.13	0.55	4.7
	Cotton-wheat (incorporated), cotton phase	Incorporated	7.2	0.14	0.53	8.1
	Cotton-wheat (incorporated), rotation phase	Incorporated	7.3	0.10	0.57	0.7
	Cotton-wheat (*in situ* mulch)-vetch, cotton phase	*In situ mulch*	7.1	0.10	0.56	5.5
	Cotton-wheat (*in situ* mulch)-vetch, rotation phase	*In situ mulch*	7.3	0.09	0.57	0.3
30-60	Cotton-vetch	*In situ mulch*	7.4	0.17	0.42	2.4
	Continuous cotton		7.3	0.14	0.41	2.8
	Cotton-wheat (incorporated), cotton phase	Incorporated	7.3	0.12	0.44	4.9
	Cotton-wheat (incorporated), rotation phase	Incorporated	7.2	0.13	0.46	0.3
	Cotton-wheat (*in situ* mulch)-vetch, cotton phase	*In situ mulch*	7.2	0.12	0.47	3.6
	Cotton-wheat (*in situ* mulch)-vetch, rotation phase	*In situ mulch*	7.4	0.12	0.42	0.2
60-120	Cotton-vetch	*In situ mulch*	7.4	0.19	0.44	2.9
	Continuous cotton		7.4	0.22	0.34	0.5
	Cotton-wheat (incorporated), cotton phase	Incorporated	7.3	0.15	0.38	1.6
	Cotton-wheat (incorporated), rotation phase	Incorporated	7.4	0.18	0.34	1.0
	Cotton-wheat (*in situ* mulch)-vetch, cotton phase	*In situ mulch*	7.3	0.17	0.42	1.2
	Cotton-wheat (*in situ* mulch)-vetch, rotation phase	*In situ mulch*	7.3	0.18	0.33	0.2
SEM	Rotations (R)		0.05	0.007*	0.032	0.81***
	Depths (D)		0.02***	0.009***	0.017***	0.45***
	R x D		0.06**	0.22	0.041	1.11***

Table 22. Soil properties under cotton/vetch/wheat rotations, Field D1, ACRI, October 2012. Cotton stubble was incorporated but rotation stubble was managed as indicated in table. Sampled at time of sowing cotton. *, ** and *** indicate that means differed significantly at $P < 0.05$, $P < 0.01$ and $P < 0.001$, respectively. $EC_{1:5}$, electrical conductivity of 1:5 soil: water suspension; SOC, soil organic carbon, ESP, exchangeable sodium percentage. pH was measured in a 1:5 soil: 0.01M $CaCl_2$ suspension.

Depth (cm)	**Rotation**	**Rotation stubbl management**	**pH ($CaCl_2$)**	**$EC_{1:5}$ (dS/m)**	**SOC (g/100g)**	**Nitrate-N (mg/kg)**	**Exchangeable cations (cmol/kg)**				**ESP**
							Ca	**Mg**	**K**	**Na**	
0-10	Cotton-vetch	*In situ mulch*	6.5	0.22	1.31	13.6	21.2	12.4	2.5	0.6	1.7
	Continuous cotton		6.7	0.16	1.17	13.0	23.7	11.9	2.4	0.6	1.6
	Cotton-wheat (incorporated), cotton phase	Incorporated	6.5	0.16	1.35	12.7	22.1	11.2	2.5	0.5	1.4
	Cotton-wheat (incorporated), rotation phase	Incorporated	6.6	0.21	1.35	22.0	22.1	10.7	2.6	0.6	1.6
	Cotton-wheat (*in situ* mulch)-vetch, cotton phase	*In situ mulch*	6.5	0.20	1.68	18.3	22.5	12.9	3.1	0.5	1.4
	Cotton-wheat (*in situ* mulch)-vetch, rotation phas	*In situ mulch*	6.5	0.22	1.64	16.6	21.7	11.2	2.9	0.6	1.6
10-30	Cotton-vetch	*In situ mulch*	7.2	0.14	0.69	3.9	22.4	14.6	1.0	1.7	4.3
	Continuous cotton		7.2	0.12	0.69	3.8	22.4	12.2	1.0	1.5	4.0
	Cotton-wheat (incorporated), cotton phase	Incorporated	7.1	0.12	0.67	6.6	22.4	12.5	1.0	1.2	3.3
	Cotton-wheat (incorporated), rotation phase	Incorporated	7.2	0.12	0.73	0.8	21.5	14.0	1.0	1.8	4.7
	Cotton-wheat (*in situ* mulch)-vetch, cotton phase	*In situ mulch*	7.2	0.13	0.76	3.9	22.5	14.2	1.1	1.3	3.3
	Cotton-wheat (*in situ* mulch)-vetch, rotation phas	*In situ mulch*	7.1	0.12	0.68	1.7	23.2	13.6	1.1	1.3	3.3
30-60	Cotton-vetch	*In situ mulch*	7.3	0.19	0.56	2.2	18.8	14.6	0.8	3.2	8.6
	Continuous cotton		7.3	0.17	0.56	2.2	20.7	14.0	0.8	2.5	6.5
	Cotton-wheat (incorporated), cotton phase	Incorporated	7.3	0.15	0.51	3.8	20.4	15.2	0.8	2.4	6.0
	Cotton-wheat (incorporated), rotation phase	Incorporated	7.3	0.16	0.51	0.3	20.3	14.0	0.8	2.2	5.8
	Cotton-wheat (*in situ* mulch)-vetch, cotton phase	*In situ mulch*	7.3	0.15	0.54	2.1	20.4	15.2	0.9	2.6	6.6
	Cotton-wheat (*in situ* mulch)-vetch, rotation phas	*In situ mulch*	7.2	0.14	0.55	0.2	20.3	14.0	0.7	2.4	6.4
60-120	Cotton-vetch	*In situ mulch*	7.1	0.25	0.45	1.2	16.4	17.0	0.8	4.6	11.8
	Continuous cotton		7.0	0.22	0.46	1.3	17.2	15.8	0.9	3.7	9.7
	Cotton-wheat (incorporated), cotton phase	Incorporated	7.1	0.22	0.47	1.7	17.3	16.5	0.9	3.7	9.5
	Cotton-wheat (incorporated), rotation phase	Incorporated	7.0	0.23	0.43	0.3	16.2	15.6	0.7	3.9	10.6
	Cotton-wheat (*in situ* mulch)-vetch, cotton phase	*In situ mulch*	7.1	0.22	0.47	0.8	16.8	16.4	0.9	4.2	10.7
	Cotton-wheat (*in situ* mulch)-vetch, rotation phas	*In situ mulch*	7.0	0.23	0.43	0.2	17.7	15.9	0.8	3.9	9.8
	Rotations (R)		0.02	0.008	0.025*	0.92	0.50	0.53	0.04**	0.14	0.34
SEM:	Depths (D)		0.02***	0.007**	0.019**	0.64***	0.29**	0.21**	0.03***	0.16***	0.35***
	R x D		0.05	0.010	0.047**	1.56*	0.50	0.51	0.08***	0.35	0.86

Table 23. Soil properties under cotton/vetch/wheat rotations, Field D1, ACRI, October 2013. Cotton stubble was incorporated but rotation stubble was managed as indicated in table. Sampled at time of sowing cotton. *, ** and *** indicate that means differed significantly at $P < 0.05$, $P < 0.01$ and $P < 0.001$, respectively. $EC_{1:5}$, electrical conductivity of 1:5 soil: water suspension; SOC, soil organic carbon, ESP, exchangeable sodium percentage. pH was measured in a 1:5 soil: 0.01M $CaCl_2$ suspension.

Depth (cm)	**Rotation**	**Rotation stubble management**	**pH ($CaCl_2$)**	**$EC_{1:5}$ (dS/m)**	**SOC (g/100g)**	**Nitrate-N (mg/kg)**	**Exchangeable cations (cmol/kg)**				**ESP**
							Ca	**Mg**	**K**	**Na**	
0-10	Cotton-oats	*In situ mulch*	7.1	0.23	1.16	13.6	21.5	13.5	1.7	0.9	2.3
	Continuous cotton		7.0	0.19	1.12	13.0	22.5	13.0	1.8	0.7	1.9
	Cotton-wheat (incorporated), cotton phase	Incorporated	6.9	0.12	1.09	22.0	21.4	12.5	1.8	0.6	1.5
	Cotton-wheat (incorporated), rotation phase	Incorporated	7.0	0.21	1.17	12.7	22.4	12.5	1.9	0.7	1.8
	Cotton-wheat (*in situ* mulch)-vetch, cotton phase	*In situ mulch*	6.8	0.16	1.11	16.6	21.2	12.2	1.7	0.5	1.4
	Cotton-wheat (*in situ* mulch)-vetch, rotation phase	*In situ mulch*	7.1	0.17	1.10	18.3	22.1	13.3	1.9	0.7	1.8
10-30	Cotton- oats	*In situ mulch*	7.3	0.14	0.67	3.9	21.1	14.3	0.7	1.7	4.5
	Continuous cotton		7.3	0.16	0.61	3.8	21.5	14.5	0.6	1.8	4.8
	Cotton-wheat (incorporated), cotton phase	Incorporated	7.1	0.12	0.63	0.8	21.0	13.6	0.7	1.2	3.2
	Cotton-wheat (incorporated), rotation phase	Incorporated	7.1	0.14	0.66	6.6	21.8	14.1	0.8	1.4	3.6
	Cotton-wheat (*in situ* mulch)-vetch, cotton phase	*In situ mulch*	7.2	0.09	0.64	1.7	21.9	13.8	0.7	1.2	3.3
	Cotton-wheat (*in situ* mulch)-vetch, rotation phase	*In situ mulch*	7.2	0.12	0.66	3.9	21.1	14.9	0.7	1.4	3.6
30-60	Cotton- oats	*In situ mulch*	7.4	0.18	0.66	2.2	19.3	16.7	0.5	3.3	8.1
	Continuous cotton		7.4	0.19	0.63	1.6	19.1	16.1	0.5	3.1	7.7
	Cotton-wheat (incorporated), cotton phase	Incorporated	7.3	0.12	0.60	0.3	20.0	15.6	0.5	2.4	6.0
	Cotton-wheat (incorporated), rotation phase	Incorporated	7.3	0.13	0.64	3.8	20.7	16.0	0.6	2.5	6.1
	Cotton-wheat (*in situ* mulch)-vetch, cotton phase	*In situ mulch*	7.3	0.13	0.67	0.3	19.2	15.4	0.5	2.7	7.1
	Cotton-wheat (*in situ* mulch)-vetch, rotation phase	*In situ mulch*	7.3	0.14	0.61	2.1	19.1	16.1	0.6	2.9	7.4
60-120	Cotton- oats	*In situ mulch*	7.5	0.28	0.56	1.2	15.4	16.6	0.7	5.0	13.2
	Continuous cotton		7.5	0.28	0.46	1.3	16.7	16.9	0.6	4.4	11.2
	Cotton-wheat (incorporated), cotton phase	Incorporated	7.4	0.21	0.49	0.3	15.9	16.4	0.6	4.0	10.5
	Cotton-wheat (incorporated), rotation phase	Incorporated	7.5	0.24	0.44	1.7	15.9	16.4	0.7	4.4	11.5
	Cotton-wheat (*in situ* mulch)-vetch, cotton phase	*In situ mulch*	7.4	0.20	0.53	0.2	16.7	15.3	0.6	3.6	9.9
	Cotton-wheat (*in situ* mulch)-vetch, rotation phase	*In situ mulch*	7.4	0.18	0.49	0.8	16.6	16.8	0.7	4.3	11.1
SEM	Rotations (R)		0.04	0.015*	0.025	0.92	0.33	0.30	0.03	0.17	0.42
	Depths (D)		0.02***	0.009***	0.019***	0.64***	0.26***	0.16***	0.04***	0.18***	0.42***
	R x D		0.06	0.022	0.047	1.57*	0.63	0.38	0.09	0.43	1.03

Table 24. Effect of wheat stubble incorporation with Aer-way cultivator, on soil chemical properties at Federation Farm, Narrabri, October 2011. *, ** and *** indicate that means differed significantly at $P < 0.05$, $P < 0.01$ and $P < 0.001$, respectively. $EC_{1:5}$, electrical conductivity of 1:5 soil: water suspension; SOC, soil organic carbon, ESP, exchangeable sodium percentage; ESI, electrochemical stability index; pH was measured in a 1:5 soil: 0.01M $CaCl_2$ suspension. N.B. Corn sown during 2011-12 season.

Depth (cm)	**Historical tillage and rotation**	**pH ($CaCl_2$)**	**$EC_{1:5}$ (dS/m)**	**SOC (g/100g)**	**Exchangeable cations (cmol/kg)**				**ESP**	**ESI**
					Ca	**Mg**	**K**	**Na**		
0-10	Stubble incorporation	7.2	0.14	1.03	20.8	10.8	2.0	3.1	8.3	0.02
	Standing wheat stubble	7.3	0.13	0.90	20.4	10.2	2.0	2.3	6.4	0.02
10-30	Stubble incorporation	7.4	0.18	0.53	18.2	13.1	1.0	5.1	13.6	0.01
	Standing wheat stubble	7.4	0.17	0.57	17.8	12.9	1.0	5.0	13.6	0.01
30-60	Stubble incorporation	7.4	0.25	0.46	16.7	14.6	0.8	5.7	15.0	0.02
	Standing wheat stubble	7.5	0.21	0.49	15.9	15.9	0.8	5.9	15.2	0.01
60-120	Stubble incorporation	7.5	0.39	0.36	15.2	17.6	0.8	5.7	14.4	0.03
	Standing wheat stubble	7.5	0.23	0.41	14.4	16.3	0.9	5.2	14.0	0.02
120-180	Stubble incorporation	7.5	0.27	0.31	14.5	18.1	1.0	6.3	15.7	0.02
	Standing wheat stubble	7.6	0.26	0.26	11.7	16.6	0.8	5.7	16.5	0.02
	SEM									
	Stubble incorporation (S)	0.05	0.013	0.036	0.24	0.62	0.02	0.52	1.02	0.0008
	Depth (D)	0.04***	0.030**	0.044***	0.34***	0.27***	0.07***	0.35***	0.81***	0.002***
	S x D	0.05	0.043	0.063	0.48	0.39*	0.10	0.50	1.15	0.003

6.3.3 Soil fauna

The mean numbers of soil fauna species trapped over the sampling period for the two cropping systems varied. There were significantly ($P < 0.001$) higher numbers of silken fungus beetle, antlike flower beetle, earwigs, rove beetles, thrips and wasp in cotton-cotton relative to cotton-wheat-vetch, but the reverse occurred with respect to ants, aphids, millipedes, weevils and flies (Fig. 12). There were generally more insects during summer than winter, and insect numbers increased over the season. Early-season arthropods consisted mainly of beetles followed by ants, wasps, thrips and mosquitoes (Fig. 13). The warmer conditions during spring and summer favoured arthropods build-up and, thus, total numbers of individual species increased in both treatments. Further work will be needed to confirm and specify the abundance of the soil fauna present and their importance to the structure and quality of the soil.

Assessment of wolf spider assemblages was performed at the same time by Dalila Rendon, a PhD candidate from Macquarie University. A summary of her findings is given in Appendix 6.

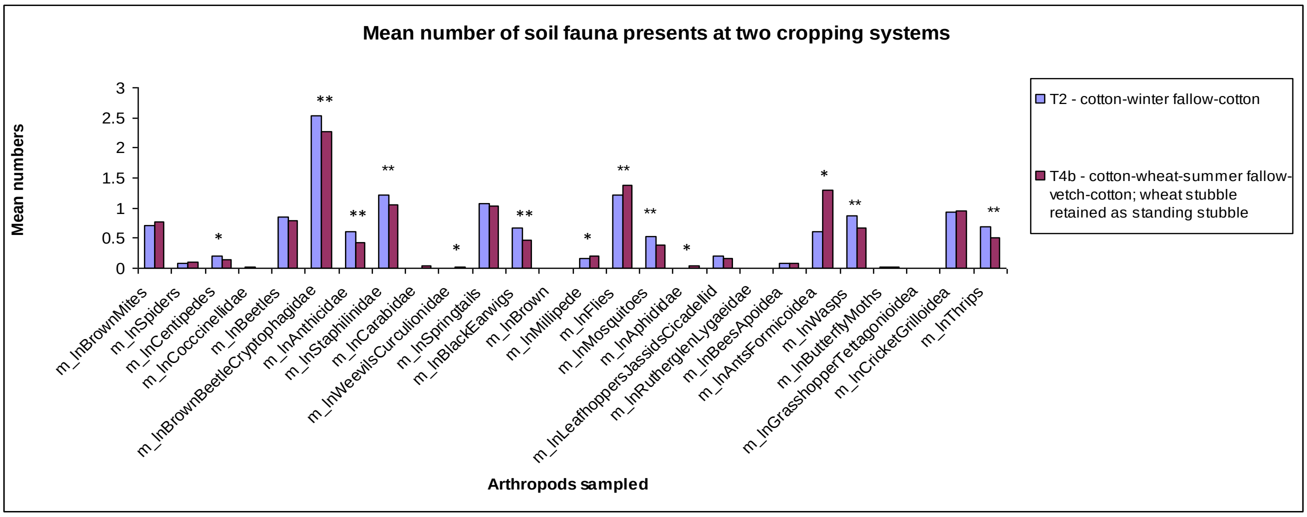

Fig 12. Soil fauna species present in two cropping systems at ACRI, 2011-2012

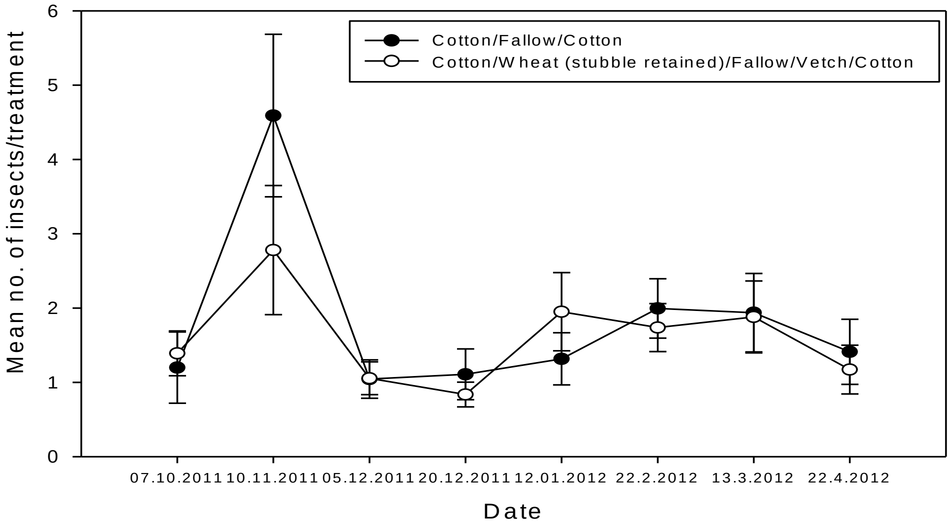

Fig.13. Mean total insects in pitfall traps for two different cropping systems during the cotton cropping season 2011-2012

6.3.4 Soil microflora

Samples of soil from Field C1 were provided to Dr. Nele Verhulst from the International Maize and Wheat Improvement Centre in Mexico (CIMMYT) and from Field D1 to Dr. V.V.S.R. Gupta[1] of CSIRO to assess the microbial ecology of the two experiments. No results have been received as yet.

6.4 Irrigation water quality

At ACRI irrigation water quality was generally alkaline, had a moderate SAR which at times exceeded the threshold (4.5) for structural deterioration[2], had moderate to high concentrations of Na, moderate concentrations Ca, K and Mg, and low concentrations of nitrate-N (Table 26). The values of nitrate-N are very much lower than those reported in previous reports from these sites. This may be because nitrate-N, which was previously analysed in the ACRI CSIRO laboratory, was analysed from 2010 onwards in NSW DPI's laboratory at Wollongbar, and may reflect the inter-laboratory variation or losses in N during transportation.

In comparison with ACRI, irrigation water (treated sewage effluent) at "Federation Farm" had very high SAR, EC_w, and soluble Cl concentration (Table 25). K concentration and pH_w were higher than at ACRI, but Ca and Mg were similar during 2010-11 and 2011-12 but lower during 2013-14. In spite of the relatively high EC_w, the very high SAR suggests that soil structural stability may be poor in this site. Previous measurements of dispersion index in this site have shown that values were of the order of 12-20. In comparison, during the September 2001 (one year after irrigation with treated sewage effluent commenced) it was 8 in the 0-10 cm depth, 4 in the 10-30 cm depth, 3 in the 30-60 cm depth, and 6 in the 60-120 cm depth. Irrigation with treated sewage effluent may, therefore, have increased structural instability, and thus internal water redistribution within the soil profile at "Federation Farm".

Table 25. Irrigation water quality July 2011-June 2012, and July 2013-june 2014 at "Federation Farm", Narrabri. SAR, sodium adsorption ratio. DOC, dissolved organic carbon; TOC, total organic carbon

Season	**Date**	**Cl**	**K**	**Ca**	**Mg**	**Na**	**NO_3-**	**DOC**	**TOC**	**SAR**	**pH_w**	**EC_w**
						(mg/L)						**(dS/m)**
2011-12	1/1/2012	111	2.5	6.7	1.6	85.2	<0.02	18	19	7.5	10.0	1.09
Average seasonal sum (kg/ha)		111	2.5	6.7	1.6	85	<0.02	18	19			
2013-14	22/10/2013	117	19.2	45.0	17.9	486.4	12.4	18.0	18.5	15.3	8.2	0.72
	14/11/2013	138	25.5	29.0	16.3	406.7	7.2	14.5	15.0	14.7	8.3	0.77
	20/12/2013	141	25.6	23.5	15.1	546.0	3.0	13.5	15.0	21.0	8.4	0.73
	8/01/2014	161	34.0	14.7	13.4	443.2	0.1	18.0	18.5	20.6	8.8	1.01
	17/01/2014	143	23.7	14.2	14.2	177.6	0.6	15.0	16.0	7.8	8.5	0.85
	31/01/2014	160	18.0	17.0	11.4	481.0	0.4	21.0	22.0	21.7	8.3	0.83
Average seasonal sum (kg/ha)		859	116	143	88	2541	23.7	100	105			

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[1] CRDC project CSE 1401

[2] Maas, S., and Chapman, V. 2005. Water and soil quality, Australian Cotton Industry BMP. http://WWW.cottoncrc.org.au/files/ac52fc81-494a-420a-b398-994d00a50998/ISWQ_BMP.pdf

Table 26. Irrigation water quality 2011-2014 at ACRI (Fields C1 and D1), Narrabri. SAR, sodium adsorption ratio. DOC, dissolved organic carbon; TOC, total organic carbon

Season	Site	Date	Cl	K	Ca	Mg	Na	Nitrate-N	DOC	TOC	SAR	pH_w	EC_w
							(mg/L)						(dS/m)
2011-12	Tillage/rotation	11/11/2011	18.0	1.3	14.2	6.8	37.4	4.9	6.4	6.7	2.0	8.3	0.37
	experiment	10/01/2012	24.0	2.5	19.1	13.8	49.9	0.36	10.0	10.2	2.1	8.5	0.31
	Field C1,	24/02/2012	19.0	1.0	10.1	6.4	41.5	0.08	7.5	7.7	2.5	8.4	0.31
	ACRI,	30/03/2012	31.0	1.1	14.4	8.3	51.6	<0.02	7.2	7.5	2.7	8.0	0.38
	Seasonal sum (kg/ha)		92	6	58	35	180	5	31	32			
	Cotton/vetch/wheat	10/01/2012	18.0	2.5	18	12.1	46.1	0.08	12.0	12.0	2.1	8.3	0.37
	rotation experiment	24/02/2012	24.0	1.2	10.5	8.4	57.7	0.13	7.4	7.5	3.2	8.5	0.31
	Field D1, ACRI,	2/04/2012	19.0	1.5	15.8	11.6	52.1	0.06	7.8	8.1	2.4	8.4	0.31
	Seasonal sum (kg/ha)		61	5	44	32	156	0.3	27	28			
2012-13	Tillage/rotation	30/10/2012	-	3.2	31	20.3	141.0	3.50	9.6	10.0	4.8	8.2	0.60
	experiment	4/12/2012	-	1.9	16.1	12.4	20.7	0.22	9.1	9.5	0.9	8.4	0.29
	Field C1, ACRI	18/12/2012	-	2.4	16.7	12.8	25.5	0.09	9.8	10.0	1.1	8.4	0.30
		10/1/2013	-	2.2	19.6	15.0	87.5	0.33	10.0	11.0	3.6	8.3	0.33
		24/1/2013	-	2.3	18.4	14.5	83.1	0.05	10.0	11.0	3.5	8.5	0.32
		21/2/2013	-	2.8	21.3	14.9	84.4	0.05	9.4	10.0	3.4	8.3	0.36
	Seasonal sum (kg/ha)			15	123	90	442	4	58	62			
	Cotton/vetch/wheat	23/10/2012	-	2.4	22.2	16.3	30.6	0.70	9.4	9.8	1.2	8.7	0.34
	rotation experiment	13/11/2012	-	2.7	25.2	21.8	27.1	1.70	10.0	10.0	0.9	8.4	0.48
	Field D1,	6/12/2012	-	2.4	19.8	17.8	30.0	0.74	10.0	10.0	1.2	8.7	0.36
	ACRI,	19/12/2012	-	2.3	17	14.8	86.6	0.04	9.8	10.0	3.7	8.6	0.29
	Narrabri	9/1/2013	-	2.5	16.5	14.8	129.7	0.07	11.0	12.0	5.6	8.7	0.32
		23/1/2013	-	2.4	17.8	12.7	84.5	0.04	9.4	9.8	3.7	8.6	0.33
		20/2/2013	-	2.6	22.4	19.1	29.3	0.04	8.6	10.0	1.1	8.1	0.41
	Seasonal sum (kg/ha)			17	141	117	418	3	68	72			
2013-14	Tillage/rotation	31/10/2013	23.0	3.1	17.7	17.2	69.9	0.03	7.8	7.8	2.8		0.26
	experiment	18/12/2013	25.0	5.3	22.9	27.1	203.1	3.2	9.6	11.0	6.8		0.32
	Field C1,	7/01/2014	28.0	4.8	26.4	22.8	152.6	2.2	9.6	10.0	5.2		0.28
	ACRI, Narrabri	15/01/2014	26.0	6.2	37.4	28.2	69.6	1.3	9.5	9.9	2.1		0.29
		30/01/2014	17.0	5.0	26.6	22.2	43.7	<0.02	8.3	8.8	1.5		0.28
		7/02/2014	20.0	5.8	32.7	26.2	139.2	<0.02	7.9	8.2	4.4		0.24
		17/02/2014	19.0	5.0	26.1	25.4	112.3	<0.02	7.5	7.8	3.7		0.22
		28/02/2014	19.0	5.1	37.3	25.5	157.2	<0.02	7.5	7.8	4.8		0.27
	Seasonal sum (kg/ha)		177	40	227	195	948	7	68	72			

Cotton/vetch/wheat rotation experiment Field D1, ACRI, Narrabri	30/10/2013	36.0	4.5	28.0	27.0	116.4	0.76	8.4	8.9	3.7	7.6	0.35
	15/11/2013	31.0	4.5	16.5	24.4	118.3	0.08	9.8	9.7	4.3	7.4	0.31
	19/12/2013	28.0	6.0	33.0	31.7	129.8	1.5	9.6	9.8	3.9	7.4	0.24
	8/01/2014	27.0	5.4	23.3	24.0	85.4	0.78	10.0	11.0	3.0	7.5	0.21
	5/02/2014	19.0	5.0	31.8	26.8	82.3	<0.02	8.0	8.4	2.6	7.4	0.37
	26/02/2014	19.0	4.9	26.8	23.6	106.8	<0.02	8.0	8.6	3.6	7.2	0.37
	4/03/2014	23.0	5.2	36.2	27.0	129.4	<0.02	7.2	7.6	3.9	7.2	0.27
Seasonal sum (kg/ha)		183	36	196	185	768	3	61	64			

6.5 Soil hydrology

6.5.1 Including corn in cotton-cotton and cotton-wheat rotations under conventional tillage and minimum tillage (permanent beds) (Field C1, ACRI, Narrabri)

6.5.1.1 Soil water storage

Due to heavy and frequent rainfall and flooding during the 2011-12 season, measurements were possible on only one occasion during November and once in January. Thereafter observations were abandoned.

During the 2012-13 season, soil water storage did not differ significantly among cropping systems but did so during dates of measurement (Fig. 14). These results differ from previous years when soil water storage was highest in plots that had been sown with a cotton-wheat rotation. Laser levelling during 2011 followed by poor growth of the subsequent wheat crop may have contributed to this difference. Nonetheless, soil water storage was less in both minimum-tilled treatments during the latter part of the season, indicating that water extraction was greater than that in conventional tillage (NB. Max till= conventional tillage). The higher water storage may also have been caused by higher drainage in both minimum-tilled treatments and has been documented in past research at this site.

A similar response to 2012-13 was observed during the 2013-14 season (Fig. 15) when both corn and cotton were sown, with higher water storage values ($P < 0.05$) occurring under plots with a history of conventionally tilled continuous cotton. Due to the excessively high temperatures (up to 48 °C) and evaporation rates, irrigation was frequent (i.e. weekly). Water storage in the less well drained conventionally-tilled plots may, therefore, have been greater than usual. In addition, water extraction may also have been less than in the minimum-tilled plots.

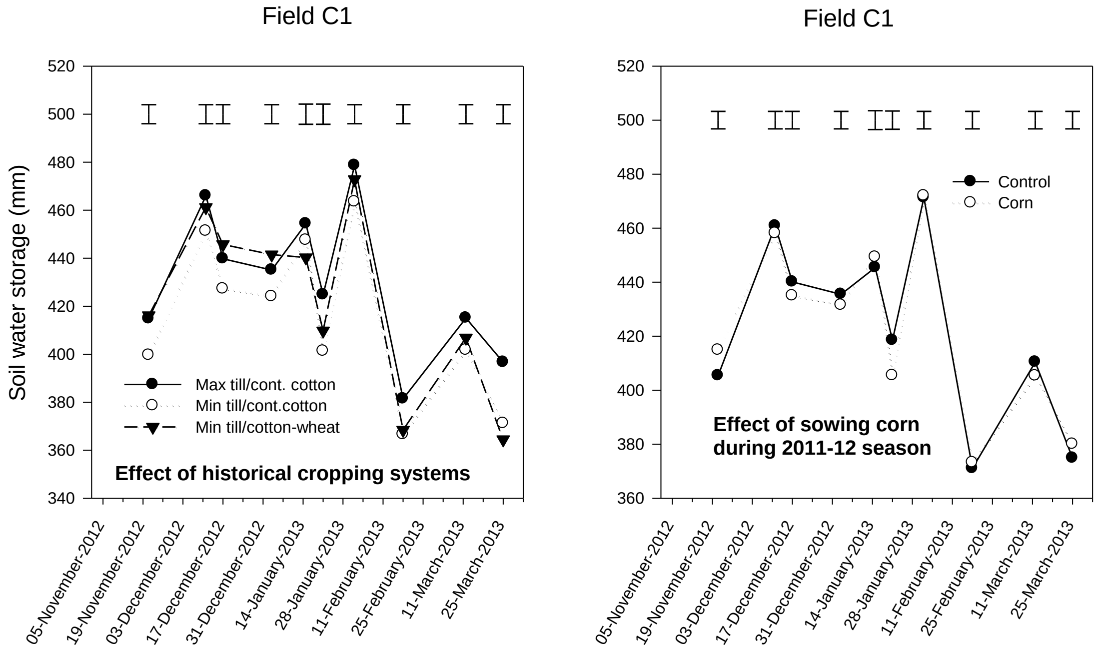

Fig. 14. Variation of soil water storage in the 0-1.2 m depth with cropping system (2012-13 season). Vertical bars are standard errors of the means

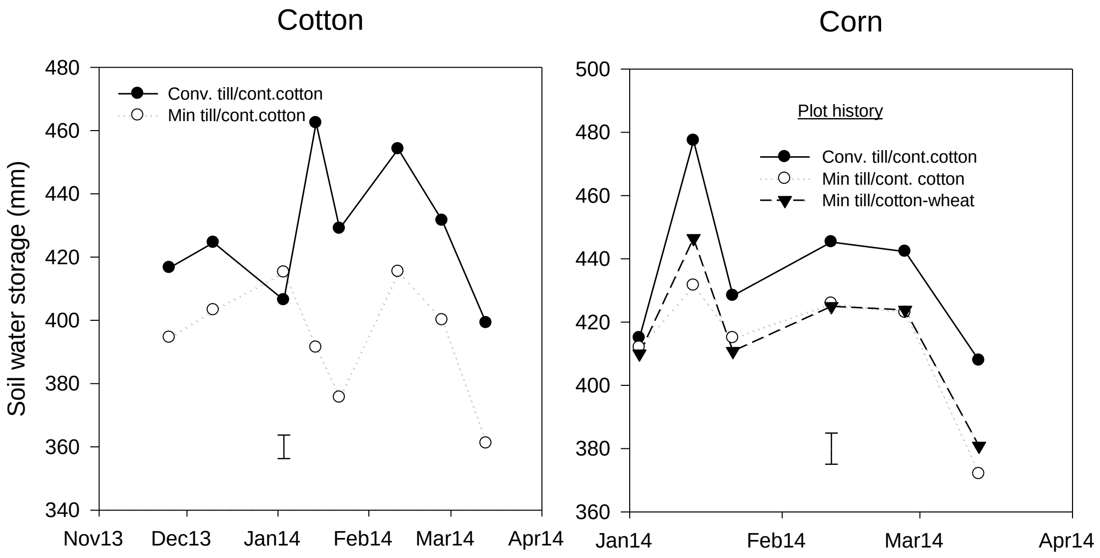

Fig. 15. Influence of cropping system on variation of soil water storage in the 0-1.2 m depth under corn and cotton in Field C1, ACRI, Narrabri (2013-14). Vertical bars are standard errors of the means

6.5.2 Managing rotation crop stubble and including vetch as a rotation crop in irrigated cotton-based cropping systems

6.5.2.1 Soil water storage during cotton seasons

Due to heavy and frequent rainfall and flooding, measurements were possible on only one occasion during October and once in January during the 2011-12 cotton season. Thereafter observations were abandoned.

In treatments sown with cotton during the 2012-13 and 2013-14 seasons, soil water storage was higher in during the latter half of the 2012-13 season and the early part of the 2013-14 season in the cotton-wheat-vetch rotation (Fig. 16). This observation is similar to those made in previous years. The main reason for this may be the water conserving ability of the vetch mulch, viz. reduction of evaporation and runoff, and enhancement of infiltration. During the summer fallows of the cotton-wheat (stubble incorporated) and cotton-wheat-vetch (standing stubble) rotations indicate that water storage was greater in the latter (Fig. 16). This is not unexpected as evaporation would have been reduced by the undisturbed soil and crop residues in the cotton-wheat-vetch whereas incorporation of wheat stubble in the cotton-wheat would have enhanced it. As there was no rainfall during most of the 2013-14 season except for approximately 30 mm in mid-November, runoff conservation and infiltration enhancement would have been negligible in all treatments.

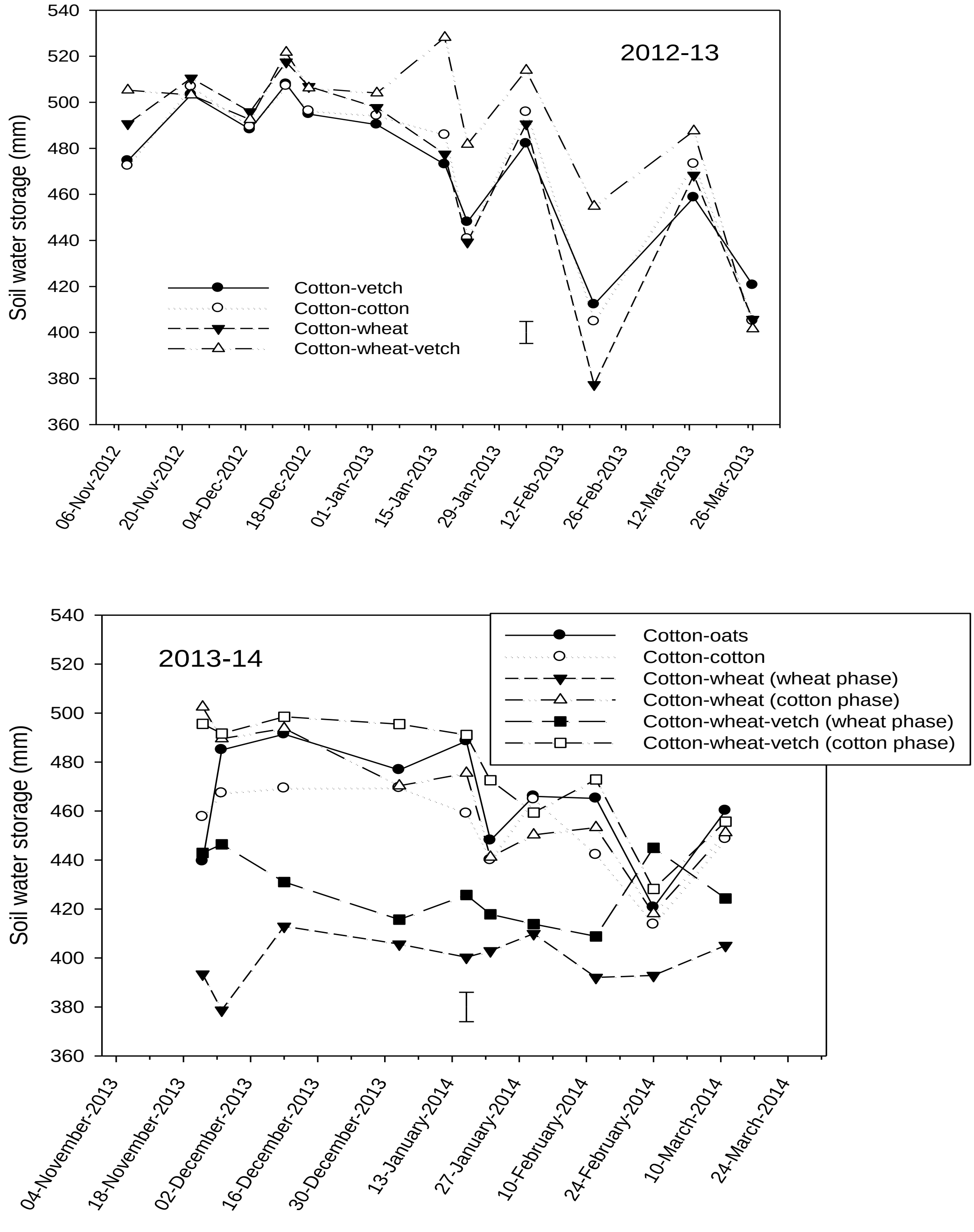

Fig. 16. Soil water storage in cotton-based crop rotations, cotton growing seasons 2012-13 and 2013-14, Field D1, ACRI, Narrabri. Vertical bar is standard error of the means (treatment x date)

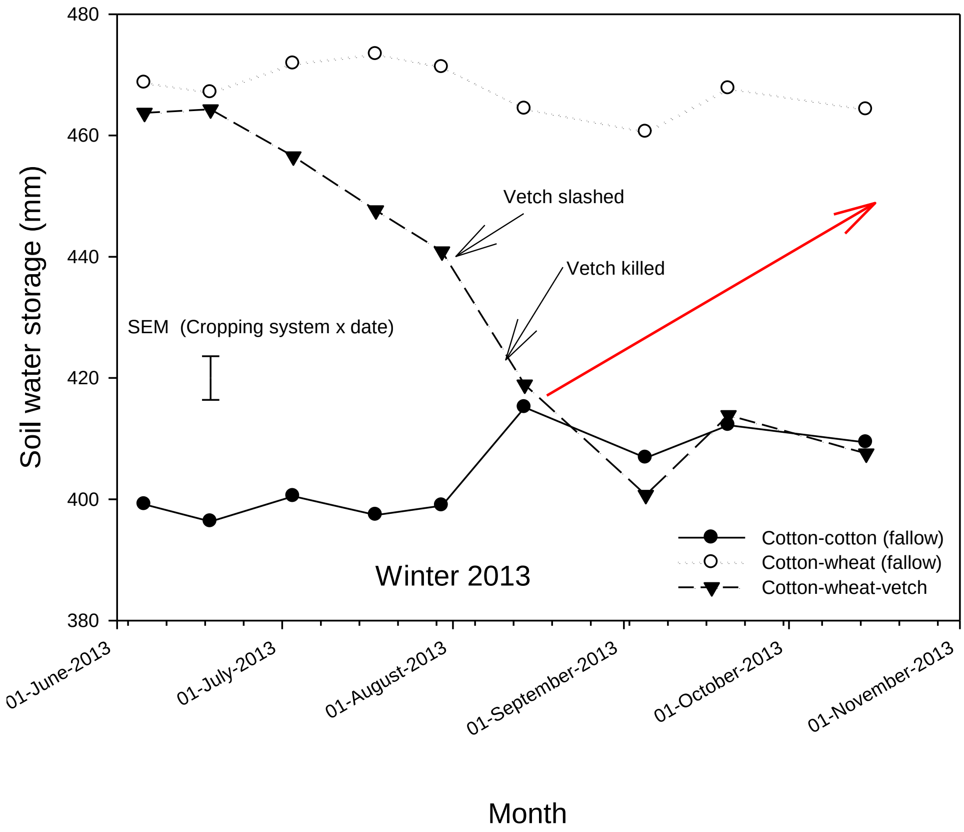

Fig. 17. Soil water storage in cotton-based crop rotations under rotation crop and fallows, Winter 2013, Field D1, ACRI, Narrabri

6.5.2.2 Soil water storage under winter fallow

Soil water storage was highest in the winter fallow of the cotton-wheat rotation (Fig. 17). The water stored under this treatment was a combination of that received during the summer fallow and the limited rain received during winter. There was no rain during the early spring (October and the first half of November). Unlike in previous years, soil water storage under the cotton-wheat-vetch rotation was not replenished after vetch was killed because there was no spring rain. This differs from most previous years when replenishment took place such that cotton could be sown into a moist soil. A typical pattern of replenishment is indicated by the red arrow in Fig. 17. Continuous cotton had the driest soil profile because, as stated previously, winter rainfall was poor and spring rainfall absent.

6.6 Crop growth and yield

6.6.1 Growth of cotton, corn and vetch

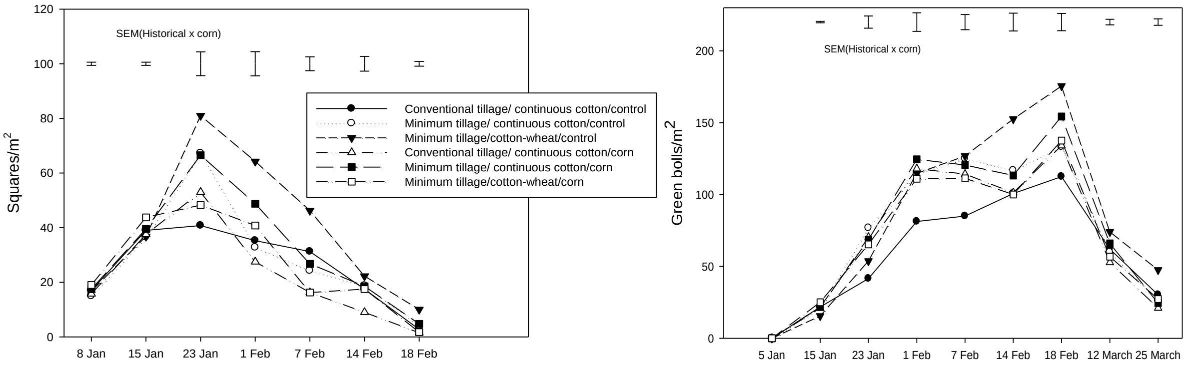

Fig. 18. Reproductive physiological growth parameters of cotton, Field C1, ACRI, 2012-13. Vertical bars are standard errors of the means.

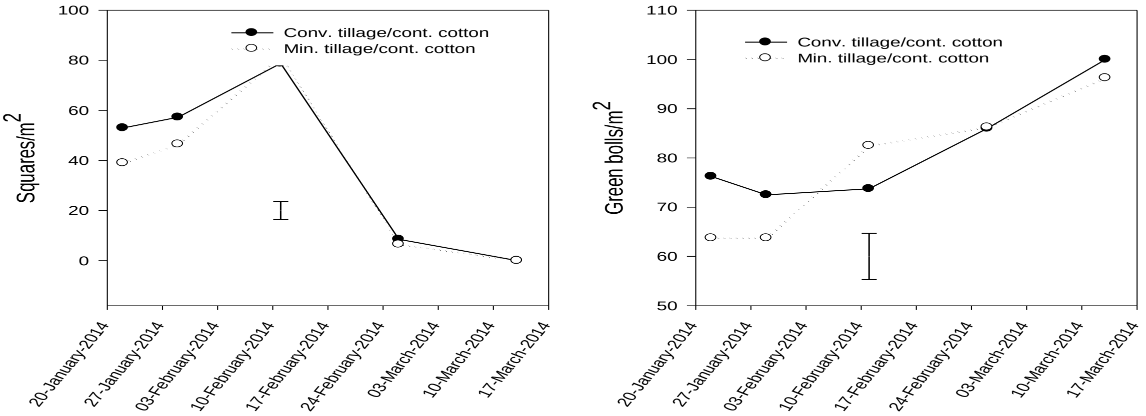

Fig. 19. Reproductive physiological growth parameters of cotton, Field C1, ACRI, 2013-14. Vertical bars are standard errors of the means.

6.6.1.1 Field C1 (cotton and corn)

Regular monitoring of cotton and corn physiological growth parameters could not be performed during the 2011-12 summer season due to the frequent rainfall and flooding at the site (Field C1, ACRI).

During the 2012-13 season, when all treatments were sown with cotton, there was a broad trend such that the peak numbers of squares (late January) and green bolls (latter half of February) were greater with minimum tillage (Fig. 18). During 2013-14 there were no significant differences between the control treatments of conventionally-tilled and minimum-tilled continuous cotton (Fig. 19). This may have been due to the frequent irrigation during this season that was required because of the very high temperatures and evaporation rates. The control plots of the cotton-wheat rotation were in fallow, and thus there was no cotton sown in them.

Corn suffered from heat stress during January 2014 resulting in widespread “rootless corn syndrome” (Fig. 20). Rootless corn syndrome is characterised by short, stubby roots, and in some instances absence of feeder roots, ultimately culminating in restricted water and nutrient uptake. The absence of roots also results in the plant lacking any physical support, and it will thus eventually topple over and die. In field C1, approximately 15% of the crop perished under the very hot and dry conditions during January 2014.

During the 2013-14 season, vegetative and reproductive physiological growth stages of corn were similar among all three historical treatments in Field C1; *viz*. conventionally-tilled continuous cotton, minimum-tilled continuous cotton and minimum-tilled cotton-wheat. Physiological growth ranged from the 10 leaf stage on 22 of January 2014 to tasselling on 26 February 2014 and grain filling from the 15 March onwards.

Fig. 20. Rootless corn syndrome in corn sown in Field C1, ACRI, January 2014

6.6.1.2 Field D1(cotton and vetch)

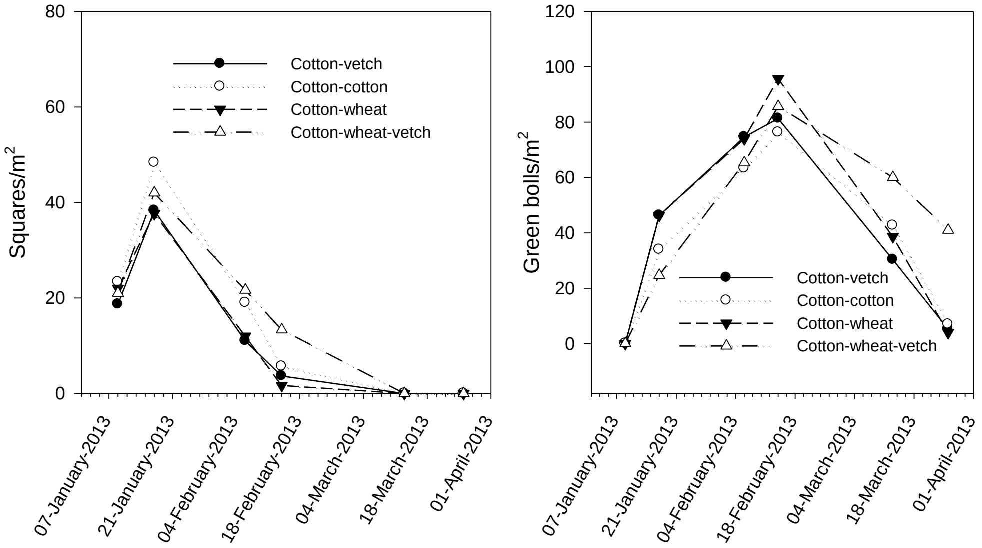

Fig. 21. Reproductive physiological growth parameters of cotton as influenced by cropping system, Field D1, ACRI, 2012-13. Data was analysed after $\log_e$ transformation. Values shown are back-transformed values

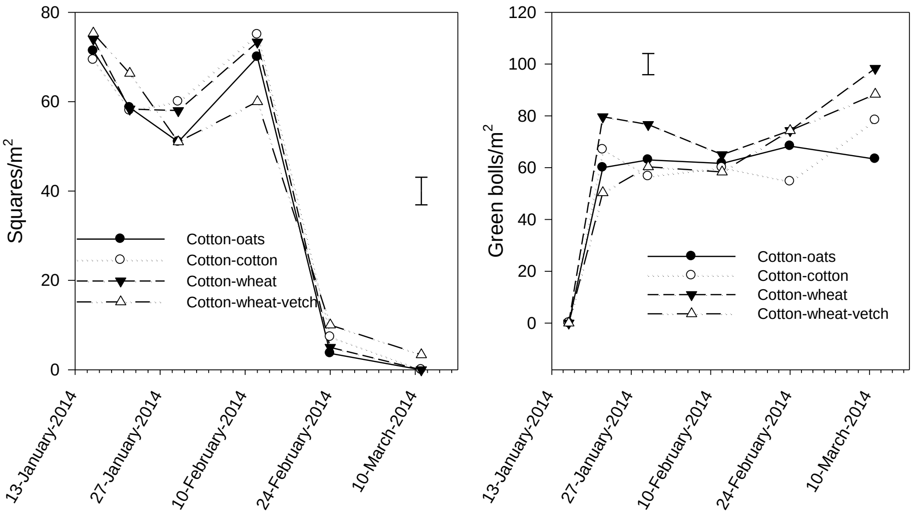

Fig. 22. Reproductive physiological growth parameters of cotton as influenced by cropping system, Field D1, ACRI, 2013-14. Vertical bars are standard errors of the means.

Due to heavy rainfall and flooding during the 2011-12 season, agronomic measurements were not conducted in the cotton crop. Results of squares/m^2 and green bolls /m^2 for the 2012-13 cotton season were analysed after log$_e$ transformation (Fig. 21). The analyses indicated that significant differences ($P < 0.05$) occurred among cropping systems with respect to both of the abovementioned parameters. Highly significant differences also occurred among times of sampling ($P < 0.001$) and interactions between times of sampling and cropping systems ($P < 0.001$) with respect to squares/m^2 and green bolls /m^2. Significant differences among treatments with respect to numbers of squares and bolls per unit area were not present among cropping systems sown in Field D1 during the cotton season of 2013-14 (Fig. 22). This may be due to the frequent irrigation, and thus, minimisation of stress that occurred during 2013-14. This was necessary to avert the consequences of the excessively high temperatures and evaporation rates that occurred during the 2013-14 cotton season. The management practices implemented in this experiment (i.e. stubble retention, mulching, minimum tillage etc.) are focussed on water conservation, and thus, under conditions of freely available water, treatment effects tend to be minimised. Significant ($P < 0.001$) differences were present during 2013-13 and 2013-14 cotton season with respect to time of sampling.

N contents in vetch DM averaged 9.5 kg N/ha in the cotton-vetch rotation and 113 kg N/ha in the cotton-wheat-vetch (Table 27). The very low N-fixation by vetch in the cotton-vetch was caused by poor growth due to herbicide damage, weed competition and cold shock. The variety "Racina" that was sown in 2011 and 2012was found to be sensitive to cold in addition to producing less. As the vetch in cotton-wheat-vetch was sown in late February, cold shock was not an issue in this rotation. Racina was replaced with a more cold-tolerant variety, "Capello", in 2013.

Table 27. Nitrogen in vetch dry matter, rotation experiment, Field D1, ACRI, Narrabri. *, ** and *** indicate that treatments differ significantly at $P < 0.05$, $P < 0.01$ and $P < 0.001$, levels, respectively. Vetch in cotton-vetch was replaced with oats in 2013.

Rotation	**Rotation crop stubble management**	**N in above-ground dry matter (kg/ha)**			**N concentration in above-ground DM (%)**		
		2011	**2012**	**2013**	**2011**	**2012**	**2013**
Cotton-vetch	Mulched	10.0	9.0	-	4.3	3.1	-
Cotton-wheat-vetch	Mulched	147.9	78.3	173.9	3.8	3.3	3.6
SEM		5.55***	4.37***		0.06***	0.11	

6.6.2 Root growth

6.6.2.1 Grain sorghum

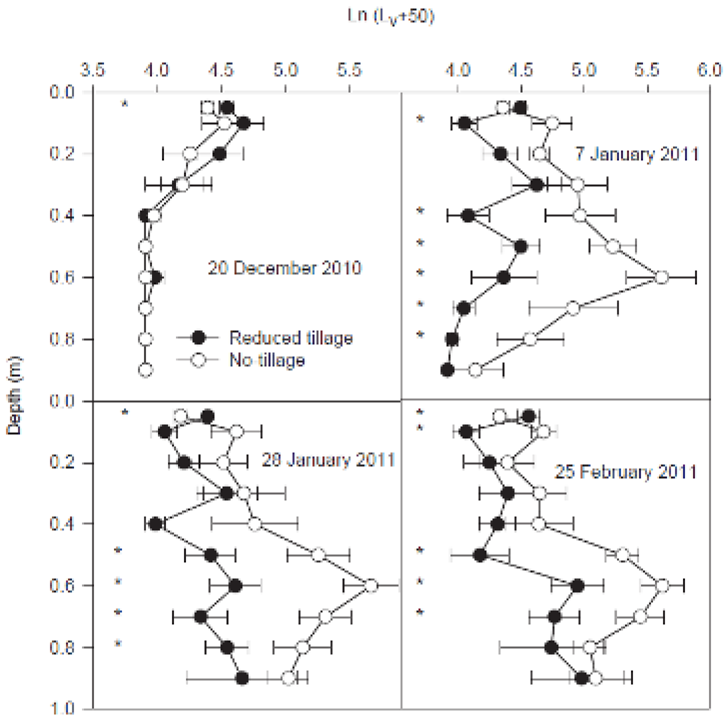

Fig. 23. Variation in root length density (L$_v$, mm/cm^3) with depth and time during summer 2010-11 summer. Horizontal bars are standard errors of the means. Depths at which significant differences were present are indicated by ‘*’.

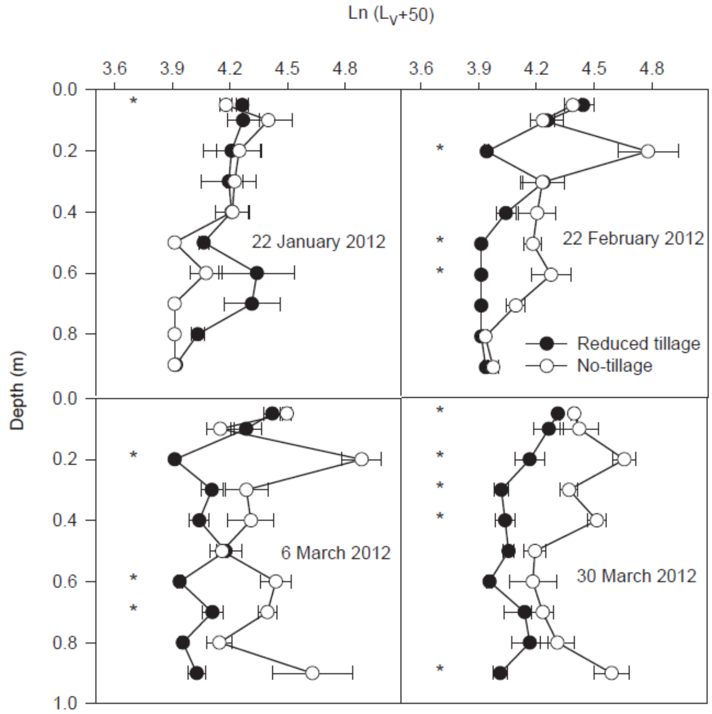

Fig. 24. Variation in root length density (L$_v$, mm/cm^3) with depth and time during summer 2011-12 summer. Horizontal bars are standard errors of the means. Depths at which significant differences were present are indicated by ‘*’.

v1

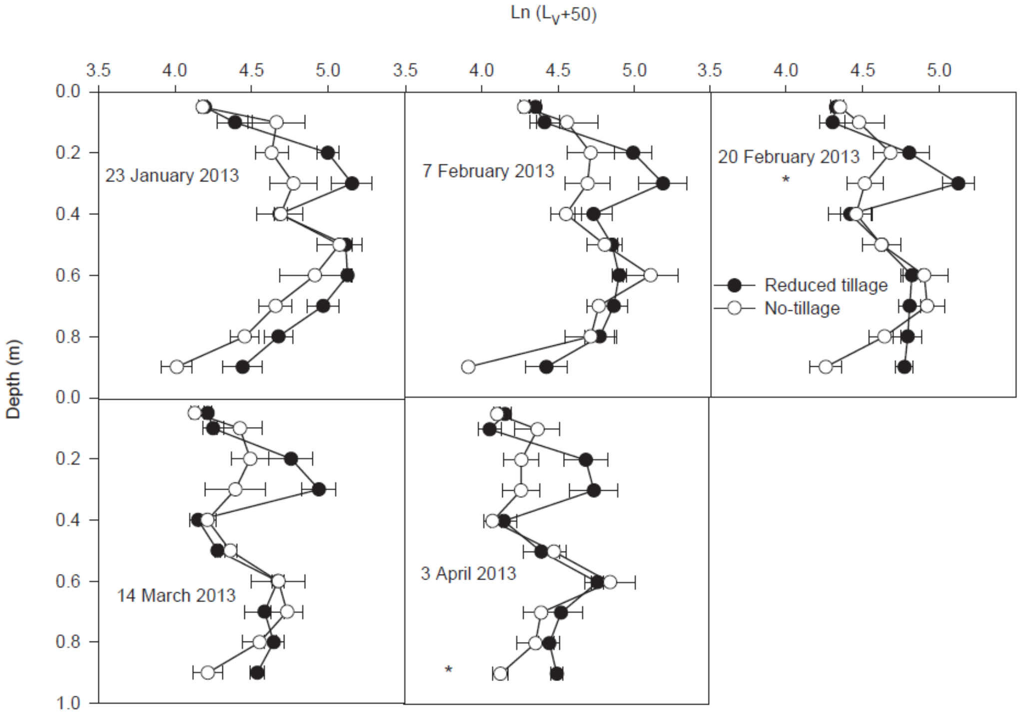

Fig. 25. Variation in root length density (L_v, mm/cm^3) with depth and time during summer 2012-13 summer. Horizontal bars are standard errors of the means. Depths at which significant differences were present are indicated by '*'.

Growth conditions varied among the three seasons, and may have affected root distribution of the sorghum. The 2010-11 season was characterised by frequent rainfall during winter, spring and early summer, but was drier subsequently. Rainfall was 161 mm during December 2010, 32 mm during January 2011 and 41 mm during February 2011. Surface and subsoils were saturated for extended periods during December 2010, and irrigation was required only during January (1 irrigation) and February 2011 (2 irrigations). Frequent rainfall was a feature of the 2011-12 season, culminating in inundation of the experiment for a week during late January/early February. Thus only a very limited amount of irrigation was required during this season (1 irrigation during November). Rainfall was 162 mm during December 2011, 148 mm during January 2012 and 182 mm during February 2012. In comparison with the preceding seasons, 2012-13 was relatively dry; 32 mm of rain fell during December 2012, 109 mm during January 2013 and 50 mm during March 2013. In addition, ambient temperatures were relatively high such that average daily maximum temperature during January was of the order of 41^{o}C. Irrigation water was, therefore applied frequently (3 irrigations during January, and 2 during February).

Sorghum root densities in the surface 0.5 m were generally similar in reduced tilled and no-tilled plots (Figs. 23-25). The exception was during January 2011 when those at 0.4-0.5 m were greater with no-tillage than with the reduced tillage, and the reverse occurred in the surface 0.1 mm throughout the season. Root densities in the 0.6-0.9 m soil horizon were greater with no-tillage than with reduced tillage during flowering only during the 2010-11 season and grain filling during the 2010-11 and 2011-12 seasons (Figs. 23 and 24). Root densities were generally similar and no consistent trends were observed in both treatments during the 2012-13 season (Fig. 25). Average L_A during flowering in the 0.6-0.9 m horizon was 25 km/m2 with no-tillage and 2 km/m^2 with reduced tillage during the 2010-11 season, 0 km/m2 with no-tillage and 4 km/m^2 with reduced tillage during the 2011-12 season, and 16 km/m2 with no-tillage and 22 km/m^2 with reduced tillage during the 2012-13 season. During grain filling, average L_A in the 0.6-0.9 m horizon was 45 km/m^2 with no-tillage and 17 km/m^2 with reduced tillage during the 2010-11 season, 6 km/m^2

with no-tillage and 2 km/m2 with reduced tillage during the 2011-12 season, and 18 km/m^2 with no-tillage and 7 km/m^2 with reduced tillage during the 2012-13 season. Relative root distributions during 2010-11 were such that at flowering no-tillage accounted for 31% of total root length in the 0.6-0.9 m depth and reduced tillage 11%, and during grain filling 49% of total root length in both treatments. During 2011-12 no-tillage at flowering had 0% of total root length in the 0.6-0.9 m depth and reduced tillage 30%, and during grain filling 23% and 16% of total root length of the no-tilled and reduced tilled treatments, respectively, were present in the 0.6-0.9 m. During 2012-13 no-tillage at flowering had 31% of total root length in the 0.6-0.9 m depth and reduced tillage 32%, and during grain filling 45% and 38% of total root length of the no-tilled and reduced tilled treatments, respectively, were present in the 0.6-0.9 m. Sorghum grain yield did not differ significantly between treatments and 3-year averages were of the order of 6.7 t/ha with no-tillage and 5.5 t/ha with reduced tillage (P = n.s., SEM = 0.49).

In summary, sorghum root growth in the 0.6-0.9 m horizon was in the order of 2010-11 > 2012-13 > 2011-12, and was thus lowest during the 2011-12 season, presumably due to the previously mentioned wet conditions and inundation. The similarity between treatments during the 2012-13 season and the greater values under no-tillage during 2010-11 and 2011-12 seasons may be a reflection of root growth patterns of crops grown under virtual full irrigation (2012-13) and those grown under frequent rainfall and limited irrigation (2010-11, 2011-12). In a lysimeter study conducted in this same field, drainage under full irrigation occurred mainly through preferential flow systems (i.e. cracks) whereas that under frequent rainfall occurred primarily as matrix flow. In other words, preferential flow drainage occurred without wetting up the soil profile whereas the entire soil profile was wetted to near saturation with matrix flow drainage. Consequently, profile aeration was likely to be greater with the former. It is also known that soil structural attributes such as pore continuity and stability are better in no-tilled than in tilled Vertosols[1]. Drainage is, hence, faster under saturated conditions in untilled than in tilled Vertosols. It is suggested, therefore, under frequent rainfall (2010-11, 2011-12), the better drainage, and thus better aeration, under no-tillage facilitated subsoil root growth, whereas under frequent irrigation as subsoil aeration was not limiting, differences between treatments were negligible. Nonetheless, irrespective of tillage system, subsoil root growth was relatively high under sorghum. Sorghum is thus similar to corn[2], presumably because it also has the ability increase numbers of aerenchyma under anaerobic conditions[3] in addition to having tolerance to the chemical and microbial changes that occur concurrently[4]. The high root densities in the 90 cm depth also suggests that significant root growth may have been present at deeper depths. As the minirhizotron tubes did not extend beyond this depth, this could not be verified. The deep and extensive root system of sorghum does show, however, that roots of crops such as sorghum and corn, both C4 crops, can be important sources of carbon inputs into the soil.

6.6.2.2 Cotton sown after corn

Cotton sown after corn had deeper and more extensive roots densities than cotton sown after cotton or wheat (Fig. 26). Previous research at this site[2] has shown that corn roots were able to proliferate in the wetter and oxygen-poor subsoil because of the high density of aerenchyma tissues that were present in corn roots. It is likely that the following cotton crop was able to use the pores created by the corn roots as preferential pathways to penetrate the subsoil. In addition the corn roots may have improved subsoil aeration directly through these root pores and indirectly by

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[1] McGarry D, *et al.* (2000) Contrasting soil physical properties after zero and traditional tillage of an alluvial soil in the semi-arid subtropics. *Soil and Tillage Research* **53**, 105-115.

[2] Hulugalle, N.R., *et al* (2011). “Final Report to Cotton Catchment Communities Co-operative Research Centre on CRC Project 1.04.16 (Maintaining profitability and soil quality in cotton farming systems III)”, 105 pp.

[3] Promkhambut A, *et al.* (2010) Morphological and physiological responses of sorghum (*Sorghum bicolor* L. Moench) to waterlogging. *Asian Journal of Plant Science* **9**, 183-193.

[4] Setter TL, *et al.*. (2009) Review of wheat improvement for waterlogging tolerance in Australia and India: the importance of anaerobiosis and element toxicities associated with different soils. *Annals of Botany* **103**, 221-235.

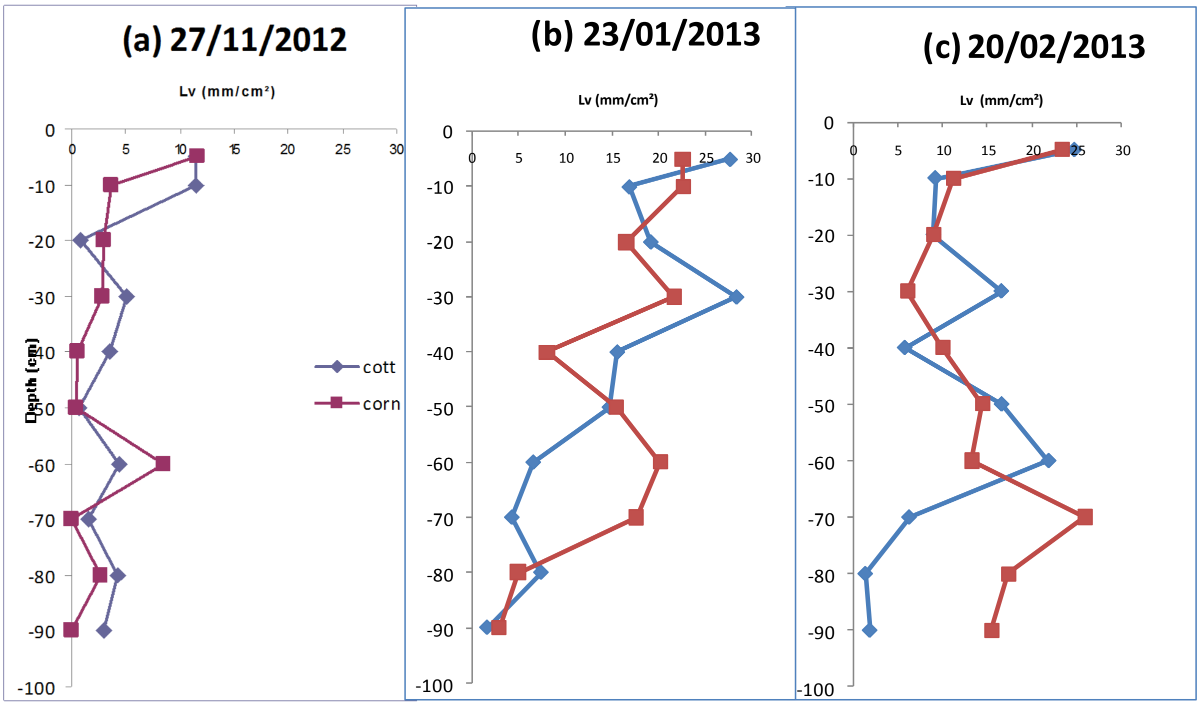

Fig. 26. Cotton root length density (mm/cm^3) for individual depth intervals after corn and control (no corn) treatments (a) 27 November 2012, (b) 23 January 2013 and (c) 20 February 2013. Data collected by Camille Coleman.

enhancing the intensity of wet/dry cycles, and thus improving soil structural attributes such as air-filled porosity.

6.6.3 Cotton and rotation crop yields

6.6.3.1 Including corn as a rotation crop

At ACRI, including corn in the tillage/rotation experiment (experiment 5.1.1) resulted in significant ($P < 0.01$) differences in corn grain yields during 2010-11 but not 2013-14, and cotton lint yields during 2012-13 (Table 28). During the 2011-12 season corn yields were highest in the cotton-wheat rotation under minimum tillage and lowest in the conventionally-tilled continuous cotton and reflect soil quality in these treatments. The absence of any treatment effects on corn yield during the 2013-14 season may be due to confounding by the heat stress that the crop suffered during January 2014. Overall, corn improved yield of the following cotton crop in 2012-13. In conventionally-tilled continuous cotton plots the increase was of the order of 22%, in minimum-tilled continuous cotton plots 12%, in minimum-tilled cotton-wheat plots 4%. Cotton lint increases were, therefore, greatest in the most degraded plots that had highest disease intensity. Measurement of black root rot infestation in cotton by the ACRI pathology unit indicated that lower black root rot scores occurred after sowing corn (see later discussion). The improvements in cotton yields appear to be related to both lower black root rot incidence and improved soil quality. Although other diseases were not monitored, it is possible that they too were reduced by sowing corn. Corn, therefore, has the potential to play a role as break crop to manage diseases in cotton farming systems.

Table 28. Yields of cotton and wheat in the tillage/rotation experiment, Field C1, ACRI. *, ** and *** indicate that treatments differ significantly at $P < 0.05$, $P < 0.01$ and $P < 0.001$, levels, respectively. 1 bale = 227 kg. What was not harvested in 2011 due to poor growth after laser levelling.

+/- Corn	**Rotation**	**Tillage system**	**Corn grain (t/ha)**			**Cotton lint (bales/ha)**			**Wheat grain (t/ha)**		
			2011-12	**2012-13**	**2013-14**	**2011-12**	**2012-13**	**2013-14**	**2011-12**	**2012-13**	**2013-14**
+Corn	Cotton-cotton	Conventional	7.0	-	5.5	-	10.0	-	-	-	-
	Cotton-cotton	Permanent beds	8.3	-	5.7	-	10.1	-	-	-	-
	Cotton-wheat	Permanent beds	8.8	-	5.6	-	10.7	-	-	-	1.8
-Corn (control)	Cotton-cotton	Conventional	-	-	-	7.1	8.2	10.8	-	-	-
	Cotton-cotton	Permanent beds	-	-	-	7.5	9.0	11.4	-	-	-
	Cotton-wheat	Permanent beds	-	-	-	-	10.3	-	-	-	1.9

SEM:

Parameter	**Cropping systems (CS)**			**+/- Corn (C)**			**CS x C**		
	2011-12	**2012-13**	**2013-14**	**2011-12**	**2012-13**	**2013-14**	**2011-12**	**2012-13**	**2013-14**
Corn grain	0.18**	-	0.12	-	-	-	-	-	-
Cotton lint	0.33	0.32	0.39	-	0.25**	-	-	0.44	-
Wheat grain	-	-	-	-	-	-	-	-	-

6.6.3.2 Sowing cotton into standing cereal stubble

Cotton lint yield was not significantly affected by wheat stubble management (Table 29), although sorghum grain yields at ACRI were improved. Cotton yields (2011-12) were similar under both stubble management systems at Federation Farm. This result is similar to other years where cultivation with an Aer-way cultivator under dry conditions did not significantly decrease cotton lint yields at “Federation Farm”. Cultivation with an Aer-way cultivator under dry conditions results in less soil disturbance than with conventional methods such as disc-ploughing (Fig. 4). Previous research in this site has suggested that tillage system may have minimal effects on soil quality as it appears to be the influenced more by the quality of irrigation water (i.e. treated sewage effluent, see Table 21).

Relative to cotton-wheat, both cotton and wheat yields in Field D1 did not differ from those in the cotton-wheat-sorghum sequence. In Field C1 at ACRI, retaining stubble as an *in situ* mulch resulted in sorghum grain yields increasing by an average of 31% over stubble incorporation.

Table 29. Effect of wheat stubble management on cotton lint yield (bales/ha), and wheat, sorghum, chickpea and soybean grain yields (t/ha) at on-farm and on-station sites. NA, not available

Site	**Cropping system**	**2011-12**		**2012-13**		**2013-14**	
		Rotation	**Cotton**	**Rotation**	**Cotton**	**Rotation**	**Cotton**
“Federation Farm”, Narrabri	Cotton-wheat (incorporated)	-	9.7	0.5[1]	8.5	3[2]	Not picked
	Cotton-wheat (*in situ* mulch)		9.7				
	SEM		0.33				
“Merrowie”, Hillston[3]	Cotton-wheat	2.7	-	Experiment terminated			
	Cotton-wheat-sorghum	2.7	-				
	SEM	0.11	-				
“New Haven”, Narromine	Corn (burnt) fb. Cotton-wheat	-	10.4	NA[4]	-	-	
	Cotton-wheat (*in situ* mulch)	-	9.1	-	10.9	-	
	t-value	-	3.34*	-	-		
Field D1, ACRI, Narrabri[5]	Cotton-wheat-sorghum (*in situ* mulch)	Cotton = 8.8 ba/ha; Wheat = 2.5 t/ha; sorghum = 5.4 t/ha					
	Cotton-wheat (*in situ* mulch)	Cotton = 9.5 ba/ha; Wheat = 2.4 t/ha;					
	SEM	Cotton = 1.47 wheat = 0.19					
Field C1, ACRI Narrabri[6]	Stubble incorporated	6.5	-	4.8	-	Experiment terminated	
	In situ mulch	8.8	-	6.0	-		
	t-value	6.16*	-	6.06*	-		

6.6.3.3 Managing rotation crop stubble

Wheat yields were not significantly changed by sowing vetch (Table 30). Cotton yields were highest with the wheat-cotton rotation during 2012-13 and with the cotton-wheat-vetch sequence during 2013-14. In comparison with the cotton-cotton sequence, inclusion of vetch and concomitant reduction in mineral fertiliser inputs in the cotton-vetch rotation did not result in a decrease in cotton yields, thus suggesting that the N-fixed by the vetch sufficed to maintain cotton yields. Inclusion of vetch in a cotton-wheat rotation however, resulted in significantly reducing yields of cotton during the 2012-13 season but increased yields during the 2013-14 season. The increase in yields during 2013-14 may be associated with the fact that vetch and wheat stubble were retained as undisturbed, *in situ* mulch, thus mitigating excessively high temperatures and evaporation; both of which were a feature of the 2013-14 season. Stubble was, however,

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[1] Chickpea was sown in reps 1 and2, and cotton in rep 3. This was the grower’s decision

[2] Wheat sown in rep 3; reps 1 and 2 were fallow

[3] Sorghum crops not sown. Rotation crop yields are for wheat grain.

[4] Not assessed

[5] Analyses as a RCB design with year as replication

[6] Grain sorghum

incorporated in the cotton-wheat, thereby exposing the soil, and thus, the cotton crop to the abovementioned environmental constraints.

Table 30. Yields of wheat and cotton in rotation experiment, Field D1, ACRI.

Rotation	**Rotation crop stubble management**	**Wheat grain yield (t/ha)**			**Cotton lint yield (bales/ha)**		
		2011-12	**2012-13**	**2013-14**	**2011-12**	**2012-13**	**2013-14**
Cotton-vetch fb. cotton-oats	Mulched	-	-	-	9.9	8.8	8.1
Cotton-cotton	-	-	-	-	9.5	8.9	9.3
Cotton-wheat	Incorporated	4.3	1.9	1.9	10.5	10.9	9.2
Cotton-wheat-vetch	Mulched	4.3	1.9	2.1	9.7	9.2	11.2
SEM		0.14	0.14	0.14	0.40	0.36*	0.46*

6.6.4 Cropping systems and fibre quality

Lint fibre quality parameters are shown only for the season when all plots were sown with cotton. Cotton lint fibre quality in the tillage/rotation experiment in Field C1 was unaffected by experimental treatments during the 2012-13 season (Table 31).

Crop rotation and stubble management did not have any significant effect on fibre quality indices in the experiment in Field D1, ACRI, although fibre strength ($P < 0.01$) and micronaire ($P < 0.05$) increased significantly from 2011-12 to 2012-13 seasons (Table 32).

Table 31. Effect of cropping system on cotton fibre quality indices, Tillage/rotation experiment, Field C1, ACRI, Narrabri, 2012-13 cotton season. . *, ** and *** indicate that treatments differ significantly at P < 0.05, P < 0.01 and P < 0.001, levels, respectively.

Historical tillage and rotation	**+/- corn**	**Elongation (%)**	**Length (in")**	**Micronaire (µg/in")**	**Short-fibre index (%)**	**Strength (g/tex)**	**Uniformity (%)**
Conventional till/continuous cotton	+corn	6.9	1.20	4.6	10.6	30.5	82.2
Minimum tillage/continuous cotton		6.7	1.22	4.5	10.0	31.7	83.1
Minimum tillage/cotton-wheat		7.0	1.21	4.6	10.3	30.7	82.9
Conventional till/continuous cotton	-corn	7.1	1.19	4.7	11.0	30.8	82.1
Minimum tillage/continuous cotton		6.7	1.24	4.5	9.2	32.7	83.3
Minimum tillage/cotton-wheat		7.3	1.21	4.6	10.4	30.0	82.7

SEM:

Parameter	**Elongation**	**Length**	**Micronaire**	**Short-fibre index**	**Strength**	**Uniformity**
Historical cropping system (HCS)	0.13	0.009	0.06	0.45	0.49	0.44
+/- corn (C)	0.08	0.007	0.03	0.30	0.34	0.35
HCS x C	0.14	0.012	0.05	0.52	0.60	0.60

Table 32. Effect of crop rotation and stubble management on cotton fibre quality indices, in rotation experiment, Field D1, ACRI, 2011-12 and 2012-13 seasons. *, ** and *** indicate that treatments differ significantly at P < 0.05, P < 0.01 and P < 0.001, levels, respectively.

Season	**Rotation**	**Rotation crop stubble management**	**Elongation (%)**	**Length (in")**	**Micronaire (µg/in")**	**Short-fibre index (%)**	**Strength (g/tex)**	**Uniformity (%)**
2011-12	Cotton-vetch	Mulched	6.5	1.19	4.5	10.5	29.3	82.3
	Cotton-cotton	-	6.5	1.18	4.6	10.5	29.2	81.6
	Cotton-wheat	Incorporated	6.7	1.16	4.5	11.7	28.9	82.8
	Cotton-wheat-vetch	Mulched	6.6	1.18	4.6	11.6	28.9	81.6
2012-13	Cotton-vetch	Mulched	6.5	1.18	4.7	11.2	31.3	80.7
	Cotton-cotton	-	6.5	1.20	4.7	10.5	32.1	82.3
	Cotton-wheat	Incorporated	6.9	1.19	4.6	11.0	31.2	82.0
	Cotton-wheat-vetch	Mulched	6.7	1.22	4.7	9.7	30.9	83.4

SEM:

Parameter	**Elongation**	**Length**	**Micronaire**	**Short-fibre index**	**Strength**	**Uniformity**
Season (Y)	0.07	0.005	0.02	0.32	0.11	0.36
Cropping system (CS)	0.11	0.009	0.04	0.69	0.34	0.56
Y x CS	0.15	0.013	0.05	0.97	0.48	0.80

6.6.5 Cropping systems and profitability[1]

6.6.5.1 Tillage/rotation experiment in Field C1

The experiment in Field C1 is a continuation of the tillage comparisons for two cotton farming systems, continuous cotton and cotton-wheat. In the 2011-12 season, this experiment was extended to include corn. The extended experiment, each of the three historical cropping systems (yellow boxes, see below), now includes 2 subplots that include the historical treatment (a) and a corn crop every second summer (b).

Historical cropping system	**Current crop rotation**
Conventional tillage/continuous cotton	**a. Cotton-fallow-Cotton-fallow (CCmax)**
	b. Cotton-fallow-Corn-fallow (CCmax.Cn)
Minimum tillage/continuous cotton min till	**a. Cotton-fallow-Cotton-fallow (CCmin)**
	b. Cotton-fallow-Corn-fallow (CCmin.Cn)
Minimum tillage/cotton-wheat	**a. Cotton-Wheat-fallow-fallow (CWmin)**
	b. Cotton-Wheat-Corn-fallow (CWmin.Cn)

This analysis considers the recent seasonal gross margins for the year 2012-2013, the 2 seasons of data for the Corn trial and the 13 seasons of data for cumulative and average results of the three historical trials.

Gross margin results were calculated using a cotton lint price of $450 per bale, cotton seed price of $170 per tonne, corn price of $200 per tonne (ex farm) and estimated costs for the actual operations conducted on each treatment, including fallow costs.

Gross margin for one hectare of cotton also considers the associated refuge crop. In the 2012/13 season, unsprayed pigeon peas were grown as the refuge, for every 1 hectare of Bollgard II cotton grown, there is 0.05 hectare of unsprayed pigeon pea for refuge. Therefore, in the gross margin comparison 1 hectare of cotton is .95 Bollgard II and .05 unsprayed pigeon peas.

Table 33. 2012-13 Season Results

SUMMER 2012-13	**CCmax**	**CCmax.Cn**	**CCmin**	**CCmin.Cn**	**CWmin**	**CWmin.Cn**
Crop	*Cotton*	*Cotton*	*Cotton*	*Cotton*	*Cotton*	*Cotton*
Yield (bales/ha)	7.93	**9.78**	9.08	**10.13**	9.90	**10.68**
Yield (t/ha)	2.00	2.48	2.35	2.58	2.53	2.73
Income ($/ha)	3,555	4,386	4,080	**4,545**	4,445	**4,793**
Variable Costs ($/ha)	**2,136**	2,270	2,220	2,296	2,234	2,335
Applied Irrigation Water (ML)	5.53	5.53	5.53	5.53	5.53	5.53
Gross Margin ($/ha)	1,418	2,115	1,860	2,249	2,210	**2,458**
Gross Margin ($/ML)	267	383	337	407	400	**445**

This season, every subplot grew a cotton crop, being the second year of the trial it gives a good comparison between the various rotations and tillage treatments. The initial stand out result is that the cotton treatments that included corn, significantly outperformed their

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[1] Results presented are only up to the June 2013 as Janine Powell has been on maternity leave since August 2013.

counterparts in yield for all three trials. The cotton-wheat-corn, minimum tillage treatment achieved the highest yield at 10.68 bales per hectare, closely followed by the cotton-corn minimum tillage treatment at 10.13 bales per hectare. This was a significant increase on the cotton yield in the conventional tillage, continuous cotton treatment of 28 and 35% respectively.

The trend continues for yields to be higher in the minimum tillage treatments, which is also confirmed in the corn treatments.

With very similar variable costs and water application, gross margins reflected yield results with the two minimum tillage treatments including corn returning the highest gross margins both per hectare and mega litre. The cotton-wheat-corn, minimum tillage treatment achieved the highest gross margin returns of $2458/ha and $445/ML. The lowest returns were from the continuous cotton rotation with conventional tillage of $1418/ha, $267/ML.

Full year results: Winter 2012 and summer 2012-13 seasons

When the results from winter 2012 and summer 2012/13 are combined to give the results for a full year, the gross margin results do not vary greatly as there was no winter income and low variable costs for all of the treatments (Table 34). The minimum tillage cotton-wheat-corn rotation outperformed the other rotations in terms of income and gross margin per hectare and ML. All treatments were in fallow, except the cotton-wheat rotation which included a sprayed out wheat crop.

Table 34. Full year results

Winter 2012 + Summer 2012-13	**CCmax**	**CCmax.Cn**	**CCmin**	**CCmin.Cn**	**CWmin**	**CWmin.Cn**
Crop Sequence	*Fallow /cotton*	*Fallow /cotton*	*Fallow /cotton*	*Fallow /cotton*	*Wheat /cotton*	*Fallow /cotton*
Income ($/ha)	3,555	4,386	4,080	4,545	4,445	**4,793**
Costs ($/ha)	2,212	2,346	2,260	2,336	2,320	2,376
Water Use (ML/ha)	5.31	5.53	5.53	5.53	5.53	5.53
Gross Margin ($/ha)	1,342	2,040	1,819	2,208	2,125	**2,417**
Gross Margin ($/ML)	253	369	329	400	385	**437**

Long term results for the period 2000 to 2012-13

The table below shows total results for the historical treatments from winter 2000 to summer 2012/13 for the 'normal' irrigation treatments. This completes 13 full years for the trial.

Continuous cotton (minimum tillage) has returned the highest total gross margin to date ($21,829) and the highest average annual gross margin per hectare ($1,679/ha). The cotton-wheat treatment consistently outperforms the continuous cotton treatments in terms of gross margin per mega litre of irrigation water applied ($356/ML). The cotton-wheat treatment has grown half the number of cotton crops compared to the continuous cotton treatments and used significantly less water, this is reflected in the lower total gross margin but also the higher gross margin per ML.

The average cotton yield per hectare is highest for the cotton-wheat treatment, 19-24% higher than the continuous cotton treatments. However, the continuous cotton treatments out-performed the wheat-cotton treatment in terms of returns per hectare. There is a range of $1267 to $1678 or a 32% difference between the lowest average annual return (cotton-wheat minimum tillage) and the highest average annual return (continuous cotton/minimum tillage) It must be noted that the continuous cotton treatments have grown twice as many cotton crops and used significantly more water. In terms of return per mega litre, the treatments ranged from $287 to $356, a 24% spread between the bottom (continuous cotton/conventional tillage) and top (cotton-wheat/minimum tillage) results.

Table 35. Longer term results

Winter 2000 to Summer 2012-13	**CCmax**	**CCmin**	**CWmin**
Total gross margin	**19,039**	**21,808**	**16,466**
Water use	66.42	66.84	46.28
Average GM/ML	$ 287	$ 326	**$ 356**
Average annual gross margin	$ 1,465	**$ 1,678**	$ 1,267
Cotton Crops	13	13	7
Wheat Crops	Nil	Nil	6
Mean cotton yield bales/ha	7.81	8.12	9.69
Cotton yield/ha change from conventional till continuous cotton		4%	24%
% GM/ha difference to continuous cotton		15%	-14%
% GM/ML diff than continuous cotton		14%	24%
Cotton bales/ha change from continuous cotton		0.31	1.88

Conclusion – Long term effects

The minimum tillage, continuous cotton treatment had the highest gross margin per hectare in both the 2012/13 season and the highest cumulative return over the thirteen years of the trial. This is a result of higher yields than the conventional tillage treatment. Yield differences are a major factor when comparing the profitability of the various treatments. The minimum tillage treatments consistently outperform the conventional tillage treatments when it comes to yield, a potential reflection of the long term soil health benefits of minimum tillage.

The treatment that includes the wheat rotation has a significantly higher average yield than both the continuous cotton treatments. This yield performance is reflected in the highest average return per ML of $356/ML, however when comparing the average gross margins per hectare, the wheat treatment is 14% lower than the conventional till continuous cotton, due to growing half the number cotton crops in the same period.

Cumulative results for the period 2011 to 2012/13 – all subplots

The table below (Table 3) shows the cumulative results for all six subplots from winter 2011 to summer 2012-13. This completes 2 full years for the trial. Continuous cotton/minimum tillage has returned the overall highest cumulative gross margin to date ($2,826) and the highest average annual gross margin per hectare ($1,413/ha). The same treatment (corn subplot) has returned the highest total cumulative and average gross margin when comparing the corn treatments. It has also achieved the overall highest average gross margin per ML across all subplots at $356/ML. It also needs to be noted when comparing the results in Table 34 that only the continuous cotton subplots (columns 1 and 3) have grown 2 cotton crops, whilst all other subplots have only grown 1 cotton crop.

As yields correspond very strongly to gross margin, the trends emerging within and between the treatments are very important. As discussed in the summer 2012/13 results, the yields for the subplots including corn were significantly higher than the traditional rotations, 30%-47%

higher than the continuous cotton maximum tillage subplot. The average cotton yield per hectare was highest for the corn subplots that were grown under minimum tillage (10.13 and 10.68bales/ha), however between the corn treatments the yield differences were not as significant 4-9% higher than the maximum tillage corn treatment (9.78 bales/ha).

Table 36. Longer term results

Winter 2011 to Summer 2012/13	**CCmax**	**CCmax. Cn**	**CCmin**	**CCmin.Cn**	**CWmin**	**CWmin. Cn**
Cumulative (total) gross margin	2,150	2,209	**2,826**	**2,682**	1,275	2,587
Water use	8.22	7.53	8.44	7.53	5.53	7.53
Average GM/ML	262	294	335	**356**	231	344
Average annual gross margin	$ 1,075	$ 1,104	**$ 1,413**	**$ 1,341**	$ 637	$ 1,294
Cotton Crops	2	1	2	1	1	1
Wheat Crops					-	-
Corn Crops		1		1		1
Mean cotton yield bales/ha	7.51	9.78	8.29	10.13	9.90	10.68
Cotton yield/ha change from max till CC or C.Crn			10%	4%	32%	9%
% GM/ha difference to CC			31%	21%	-41%	17%
% GM/ML diff than CC			28%	21%	-12%	17%

In the first two years of the trial, the minimum tillage continuous cotton and cotton corn treatments have achieved the highest total gross margins per hectare ($2,826 and $2,682). The two other corn subplots follow closely behind at $2,587 and $2,209 as a result of the cotton yield premiums following the corn crop. Considering only two of the subplots have grown two cotton crops and rest have grown one, the gross margins are all quite similar (except for the cotton-wheat subplot which has only had one summer cash crop). There is a range of $637 to $1413 or a 22% difference between the lowest average annual return (cotton-wheat minimum tillage) and the highest average annual return (continuous cotton minimum tillage). In terms of return per mega litre, the treatments ranged from $231 to $356, a 54% spread between the bottom (cotton-wheat minimum tillage) and top (cotton-corn minimum tillage) results.

Conclusion – Cumulative results all treatments

Within the second year of the trial that now includes corn, it appears that corn will positively affect the profitability of all the treatments, by enabling a significant yield increase within the cotton. The Cotton-Wheat minimum tillage subplot is the only rotation that will not grow a cash crop of either cotton or corn every summer, resulting in the cumulative gross margin per hectare for this subplot being much lower, however due to lower water use and the possible soil health benefits of a long fallow, in the future this subplot may return similar gross margin per mega litre results as the other subplots.

The wheat rotations are showing positive yield benefits in the following cotton crops, for these rotations to be comparatively profitable, the wheat crop only needs to be grown at break even, where in the first two seasons of the trial the wheat crops have been grown at a loss.

6.6.5.2 Cropping systems experiment, Field D1, ACRI

Introduction

The treatments were;

T1	Cotton-vetch-cotton-vetch (C-V-C-V)
T2	Cotton-winter fallow-cotton-winter fallow (C-F-C-F)
T3a	Cotton-wheat-long fallow; wheat stubble incorporated (C-W-F-F)
T3b	Long fallow -cotton-wheat; wheat stubble incorporated (F-F-C-W)
T4a	Cotton-wheat-fallow-vetch; wheat stubble retained (C-W-F-V)
T4b	Fallow-vetch-cotton-wheat; wheat stubble retained (F-V-C-W)

Gross margin results were calculated using a cotton lint price of $450 per bale, cotton seed price of $170 per tonne, wheat price of $250 per tonne (ex farm) and estimated costs for the actual operations conducted on each treatment, including fallow costs.

Gross margin for one hectare of cotton also considers the associated refuge crop. In the 2012/13 season, unsprayed pigeon peas were grown as the refuge, for every 1 hectare of Bollgard II cotton grown, there is 0.05 hectare of unsprayed pigeon pea for refuge. Therefore, in the gross margin comparison 1 hectare of cotton is .95 Bollgard II and .05 unsprayed pigeon peas.

2012-13 Season Results

Treatment 3a returned the highest cotton yield (10.9 bales/ha), with the lowest cotton yield Treatment 1 (8.8 bales/ha). Treatment 3a also returned the highest gross margin per hectare and ML, with $4,897/ha and $398/ML. Treatments 1 & 2 both had the lowest costs, however due to lower yields, they also returned the lowest gross margins per hectare and ML. Treatments T3b and T4b were in fallow.

Table 37. 2012-13 summer results

2012-13	T1: C-V-C-V	T2: C-F-C-F	T3a: C-W-F-F	T3b: F-F-C-W	T4a: C-W-F-V	T4b: F-V-C-W
Crop	*cotton*	*cotton*	*cotton*	*fallow*	*cotton*	*fallow*
Lint Yield	8.80	8.90	**10.90**		9.20	
Seed yield	2.20	2.20	2.80		2.30	
ML applied	6.95	6.95	6.95		6.95	
Income	3,944	3,985	**4,897**	-	4,123	-
Variable Costs	1,976	1,985	**2,130**	144	2,016	110
Gross Margin (ha)	1,968	2,000	**2,767**	(144)	2,107	(110)
Gross Margin (ML)	283	288	**398**	na	303	na

Full year results: Winter 2012 and Summer 2012-13 seasons

When the results from winter 2012 and summer 2012-13 are combined to give the results for a full year there was little change to the comparable results with Treatment 3a still returning significantly higher gross margin per hectare and ML. The costs of the vetch in T1 and T4a were higher than the fallow costs of T2, so for the twelve month period, T2 was slightly more profitable than both T1 & T4a both in term of per hectare and ML.

Table 38. Twelve month results (Winter 2012 & Summer 2012-13)

2012 winter and 2012-13 summer	T1: C-V-C-V	T2: C-F-C-F	T3a: C-W-F-F	T3b: F-F-C-W	T4a: C-W-F-V	T4b: F-V-C-W
Crop	*vetch/cotton*	*fallow/cotton*	*fallow/cotton*	*wheat/fallow*	*vetch/cotton*	*wheat/fallow*
Income	3,944	3,985	**4,897**	475	4,123	468
Variable Costs	2,242	2,006	2,150	542	2,248	508
Gross Margin	1,702	1,979	**2,747**	(67)	1,875	(40)
ML applied	8.0	7.0	7.0	2.0	7.0	2.0
GM/ML	214	285	**395**	(33)	270	(20)

The wheat yields in treatments T3b and T4b were 1.90 and 1.87t/ha respectively, at $250/t income was slightly higher than costs, for the season, however still resulting in a loss for the 12 month period.

Cumulative results for the period 2003 to 2012-13 with T3 and T4 averaged

Treatments 3a/3b and 4a/4b are different phases of the same treatment, so averaging them helps to remove some of the phase effect in the treatments. The phase effect means the results of the individual treatments can be skewed by having a different number of cotton and wheat crops. Table shows the summary for 2003-2012/13 with the treatment phases for 3 and 4 averaged.

Treatment 1 and 2 have the highest cumulative incomes per hectare, with $43,296/ha and $43,345/ha respectively, however due to lower costs for Treatment 2, it returns the highest cumulative gross margin per hectare ($20,449/ha). Cotton is grown annually in the first two treatments and bi-annually in treatments 3 & 4, it is notable that Treatments 3 and 4 have returned the highest yield (in bales/ha terms) and lowest water use. In terms of gross margin per megalitre of irrigation water, T2 and T3 have the highest returns of $405/ML and $396 respectively.

Table 39. Cumulative results for the period 2003 to 2011/12 with T3 and T4 averaged

AVERAGES	T1	T2	T3	T4
Total Income ($)	43,296	43,345	27,820	26,615
Total VC ($)	24,367	22,896	14,644	14,808
Total Gross Margin ($/ha)	18,929	**20,449**	13,176	11,807
Ave cotton yield (bales/ha)	8.9	8.8	**10.4**	9.8
Average GM/ML ($/ML)	316	**405**	**396**	335
Average GM/ha ($/ha)	1,893	**2,045**	1,318	1,181
GM/VC ratio	0.78	**0.89**	**0.90**	0.797
Total water use/ha	60.0	50.5	**32.2**	35.2

Whilst Figure 27 indicates a superior performance of T1 and T2 in terms of gross margin per hectare, it needs to be considered that Treatment 1 and 2 grow cotton annually, compared to Treatment 3 and 4 which grow cotton bi-annually. Consequently T1 and T2 have also used significantly more water per hectare than T3 and T4.

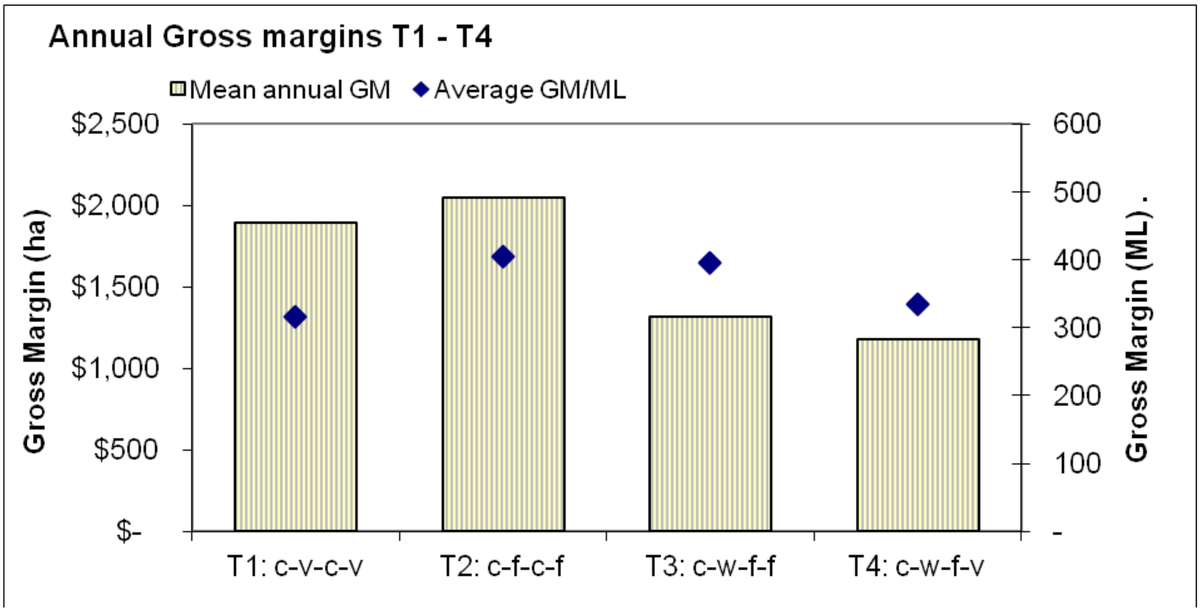

Figure 27. Average annual gross margin results from 2003

Treatment 1 and treatment 2 are both continuous cotton rotations, with T1 growing vetch in winter and T2 having a winter fallow. The income from the two treatments is very similar, however the costs and water use of T1 (vetch treatment) are higher than T2, resulting in a lower gross margin both per hectare and per ML. Whilst the yields of T1 are slightly higher than T2, the yield increase is not significant enough to compensate for the higher costs and water use of included vetch within the rotation.

The cotton wheat treatments tell a similar story. Whilst the costs are very similar, Treatment 3 (non-vetch treatment) has given slightly higher yields, and is more profitable both per hectare and mega litre.

Conclusion

The results from the 10 year experiment in D1 are showing clear trends. Whilst managing expenses can be important in maximising gross margin, they key driver is yield. Rotation profitability closely follows the yield of the cotton crop. The long term results indicate that it is more profitable (per hectare) to grow continuous cotton rather than a rotation with a bi-annual crop (these are purely economic results and do not take into consideration long term soil health). In terms of gross margin per mega litre it is more profitable to grow cotton without the inclusion of vetch, either annually (T2) or bi-annually (T3).

The results also suggest that in a cotton rotation, the inclusion of vetch is less profitable than a fallow or wheat rotation. Long term results indicate there is not a yield benefit by including vetch within the rotation. The vetch rotations are higher in cost and water use resulting in lower gross margins.

It is difficult to compare economic returns of the T3 and T4 in terms of stubble retention v stubble retained, as the T4 rotation includes vetch and T3 does not.

6.6.6 Determinants of cotton lint yield, water use efficiency and nitrogen use efficiency

6.6.6.1 Cotton lint yield

Table 40. Results of multiple linear regression analyses of management and climatic variables on cotton lint yields in individual sites. Max till, number of tillage operations > 10 cm deep; Min till, number of tillage operations < 10 cm deep; N, N fertiliser applied (kg N/ha); SOC, soil organic carbon storage in the surface 60 cm; Water, total water inputs, irrigation and rainfall (mm); T_{max}, annual average daily maximum temperature (^oC); T_{min}, annual average daily minimum temperature (^oC); VIF, variance inflation factor. Interaction terms, when significant, had only a small effect on the fit of the data, and were thus, dropped from the models.

Site	**Variable**	**Coefficient**	**VIF**	**P <**	**R^2**	**n**
Field C1, ACRI, Narrabri, NSW	N	0.013	1.4	0.05	0.42***	67
	Water	0.0033	1.3	0.01		
	SOC	-0.099	1.2	0.01		
Field D1, ACRI, Narrabri, NSW	Water	0.0056	2.5	0.001	0.86***	72
	N	0.021	2.1	0.01		
	Max till	-0.94	1.6	0.01		
	Min till	0.75	1.3	0.001		
	T_{min}	1.37	1.1	0.001		
“Glenarvon”, Wee Waa, NSW	Max till	1.03	1.0	0.01	0.54**	16
“Beechworth”, Merah North, NSW	Max till	-1.92	1.4	0.01	0.74***	65
	N	0.028	1.1	0.001		
	T_{min}	-3.84	1.3	0.001		
“Auscott-Warren”, Warren, NSW	T_{max}	0.48	2.2	0.01	0.87***	33
	Max till	0.80	1.7	0.001		
	Water	0.003	2.3	0.001		
	SOC	0.032	3.3	0.05		
	T_{min}	-1.32	1.4	0.001		
“Prospect”, Warra, Qld	Min till	0.37	1.2	0.001	0.66***	44
	N	0.034	1.2	0.001		
Pooled results for all sites[1]	Water	0.0039	1.9	0.001	0.67***	302
	N	0.020	1,8	0.001		
	T_{min}	-1.17	1.2	0.001		
	T_{max}	0.47	1.3	0.01		
	SOC	-0.018	1.1	0.05		

Within site multiple linear regression of management and climatic variables with cotton lint yields for the sites listed in Table 40 produced varying results. Except for “Glenarvon”, either N or water, or both had a positive relationship to lint yields at all sites. Variations in cotton lint yields at the rainfed site at Warra were affected significantly by amounts of N added to the cotton crops and numbers of minimum tillage operations, but not by water inputs (i.e. rainfall).

Lint yield was related negatively to annual average minimum temperature at “Auscott-Warren” and “Beechworth” and positively to average annual maximum temperature at “Auscott-Warren”. The relationships to temperature at Warren and Merah North may be associated with the cooler conditions in the former and sodic conditions, poorer drainage and thus, cooler soil conditions in the latter. In Field D1 at ACRI, which was also sodic at depth, increasing annual temperatures had a negative effect on lint yield, and may be a reflection of the high ambient temperatures that occurred during 2012-13 and 2013-14 seasons. SOC had a negative relationship to lint yield at Field C1 but a positive relationship at Warren. The negative relationship between SOC, which is directly related to biomass retention, and yield at Field C1 (where cotton has been grown as a monoculture for 28 years) may be due to the biomass facilitating soil-borne diseases[2].

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[1] Fields C1 and D1, ACRI, Narrabri; “Glenarvon”, Wee Waa; “Auscott-Warren”, Warren, NSW; “Prospect”, Warra ; and “Merrowie”, Hillston, NSW.

[2] Rochester, I. (2004). Cotton stubble management. In “Nutripak”, pp. 13-01 to 13-03. Cotton CRC, Narrabri, NSW. www.cottoncrc.org.au/files/638ec548-c89d-4492-b6c6.../13Stubbl.pdf

Some differences occurred with respect to the number of tillage operations greater than 10 cm deep where positive relationships were present at “Glenarvon” and “Auscott-Warren”, negative relationship at “Beechworth” and Field D1 at ACRI. (The deeper tillage was, however, significant in Field C1 at P = 0.06. This may be associated with the laser levelling that occurred in Field C1, and the consequent soil compaction that was partly relieved by the deeper tillage operations. As the threshold P value was predetermined as P = 0.05, this variable was dropped from the model). The positive relationship of the tillage to lint yield in the two former sites may be related to the aeration effect previously noted whereas the negative effect at “Beechworth” may be a consequence of the sodic soil in this site. Pooling of results for all sites indicated that increasing N inputs, water (irrigation and rainfall), and falls in average daily minimum temperature and increases in daily maximum temperatures increased cotton lint yields.

In summary, cotton lint yields, in general, were positively related to water and N inputs, soil aeration in some sites and average annual daily maximum temperature in cooler or poorly-drained sites but were lowered by higher average annual daily minimum temperature. In a sodic soil, a high frequency of the tillage practices intended to aerate the soil may have caused yield decreases, presumably due to exposure of more sodic soils.

6.6.6.2 Water use efficiency

For the purpose of this study, we have defined cotton water use efficiency (WUE) as cotton lint yield per mm of water (rainfall + irrigation) inputs (bales/ha/mm).

Table 41. Results of multiple linear regression analyses of management and climatic variables on cotton water use efficiency in individual sites. Max till, number of tillage operations > 10 cm deep; Min till, number of tillage operations < 10 cm deep; N, N fertiliser applied (kg N/ha); Water, total water inputs, irrigation and rainfall (mm); T_{max}, annual average daily maximum temperature (^oC); T_{min}, annual average daily minimum temperature (^oC); SOC, soil organic carbon storage in 0-60 cm depth (t/ha), VIF, variance inflation factor. Interaction terms had only a small effect on the fit of the data, and were thus, dropped from the models.

Site	**Variable**	**Coefficient**	**VIF**	**P <**	**R^2**	**n**
Field C1, ACRI, Narrabri, NSW	Max till	-0.16	1.2	0.01	0.39***	65
	Min till	-0.23	1.2	0.01		
	T_{min}	-0.30	1.0	0.05		
	SOC	-0.061	1.4	0.001		
Field D1, ACRI, Narrabri, NSW	T_{min}	0.53	1.1	0.001	0.82***	72
	Min till	0.19	1.1	0.001		
	N	0.0037	1.7	0.001		
	Water	0.0015	1.8	0.001		
“Glenarvon”, Wee Waa, NSW	T_{max}	1.73	1.6	0.001	0.90***	16
	T_{min}	-0.92	1.6	0.001		
“Beechworth”, Merah North, NSW	Max till	-0.55	2.1	0.001	0.66***	41
	Min till	-0.26	1.5	0.001		
	N	0.0026	1.1	0.01		
	Water	-8.99E-04	1.2	0.001		
	T_{min}	-1.03	2.4	0.001		
“Auscott-Warren”, Warren, NSW	T_{max}	0.069	2.2	0.05	0.91***	33
	Max till	0.14	1.7	0.001		
	Water	-5.36E-04	2.3	0.001		
	SOC	0.007	3.3	0.05		
	T_{min}	-0.25	1.4	0.01		
“Prospect”, Warra, Qld	Min till	0.15	1.2	0.001	0.60***	45
	N	0.013	1.2	0.001		
	Water	-0.0014	1.1	0.001		
Pooled results for cotton-wheat rotations on permanent beds	Max till	0.20	1.1	0.01	0.32***	281
	Min till	0.24	1.1	0.001		
	SOC	0.031	1.1	0.001		
	Water	0.0013	1.0	0.001		

As with SOC and yield, there was considerable variation among individual sites with respect to the determinants of water use efficiency (Table 41). SOC and deep tillage were positively related to WUE at Warren whereas total water inputs had a negative relationship. Except for Warra, in all other sites average minimum temperature was negatively related to WUE but was not evident in the pooled results across all sites. In contrast to the on-farm sites, SOC was negatively related to WUE and total water had no significant effect in Field C1at ACRI, but had a positive relationship to WUE in Field D1. This may be due to higher water application rates in on farm sites. N was positively related to WUE in two sites, viz. Field D1 and Merah North, both of which had relatively high subsoil sodicity. In summary, variable such as depth and frequency of tillage, water inputs, N and SOC played significant roles in determining WUE of cotton.

6.6.6.3 Nitrogen use efficiency

For the purpose of this study, we have defined cotton nitrogen use efficiency (NUE) as cotton lint yield per kg N of mineral fertiliser (bales/ha/kg).

Table 42. Results of multiple linear regression analyses of management and climatic variables on cotton nitrogen use efficiency in individual sites. Max till, number of tillage operations > 10 cm deep; Min till, number of tillage operations < 10 cm deep; N, N fertiliser applied (kg N/ha); Water, total water inputs, irrigation and rainfall (mm); T_{max}, annual average daily maximum temperature (^oC); T_{min}, annual average daily minimum temperature (^oC); SOC, soil organic carbon in 0-60 cm depth (t/ha), Legume, dummy variable for presence (1) or absence (0) of a leguminous rotation crop in the rotation; VIF, variance inflation factor.

Site	Variable	Coefficient	VIF	P <	R^2	n
Field C1, ACRI, Narrabri, NSW	Max till	-0.68	1.2	0.01	0.27**	61
	N	-0.025	1.1	0.01		
	T_{min}	-1.50	1.1	0.05		
	SOC	-0.13	1.3	0.01		
Field D1, ACRI, Narrabri, NSW	Legumes	6.55	1.0	0.01	0.50***	72
	Min till	3.26	1.1	0.01		
	Water	0.015	1.1	0.001		
“Glenarvon”, Wee Waa, NSW	T_{max}	-3.43	1.9	0.001	0.97***	16
	Min till	0.31	1.8	0.01		
	T_{min}	-6.27	1.1	0.001		
“Beechworth”, Merah North, NSW	Max till	-3.93	1.8	0.001	0.52***	41
	Min till	-1.85	1.5	0.001		
	N	-0.015	1.1	0.01		
	T_{min}	-9.94	2.3	0.001		
“Auscott-Warren”, Warren, NSW	T_{max}	1.23	2.6	0.01	0.94***	33
	T_{min}	-2.42	2.0	0.01		
	Water	0.0048	3.2	0.001		
	SOC	-0.39	2.0	0.001		
“Prospeect”, Warra, Qld	Min till	10.91	1.0	0.05	0.08*	45
Pooled results for all sites	N	-0.042	1.0	0.05	0.06**	276
	Min till	4.01	1.0	0.001		

As with SOC, yield and WUE there was considerable variation among individual sites with respect to the determinants of NUE (Table 42). SOC was negatively related to NUE in Field C1 at ACRI and Warren, and had no significant relationship at other sites. Within individual sites, total water inputs were positively related to NUE at Warren and Field D1 whereas mineral N inputs were negatively related at Merah North and Field C1. The inclusion of legumes in a crop rotation had a large positive effect on NUE in Field D1 at ACRI but did not do so at “Glenarvon”. This is probably because N applications rates were reduced in Field D1 to account for N fixation by the legumes but was not done so at “Glenarvon”. At Warra only the number of minimum tillage operations (mostly surface scarification) were weakly related to NUE. When the results were pooled across all sites, however, only N and the number of minimum tillage operations were significantly but poorly related to NUE. In summary, variable such as frequency of minimum tillage, N, water and average maximum and minimum temperatures played significant roles in determining NUE of cotton but varied across sites. In other words, no one variable could strongly account for the variations in NUE across all sites.

6.7 Effect of crop rotation on black root rot incidence

6.7.1 Tillage/rotation experiment in Field C1, ACRI

Measurement of black root rot infestation in cotton by the ACRI pathology unit indicated that lower black root rot scores occurred after sowing corn with least numbers occurring in the ex-cotton-wheat and greatest numbers in the ex-continuous cotton/conventional tillage plots (Table 43). Although other diseases were not monitored, it is possible that they may also have been reduced by sowing corn. Corn, therefore, has the potential to play a role as break crop to manage diseases in cotton farming systems. Further research is required on the ecology of the cotton-corn rotation.

Table 43. Effect of corn and historical cropping system on black root rot infestation and seedling dry matter production of cotton, December 2012 (sampled by ACRI Pathology unit). *, significantly different at 95% level of probability

Historical cropping system	+/- corn	Black root rot score	Seedling dry weight (g/plant)
Conventional till/continuous cotton	Corn	7.7	0.26
	Control	8.5	0.18
Permanent beds/continuous cotton	Corn	7.2	0.25
	Control	9.6	0.23
Permanent beds/cotton-wheat	Corn	5.3	0.31
	Control	6.1	0.26
SEM:			
Historical cropping systems (HCS)		0.59*	0.02
Corn (C)		0.37*	0.01*
HCS x C		0.65	0.02

6.7.2 Cropping systems experiment, Field D1, ACRI

Black root rot incidence in cotton seedling was measured during December of 2008-09, 2009-10, 2011-12, 2012-13 and 2013-14 seasons. Measurements could not be made during the 2010-11 season due to heavy rainfall and waterlogging of the site. Black root increased significantly ($P < 0.001$) with time (Table 43). A strong interaction occurred among rotations and time ($P < 0.01$) such that black root incidence during the latter years (2012, 2013) was highest in the cotton-wheat-vetch rotation. This may be associated with the wetter conditions that prevailed in this treatment.

Black root rot incidence had a significant effect on cotton seedling growth (Fig. 28). Results are presented in this report for all cotton seasons except for 2010-11. Seedling dry weight, however, was unrelated to treatment (i.e. rotation) but declined exponentially with intensity of black root rot. Some anomalous results occurred during 2013-14 cotton season when high black root rot scores were associated with higher values of cotton seedling dry weight, *viz*. better growth (see circled data points in Fig. 28). This may be related to the high irrigation frequency and high temperatures that prevailed during this season.

Table 43. Effect of rotation on black root rot infestations (represented as black root rot score) in young cotton. Values within parentheses are ln(black root rot score+1) transformed values. Sampled by ACRI Pathology Unit.

Rotation	**2008**	**2009**	**2011**	**2012**	**2013**	**Mean**
Cotton-vetch fb. Cotton-oats	1.7 (0.989)	2.1 (1.139)	3.0 (1.394)	3.9 (1.587)	5.5 (1.873)	3.0 (1.397)
Cotton-cotton	0.8 (0.614)	2.7 (1.320)	3.6 (1.535)	6.0 (1.952)	4.9 (1.769)	3.2 (1.438)
Cotton-wheat	1.2 (0.786)	2.7 (1.302)	4.1 (1.625)	4.9 (1.772)	4.1 (1.634)	3.2 (1.424)
Cotton-wheat-vetch	0.1 (0.112)	2.5 (1.240)	4.3 (1.668)	6.1 (1.955)	6.0 (1.952)	3.0 (1.385)
Mean	0.9 (0.625)	2.5 (1.250)	3.7 (1.556)	5.1 (1.816)	5.1 (1.807)	
	P <	sem				
Rotation	ns	(0.0494)				
Year	0.001	(0.0594)				
Rotation x year	0.01	(0.119)				

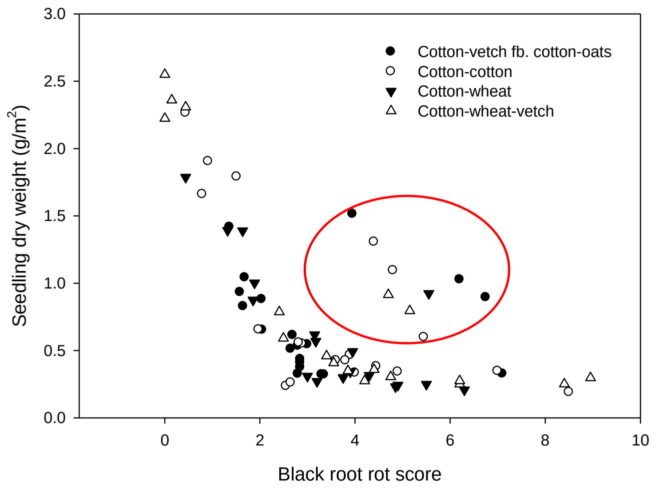

Fig. 28. Variation of cotton seedling growth (plant dry weight) with black root rot infestation rate. Pooled results from 2008-09 to 2013-14 season. Red-circled area indicates the anomalous results of 2013-14. Sampled by ACRI Pathology Unit.

7. Conclusions

Soil organic carbon:

- In general, SOC stocks in the 0-60 cm depth ranged between 50 and 70 t/ha. Legumes, even if they contribute large amounts of carbon to the soil are unable to retain it due to their low C/N ratios facilitating rapid microbial decomposition. Carbon inputs of C4 crops such as sorghum and corn were much larger than those of C3 crops such as wheat. A major proportion of that contributed by the C4 crops appear to come from their root systems. Short-term carbon storage in the subsoils may be enhanced by sowing a corn crop. However, the loss of carbon in the subsoils after only a single year suggests that the carbon deposited by the corn roots was highly labile. Further research needs to be conducted to understand the processes involved in carbon losses from the subsoil, where microbial activity is considered to be relatively low.
- SOC storage was positively related to dry matter inputs, average maximum temperature, number of minimum tillage operations and water availability but was negatively associated with N fertiliser inputs in only a single site. The results suggest that some management practices can be modified to minimise soil carbon losses
- Average maximum temperature and soil organic carbon in the 0-60 cm depth had curvilinear relationship. The temperature optima were higher in the Namoi valley (27-28 ^{o}C) than in the Macquarie (25.5 ^{o}C), presumably due to differences in the soils' ecosystems. Although not addressed in this report, it is known that that N and water have similar relationships to SOC.
- Net SOC sequestration rates were generally negative or neutral, except where a stressed soil (disease, sodicity, salinity) was in the process of recovering. Re-analysis of the results, including two previously unanalysed dryland sites (Warra, Emerald) indicated that in most sites there was an initial rapid decrease in SOC sequestration followed by a stabilisation or an increase (i.e. a reduction of the slope or a positive slope). In most, this change was associated with implementation of soil conservation measures (e.g. replacement of conventional management practices with soil conserving practices such as no-tillage, or replacing saline irrigation water with good quality water).
- Estimates of carbon inputs, based on above-ground and root dry matter, indicated that large losses of carbon were occurring in all soils. This was probably due to a combination of accelerated erosion, runoff and microbial decomposition. The carbon losses through the terrestrial pathway is being addressed in an ongoing project at ACRI.

Greenhouse gas emissions

- Life cycle analyses suggest that farming practises that could reduce emissions include reducing frequency and depth of tillage, excluding or minimising use of groundwater, sowing crops such as corn and wheat in rotation with cotton, reducing/optimising mineral N fertiliser rates, substituting a legume and thus, fixed N for mineral N fertiliser.
- Energy efficiency can be greatly improved by including crops that produce energy (e.g. grains, oilseeds etc.) in cotton-based farming systems.
- Given the constraints of the static chamber method noted earlier, the production systems studied in the project do not appear to result in sustained emissions of high concentrations of nitrous oxide. Episodic events with large fluxes were observed, and these can be correlated with incidence of gross system disturbances, such as irrigation and cultivation type operations (see above point). Carbon dioxide emissions are in line with what could be expected from an agricultural production system. Treatment effects are suggested by the data, but inherent variability masks much of the impact. In the absence of the availability of a continuous, automated system future sampling should be more intensively directed at a smaller number of targeted events.

Soil and water quality

- In a year when rainfall was frequent, surface concentrations of nitrate-N were higher where N fertiliser had been recently applied and where a legume had been sown whereas subsoil concentration were higher after the fallow in cotton-wheat or cotton-wheat-vetch. Length of fallow was also negatively correlated to SOC concentration in the soil surface.
- On-farm sampling indicated that corn crops resulted in short-term increases in surface carbon. More frequent use of corn may enhance carbon storage over the longer term.
- Enhanced leaching of nutrients and salts were indicated by the soil properties measured during 2011-2014 period.
- Soil faunal numbers during the cotton season were improved by retention of crop stubble as a surface mulch into which the cotton was sown. Further research in this area is suggested.
- Incorporation with a less aggressive implement such as an Aer-way cultivator before sowing cotton did not result in soil that was significantly different to soil where wheat stubble was retained as standing stubble. This suggests that mechanical weed control and/or control of volunteer cotton may be achieved with little impact on soil quality by using the Aer-way cultivator. Although there may be some negative consequences on water storage due to enhanced evaporation, in irrigated systems in self-mulching clay soils this may be relatively small or negligible.
- Irrigation water quality at ACRI improved during the period 2011-14 because of a greater use of good quality river and stored water from rainfall. Bore water quality was also better, presumably because of aquifer replenishment by the flooding events and heavy rainfall during the 2010-2012 period. Quality of the treated sewage effluent was generally poor and characterised by high alkalinity, salinity and SAR.

Soil hydrology

- Sowing corn as rotation crop did not have any significant effects on soil water storage during the following cotton season.
- During wet years or when irrigation was very frequent (i.e. 2013-14) conventionally-tilled treatments had higher soil water storage than minimum-tilled treatments. This may be associated with greater drainage under the latter.
- Soil water storage in the cotton-wheat-vetch rotation during the cotton season was higher than that in other rotations in Field D1. Retention of vetch and wheat mulch *in situ* in the cotton-wheat-vetch sequence may have facilitated rainfall harvesting.
- Soil water storage was highest in the winter fallow of the cotton-wheat rotation in Field D1. The water stored under this treatment was a combination of that received during the summer fallow and the limited rain received during winter. During the 2013-14 season, there was no rain during the early spring (October and the first half of November 2013). Thus, unlike in previous years, soil water storage under the cotton-wheat-vetch rotation was not replenished after vetch was killed because there was no spring rain. This differs from most previous years when replenishment took place such that cotton could be sown into a moist soil.

Root growth

- Cotton sown after corn had greater root densities than those sown after cotton
- In wet years, densities of sorghum roots were higher in the deeper subsoil than that of either wheat or vetch (see previous reports) but were comparable to that of corn, although under no-tillage sorghum values tend to be higher. In dry years, there was no difference between tilled and no-tilled sorghum. The deep and extensive root system of sorghum does show, however,

that roots of crops such as sorghum and corn, both C4 crops, can be important sources of carbon inputs into the soil.

Cotton yields and profitability

- Cotton yields were generally higher where wheat was included in the rotation. Sowing sorghum may result in yield losses due to nutrient imbalances.
- Inclusion of vetch was less profitable than a fallow or wheat rotation. With respect to gross margin/ha the difference was minor, but in terms of gross margin/ML the treatments without vetch were significantly more profitable. Generally, including vetch in the rotation did not result in sufficient improvements in cotton yield to compensate for the increase in production costs.
- In recent years, water has been the major limiting resource for cotton production, and consequently, cotton growers are looking for a farming system that gives them the greatest return by ML. The minimum-tilled cotton-wheat rotation consistently achieved the highest cotton yields and the highest gross margin/ML. In years of plentiful water (or when crop area is the limiting factor), however, reducing water application rates on a continuous cotton crop is a false economy.

Lint yield, WUE and NUE determinants

- Cotton lint yields, in general, were positively related to water and N inputs, soil aeration in some sites and average annual daily maximum temperature in cooler or poorly-drained sites but were lowered by higher average annual daily minimum temperature. In a sodic soil, a high frequency of the tillage practices intended to aerate the soil may have caused yield decreases, presumably due to exposure of more sodic soils.
- Depth and frequency of tillage, average annual maximum and minimum temperature, N and SOC played significant roles in determining WUE of cotton. The relative importance of individual factors varied greatly among sites.
- Frequency of minimum tillage, N fertiliser rates, water, presence of legumes and average maximum and minimum temperatures played significant roles in determining NUE of cotton. N fertiliser rate had a negative effect whereas legumes had a positive effect on NUE. The relative importance of individual factors varied greatly among sites.

8. Suggested areas of future research

- The processes related to long-term carbon sequestration in irrigated Vertosols and their interactions with rotation crop type, and soil physical and chemical properties such as clay mineralogy and aggregation.
- Pathways of carbon loss (erosion, dissolved organic carbon in runoff and drainage) and entry into irrigated and dryland cotton fields. It is acknowledged that this topic is under study in a separate project at ACRI (“Closing the Carbon Balance”). The authors of this report cannot emphasise too much the importance of this study.
- Identify origin of recalcitrant and stable soil carbon in cotton fields under differing management systems.
- Carbon distribution in the soil profile under differing rotation and irrigation systems. In other words, can combinations of irrigation methods and crop rotations facilitate carbon storage in the subsoil?
- Pathways of carbon loss and sequestration in the deep subsoil.
- Long-term research on crop management practices on soil fauna, and their impacts on soil structural attributes. In the same vein, how does deep compaction impact on soil fauna and

microflora? Can the soil biology be managed to minimise the deleterious effects of deep soil compaction?

9. Suggested/planned extension activities

- A significant number of extension staff from both public and private organisations equate soil management with fertiliser management, with little emphasis given to other aspects such as soil structure. Regular workshops are suggested as a pathway to extend the research outcomes from this and other projects related to soil management and farming systems and to maintain the skills base of the cotton extension staff. This is an issue that has been noted in several previous reports.
- Presentations to industry groups at workshops.
- Field tours and farm walks
- Being part of the extension network’s soil health and nutrition team and providing technical support to the Cotton extension staff when called upon to do so.
- Articles in rural industry magazines such as the “Australian Cottongrower” and “Spotlight” or newspapers such as “Agriculture Today” or the “Land”.
- Articles in local and regional newspapers.
- Via interviews with print and electronic media. The Cotton RDC could provide significant assistance in this area by identifying and contacting the relevant publications.

10. Problems encountered

- The resignation of Mr. Tim Weaver shortly after the commencement of the project resulted in the loss of significant expertise as he had been part of the research team at ACRI for more than 12 years.
- Obtaining accurate and complete records of site management practices was problematical. The Emerald farming systems experiment, for example, which was terminated in 2003 was excluded from many of the models as management inputs such as fertiliser rates were unavailable. Detailed records of site management could not be located because the Queensland DRNM staff responsible for site management had left the department some years previously.

11. Outcomes

The project had several outcomes which could be of significance to the Australian Cotton Industry. These are briefly summarised as follows:

- Identifying soil and crop management practices, and climatic variables that had direct impacts on soil carbon stocks, yield, water and nitrogen use efficiency in irrigated cotton soils. Modification of these management practices could improve soil carbon stocks, water and nitrogen use efficiency.
- Among rotation crops, identifying those that used the C4 photosynthetic pathway such as sorghum and corn as potentially being of more benefit with respect to sequestration of carbon in soil. Both of these crops have the potential to store carbon at depth because of their deep root systems when irrigated. This is not the case with cotton.
- Identifying practices that could reduce carbon footprint of cotton farming systems with life cycle analysis.

12. Training

The following student projects (Table 44) have either been completed or are on-going in the experimental sites described in this project:

Table 44. Postgraduate and honours research conducted within Project CRDC DAN 1202

Student	Degree	University	Years	Project title
T. B. Weaver	PhD (P/T)	Griffith University, Nathan, Qld.	2000-2014	Deep drainage and leaching in irrigated Vertosols
G. Quigley	B.Sc (Agric.)	University of Sydney, Sydney, NSW	2011-2012	Greenhouse gas emissions from cotton (*Gossypium hirsutum*) and corn (*Zea mays*) in farming systems in the Namoi Valley, Australia: A Lifecycle Assessment.
D. Rendon	PhD	Macquarie University, Sydney, NSW	2011-to date	Wolf spider population assemblage and predatory behavioral ecology in minimum-tilled cotton/grain rotation fields as a strategy for the conservation biological control of the bollworm *Helicoverpa*
C. Coleman	B.Sc (Agric.)	University of Sydney, Sydney, NSW	2012-2013	Potential contribution to soil carbon by cotton roots in minimum and maximum-tilled rotations

The project hosted three work experience students. They were:

- Robert Condran, Narrabri High School, Narrabri, NSW, 5 August 2013
- Kalinka Knudsen, Narrabri High School, Narrabri, NSW, 2 December 2013
- Katy Graham, Menai High School, Illawong, NSW, 4 December 2013

13. Communication of results

Results from this project have been disseminated in national and international technical journals and conferences, cotton industry publications such as the "Australian Cottongrower", ACGRA Cotton Conference Proceedings and field trial books, field days and industry workshops.

Specific details of published articles and oral presentations (1 July 2011 to 30 June 2014, including those “in press”) are given below. The hyperlinks for those items which have been published on-line are also provided.

13.1 Technical journals

1. Weaver, T.B., Ghadiri, H., Hulugalle, N.R., and Harden, S. (2012). Organochlorine pesticides in soil under irrigated cotton farming systems in Vertisols of the Namoi Valley, north-western New South Wales, Australia. Chemosphere, 88, 336-343.
2. Hulugalle, N.R., Weaver, T.B., and Finlay, L.A. (2012). Carbon inputs by wheat and vetch roots to an irrigated Vertosol. Soil Res., 50, 177-187.
3. Hulugalle, N.R., Weaver, T.B., Finlay, L.A., and Lonergan, P. (2012). Soil properties, black root-rot incidence, yield and greenhouse gas emissions in irrigated cotton cropping systems sown in a Vertosol with subsoil sodicity. Soil Res. 50, 278-292.
4. Weaver, T.B., Hulugalle, N.R., Ghadiri, H. (2013). Estimating drainage under cotton with chloride mass balance and an EM38. Comm. Soil Sci. Plant Anal., 44, 1700-1707.
5. Weaver, T.B., Hulugalle, N.R., Ghadiri, H., and Harden, S. (2013). Quality of drainage water under irrigated cotton in Vertisols of the lower Namoi valley, New South Wales, Australia. Irrig. & Drain., 62, 107-114.
6. Hulugalle, N.R., Weaver, T.B., and Finlay, L.A. (2012). Soil water storage, drainage and leaching in four irrigated cotton-based cropping systems sown in a Vertisol with subsoil sodicity. Soil Research, 50, 652-663.

7. Hulugalle, N.R., Weaver, T.B., Finlay, L.A., and Heimoana, V. (2013). Soil organic carbon concentrations and storage in irrigated cotton cropping systems sown on permanent beds in a Vertosol with restricted subsoil drainage. Crop & Pasture Sci., 64, 799-805.
8. Hulugalle, N.R. (2013). Maximum ambient temperature can influence carbon storage in Vertosols sown with cotton-based farming systems. Crop & Pasture Sci., 64, 845-855.
9. Senapati, N., Hulugalle, N.R., Smith, P., Wilson, B.R., Yeluripati, J.B., Daniel, H., Ghosh, S. Lockwood, P. (2014). Modelling soil organic carbon storage with RothC in irrigated Vertisols under cotton cropping systems in the sub-tropics. Soil Till. Res., 143, 38-49.
10. Hulugalle, N.R., Broughton, K.J., and Tan, D.K.Y (2014). Root growth and turnover of irrigated summer crops in Vertisols of Northern New South Wales Australia. Under revision.
11. Hulugalle, N.R., Broughton, K.J., and Tan, D.K.Y (2014). Fine root initiation and mortality of irrigated summer crops in cotton-based farming systems of northern New South Wales, Australia. Under revision.
12. Rendon, D., Whitehouse, M., Taylor, P., and Hulugalle, N. (2014). Influence of crop management on wolf Spider assemblages (*Araneae: lycosidae*) in an Australian cotton cropping system. Submitted.

13.2 Conference & workshop papers

1. Hulugalle, N.R., Weaver, T.B., and Tann, C. (2011). Minimum tillage systems can reduce heliothis pupae emergence in irrigated cotton farming systems. In “Resilient Food Systems for a Changing World”, Proc. 5th World Congress of Conservation Agriculture and 3rd Farming Systems Design Conference, 26-29 September 2011, Brisbane, Qld., pp. 468-469. ACIAR, Canberra, Australia.
2. Hulugalle, N.R., Finlay, L.A., and Weaver, T.B. (2011). A new approach to manage prostrate cover crops on permanent beds. In “Resilient Food Systems for a Changing World”, Proc. 5th World Congress of Conservation Agriculture and 3rd Farming Systems Design Conference, 26-29 September 2011, Brisbane, Qld., pp. 378-379. ACIAR, Canberra, Australia.
3. Hulugalle, N.R. (2011). Overcoming problems associated with retaining crop stubble on permanent beds in furrow-irrigated cotton farming systems. In “Resilient Food Systems for a Changing World”, Proc. 5th World Congress of Conservation Agriculture and 3rd Farming Systems Design Conference, 26-29 September 2011, Brisbane, Qld., pp. 380-381. ACIAR, Canberra, Australia.
4. Hulugalle, N.R. (2011). Greenhouse gas emissions from farming operations in a long-term cotton cropping systems experiment in an irrigated Australian Vertisol. Paper presented as a virtual poster at the 2011 Annual Meeting of the American Societies of Agronomy, Soil and Crop Science, San Antonio, TX, 16-19 October 2011.
5. Braunack, M., Hulugalle, N., and Rochester, I. (2012). Long-term rotation studies and the effect on soil organic carbon in cotton soils. Geophysical Research Abstracts Vol. 14, paper no. EGU2012-594. Proc. 2012 General Assembly of European Geosciences Union, Vienna, Austria, 22-27 April 2012.
6. Tan, D.K.Y., and Hulugalle, N.R. (2012). Carbon contributions from roots in cotton based rotations. Geophysical Research Abstracts Vol. 14, paper no. EGU2012-108. Proc. 2012 General Assembly of European Geosciences Union, Vienna, Austria, 22-27 April 2012.
7. Tan, D.K.Y., Broughton, K., Knox, O.G., and Hulugalle, N.R. (2012). Soil microbial biomass in Bt and non-Bt cotton. Geophysical Research Abstracts Vol. 14, paper no. EGU2012-14062.

Proc. 2012 General Assembly of European Geosciences Union, Vienna, Austria, 22-27 April 2012.

8. Hulugalle, N.R., Weaver, T.B., and Finlay, L.A. (2012). Carbon inputs by roots of wheat and vetch sown in rotation with irrigated cotton on permanent beds in a Vertisol. Proc. 19th Conference of the International Soil Tillage Research Association (ISTRO), and IVth Meeting of Sociedad Uruguaya de Ciencia del Suelo (SUCS), Montevideo, Uruguay, 24-29 September 2012, Paper no. 9. [CD-ROM]
9. Hulugalle, N.R., McCorkell, B.E., Weaver, T.B., and Finlay, L.A. (2012). Managing sodicity and exchangeable K in a rainfed Vertisol with deep tillage and soil amendments. In "Striving for Sustainable High Production", Proc. 19th Conference of the International Soil Tillage Research Association (ISTRO), and IVth Meeting of Sociedad Uruguaya de Ciencia del Suelo (SUCS), Montevideo, Uruguay, 24-29 September 2012, Paper no. 10. [CD-ROM]
10. Hulugalle, N., McCorkell, B., Weaver, T., and Finlay, L. (2012). Managing sodicity and exchangeable K with deep tillage and soil amendments. Proc. 16th Australian Cotton Conference, 14-16 August 2012, Broadbeach, Qld. http://www.australiancottonconference.com.au/2012-presentations-papers/hulugalle-nilantha-1
11. Hulugalle, N., Weaver, T., Finlay, L., and Heimoana, V. (2012). Soil carbon storage in irrigated cotton cropping systems sown on permanent beds. Proc. 16th Australian Cotton Conference, 14-16 August 2012, Broadbeach, Qld. http://www.australiancottonconference.com.au/2012-presentations-papers/hulugalle-nilantha-2
12. Guppy, C., Hulugalle, N., McLane, D. (2012). Phosphorus nutrition of vetch in cotton-based rotations. Proc. 16th Australian Cotton Conference, 14-16 August 2012, Broadbeach, Qld. http://www.australiancottonconference.com.au/2012-presentations-papers/guppy-christopher
13. Weaver, T.B., Ghadiri, H., Hulugalle, N.R., and Harden, S. (2012). Organochlorine pesticides in irrigated Vertosols of the Namoi valley, north-western New South Wales. In "Soil Solutions for Diverse Landscapes", Proc. 5th Joint Conference of Soil Science Australia and NZ Society of Soil Science, 2-7 December 2012, Hobart, Tas., p. 279. (ASSSI, Warragul, Vic., Australia)
14. Hulugalle, N.R., Weaver, T.B., and Finlay, L.A. (2012). Soil water storage and drainage under irrigated cotton sown on permanent beds in a Vertosol with subsoil sodicity. In "Soil Solutions for Diverse Landscapes", Proc. Joint Conference of Soil Science Australia and NZ Society of Soil Science, 2-7 December 2012, Hobart, Tas., pp. 610-615. (ASSSI, Warragul, Vic., Australia).
15. Brock, P.M., Herridge, D., Hulugalle, N., Madden, P., Schwenke, G.D., Tan, D., and Quigley, G. (2012). Identifying opportunities to reduce greenhouse gas emissions from agricultural production: a Life Cycle Assessment approach. In "Soil Solutions for Diverse Landscapes", Proc. 5th Joint Conference of Soil Science Australia and NZ Society of Soil Science, 2-7 December 2012, Hobart, Tas., p. 669. (ASSSI, Warragul, Vic., Australia).
16. Guppy, C., Hulugalle, N., McLane, D. (2012). Phosphorus nutrition of vetch in cotton-based rotations sown in a Vertosol from northern NSW. In "Soil Solutions for Diverse Landscapes", Proc. 5th Joint Conference of Soil Science Australia and NZ Society of Soil Science, 2-7 December 2012, Hobart, Tas., pp. 185-188. (ASSSI, Warragul, Vic., Australia).
17. Tan, D., Brock, P., Hulugalle, N., and Quigley, G. (2013). Life cycle assessment of cotton-corn farming systems in the Namoi Valley, Australia. In "Pathways to Greening Global Markets", Proc. 8th Life Cycle Conference, 16-18 July 2013, Sydney, NSW. (The Australian Life Cycle Assessment Society (ALCAS), Sydney, NSW, Australia). http://conference.alcas.asn.au/alcasprogram/Daniel_Tan_Reviewed_paper.pdf

18. Hulugalle, N.R., Weaver, T.B., Finlay, L.A., and Heimoana, V. (2013). Soil quality and CO2 emissions in irrigated cotton-based cropping systems. Proc. Inaugural Cotton Research Conference, 8-11 September 2013, Narrabri, NSW, p. 39. (Association of Australian Cotton Scientists, Narrabri, NSW, Australia).
19. Weaver, T.B., Hulugalle, N.R., Ghadiri, H., and Harden, S. (2013). Quality of drainage water under irrigated cotton in the lower Namoi valley. Proc. Inaugural Cotton Research Conference, 8-11 September 2013, Narrabri, NSW, p. 74. (Association of Australian Cotton Scientists, Narrabri, NSW, Australia).
20. Heimoana, V., and Hulugalle, N. (2013). Soil fauna under continuous cotton and a cotton-wheat-vetch rotation. Proc. Inaugural Cotton Research Conference, 8-11 September 2013, Narrabri, NSW, p. 69. (Association of Australian Cotton Scientists, Narrabri, NSW, Australia).
21. Coleman, C., Hulugalle, N.R., and Tan, D.K.Y. (2013). Root growth of cotton under monoculture and in cotton and corn rotations. Proc. Inaugural Cotton Research Conference, 8-11 September 2013, Narrabri, NSW, p. 67. (Association of Australian Cotton Scientists, Narrabri, NSW, Australia).
22. Quigley, G., Brock, P.M., Hulugalle, N.R., and Tan, D.K.Y. (2013). Cotton-corn farming systems in the Namoi valley - A life cycle assessment. Proc. Inaugural Cotton Research Conference, 8-11 September 2013, Narrabri, NSW, p. 52. (Association of Australian Cotton Scientists, Narrabri, NSW, Australia).
23. Hulugalle, N.R., Weaver, T.B., and Finlay, L.A. (2011). Soil carbon management and water conservation with irrigated permanent beds. Proc. Rural Climate Change Solutions Symposium, 3-4 May 2011, Armidale, NSW, Australia, p. 57, (Ed. A. Cowie). National Centre for Rural Greenhouse Gas Research, Armidale, Australia.
24. Hulugalle, N.R., and Heimoana, V. (2011). Cotton farming practices and greenhouse gas emissions. Proc. Climate and Soils Symposium, 21-22 September, West Pennant Hills, NSW, Australia, p. 28. NSW Department of Primary Industries, Orange, NSW, Australia.

13.3 Industry magazines, newspapers and extension publications[1]

1. Triantafilis, J., Hulugalle, N., Smith, R., Williams, D., Salinity Management subprogram of NSW DPI, and Roth, G. (2012). Irrigation salinity and water quality. In “WaterPak –A Guide for Irrigation Management in Cotton and Grain farming Systems, Version 3”, Ed. D. Wigginton, pp. 219-237. (CRDC, Narrabri, NSW, Australia).
2. King, D., Hulugalle, N., and Leven, T. (2012). Field selection and preparation. In “Australian Cotton Production Manual 2011”, pp. 58-60. (Cotton Catchment Communities CRC, Narrabri, NSW, Australia).
3. King, D., Hulugalle, N., and Leven, T. (2013). Field selection and preparation. In “Australian Cotton Production Manual 2011”, pp. 97-98. (CRDC, Narrabri, NSW, Australia).
4. Hulugalle, N.R. (2011). Cotton farming practices and greenhouse gas emissions. Paper presented at Australian Cotton Collective, 9-11 August 2011, Narrabri, NSW. http://www.cottonaustralia.com.au/news/download/7.%20SESSION%204_Nilantha%20Hulugalle_Reducing%20GHG%20emissions%20in%20cotton%20farming.pdf

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[1] Includes publications by staff from other organisations and units within NSW DPI where data collected by this project or its preceding projects were used.

5. Anonymous (2011). Mulch manager: An implement to manage vetch in cotton rotations. Australian Cottongrower 32(6), 30.
6. Anonymous (2012). New rotations increase soil water storage. P. 15, October 2012 issue of Ag Today. http://www.dpi.nsw.gov.au/aboutus/resources/periodicals/agriculture-today/october-2012/new-rotations-increase-soil-water-storage
7. Holden, J. (2013) "Research proves benefits of corn in cotton Rotation". On DuPont-Pioneer Australia's website. http://www.pioneer.com/web/site/australia/template.CMI/guid.DD42D44B-8DDE-B289-2EFA-9D7AD2940145/
8. Anonymous (2013) ""Research proves benefits of Corn in Cotton Rotation". Spring 2013 issue of "The Cob", p.8. http://www.maizeaustralia.com.au/cob_files/spring2013.pdf. (Based on an interview conducted by Stephen Smith, a journalist from the "Cob" the maize industry magazine, on developing cropping systems that include corn and cotton.

13.4 Presentations

Presentations by N. Hulugalle

1. Three poster presentations entitled (a) "Minimum tillage systems can reduce heliothis pupae emergence in irrigated cotton farming systems", (b) "A new approach to manage prostrate cover crops on permanent beds", (c) "Overcoming problems associated with retaining crop stubble on permanent beds in furrow-irrigated cotton farming systems" at the 5th World Congress of Conservation Agriculture and 3rd Farming Systems Design Conference, 26-29 September 2011, Brisbane, Qld.
2. An oral presentation entitled "Carbon inputs by roots of wheat and vetch sown in rotation with irrigated cotton on permanent beds in a Vertisol" and a poster presentation entitled "Managing sodicity and exchangeable K in a rainfed Vertisol with deep tillage and soil amendments" at the 19th Conference of the International Soil Tillage Research Association (ISTRO), and IVth Meeting of Sociedad Uruguaya de Ciencia del Suelo (SUCS), Montevideo, Uruguay, 24-29 September 2012.
3. An oral presentation entitled "Soil water storage and drainage under irrigated cotton sown on permanent beds in a Vertosol with subsoil sodicity" and an oral poster presentation entitled "Identifying opportunities to reduce greenhouse gas emissions from agricultural production: a Life Cycle Assessment approach" at the 5th Joint Conference of Soil Science Australia and NZ Society of Soil Science, 2-7 December 2012, Hobart, Tas.
4. An oral presentation entitled "Soil quality and CO_2 emissions in irrigated cotton-based cropping systems" and three oral poster presentations entitled (a) "Quality of drainage water under irrigated cotton in the lower Namoi valley", (b) "Soil fauna under continuous cotton and a cotton-wheat-vetch rotation", and (c) "Cotton-corn farming systems in the Namoi valley - A life cycle assessment" at the Inaugural Cotton Research Conference, 8-11 September 2013, Narrabri, NSW.
5. Field presentation to a group of agronomists, farmers and researchers from Israel on "Research and latest findings in long-term farming systems experiments at ACRI", ACRI, 5 February 2013.
6. Field presentation to newly-appointed Cotton Industry Development Officers on "Research and latest findings in long-term farming systems experiments at ACRI", ACRI, 6 February 2013.
7. Field presentation to a group comprising of staff from Dept of Climate Change, CRDC and Cotton Australia on "Research and latest findings in long-term farming systems experiments at ACRI", ACRI, 13 February 2013.

8. Field presentation to a group of Brazilian researchers and S. Yeates from CSIRO on “Research and latest findings in long-term farming systems experiments at ACRI”, ACRI, 21 March 2013.
9. Presentation to a group of African soils and agronomy researchers, Drs. Tan and Odeh from Sydney University on “Research and latest findings in long-term farming systems experiments at ACRI”, ACRI, 2 July 2013.
10. Field presentation to a group of TAFE (Certificate 111) students from TOCAL, Paterson, NSW on “Research in long-term farming systems experiments at ACRI”, ACRI, 6 November 2013.
11. Field presentation to a group of Young Cotton Leaders on “Research and latest findings in long-term farming systems experiments at ACRI”, ACRI, 23 January 2012. Visit organised by Cotton Australia.
12. Presentations made in field and conference room to group of Indian Researchers and producers on “Research and latest findings in long-term farming systems experiments at ACRI; laboratory management at ACRI”, 17 August 2012.
13. Field presentation to a group of Chinese research station and program managers on “Research and latest findings in long-term farming systems experiments at ACRI”, ACRI, 15 October 2012.
14. Field presentation to a group of TAFE students (Agriculture Certificate IV) on “Research and latest findings in long-term farming systems experiments at ACRI”, ACRI, 17 August 2011.
15. Field presentation to a group of Brazilian researchers and farmers on “Research and latest findings in long-term farming systems experiments at ACRI”, ACRI, 1 September 2011

Presentations by V. Heimoana

1. Oral presentation entitled “Cotton farming practices and greenhouse gas emissions” at the Climate and Soils Symposium, 21-22 September, West Pennant Hills, NSW.
2. Three poster presentations entitled (a) “Phosphorus nutrition of vetch in cotton-based rotations”, (b) “Soil carbon storage in irrigated cotton cropping systems sown on permanent beds” and (c) Managing sodicity and exchangeable K with deep tillage and soil amendments at the 16th Australian Cotton Conference, 14-16 August 2012, Broadbeach, Qld.
3. Field presentation to a group of West African soils and agronomy researchers on “Long-term farming systems experiments at ACRI”, ACRI, 15 March 2012.

Presentations by L. Finlay

1. Oral presentation on working as a technical support staff to Rotary Youth Agriculture Group on 18 May 2012 at ACRI, Narrabri, NSW.
2. Oral presentation/demonstration on soil science to years 5 and 6 students of Narrabri Public School on 3 August 2011 at Narrabri public School, Narrabri, NSW.

Presentations by other collaborators

1. Oral presentation by D. Tan entitled “Soil microbial biomass in Bt and non-Bt cotton” at the at the 2012 General Assembly of European Geosciences Union, Vienna, Austria, 22-27 April 2012.
2. Poster presentation by D. Tan entitled “Carbon contributions from roots in cotton based rotations” at the 2012 General Assembly of European Geosciences Union, Vienna, Austria, 22-27 April 2012.
3. Oral presentation by M. Braunack entitled “Long-term rotation studies and the effect on soil

organic carbon in cotton soils" at the 2012 General Assembly of European Geosciences Union, Vienna, Austria, 22-27 April 2012.

4. Oral poster presentation by T. Weaver entitled "Organochlorine pesticides in irrigated Vertosols of the Namoi valley, north-western New South Wales" at the 5th Joint Conference of Soil Science Australia and NZ Society of Soil Science, 2-7 December 2012, Hobart, Tas.
5. Oral poster presentation by C. Guppy entitled "Phosphorus nutrition of vetch in cotton-based rotations sown in a Vertosol from northern NSW" 5th Joint Conference of Soil Science Australia and NZ Society of Soil Science, 2-7 December 2012, Hobart, Tas.
6. Oral presentation by D. Tan entitled "Life cycle assessment of cotton-corn farming systems in the Namoi Valley, Australia" at the 8th Life Cycle Conference, 16-18 July 2013, Sydney, NSW.
7. Oral poster presentation by C. Coleman entitled "Root growth of cotton under monoculture and in cotton and corn rotations" 5th Joint Conference of Soil Science Australia and NZ Society of Soil Science, 2-7 December 2012, Hobart, Tas.

13.5 Theses

1. Quigley, G. (2012). Greenhouse gas emissions from cotton (*Gossypium hirsutum*) and corn (*Zea mays*) in farming systems in the Namoi Valley, Australia: A Lifecycle Assessment. B. Sc. (Agric) Honours thesis, University of Sydney, NSW
2. Coleman, C. (2013). Potential contribution to soil carbon by cotton roots in minimum and maximum- tilled rotations. B. Sc. (Agric) Honours thesis, University of Sydney, NSW.
3. Weaver, T. (2014). Deep drainage and leaching in irrigated Vertosols. PhD thesis, Griffith University, Nathan , Qld.

14. Acknowledgements

The technical assistance of Mr. L. Finlay is gratefully appreciated. Our thanks to the many cottongrowers who supported this project by providing land to conduct the trials, management expertise and continuing support and interest. Mr. B. McCorkell is thanked for biometrical support. We gratefully appreciate the support of Messrs D. Halliday (Manager ACRI) and D. Magann (Farm Supervisor, ACRI) with respect to on-station experiments, and laboratory and office facilities.

14. Budget

Item	**2011-12**	**2012-13**	**2013-14**
A. STAFFING			
Total Salaries	$81,321	$86,056	$91,068
On costs	$18,989	$20,094	$21,264
TOTAL	**$100,310**	**$106,150**	**$112,332**
B. TRAVEL			
Sustenance	$6,876	$6,510	$7,585
TOTAL	**$6,876**	**$6,510**	**$7,585**
C. OPERATING			
Soil & gas analyses	$14,522	$13,702	$14,522
Laboratory/field equipment maintenance	$2,800	$4,315	$2,831
Field sampling (inc. Vehicle costs)	$8,300	$8,875	$9,319
Replacement/upgrade parts for Minirhizotron Inc. insurance, customs duties etc.)	$15,000	$0	$0
Rental/leasing and licences/NSW DPI research levy	$13,950	$13,449	$13,892
Freight	$750	$750	$750
Economic analyses	$1,500	$1,500	$1,500
Extension/publication costs	$1,000	$1,000	$1,000
Farm operations	$35,000	$41,600	$35,000
TOTAL	**$92,822**	**$85,191**	**$78,814**
D. CAPITAL	0	0	0
GRAND TOTAL	**$200,008**	**$197,851**	**$198,731**

TOTAL FUNDS (2011-2014): $482,833

Appendix 1: Managing corn crop residues

Many growers who sow corn consider their residues to be “bulky” and manage them by either burning or incorporating with intensive tillage. However, our experience suggests that this is unnecessary, and that a permanent bed system can be maintained by careful management of the harvesting and post-harvest procedures thus:

- Harvesting: with a New Holland TR85 harvester with a 7 m open front. This left the corn stalks at a height of approximately 400 mm with the remainder being shredded as it went through the machine.
- Slashing of stubble: with a 4 m Howard slasher. Corn stalks ~ 100 mm high remained.
- Root cutting: with a 4 row hydraulic powered root cutter. This cuts the root system ~50 mm below the surface of the bed.
- The following figure shows post-harvest in-field residues and their subsequent decomposition during the winter and early spring.


Corn harvesting, March 2012


Corn residues, post-harvest 29 March 2012


July 2012


September 2012

Appendix 2: Effect of vetch in the rotation on the availability of P to subsequent crops

By Dr. C. Guppy, University of New England, Armidale

Introduction

Evidence from pot trials and some field trials suggests that break crops have the capacity to increase the availability of P to following crops, through changes in the lability of soil P reserves. To investigate this, archived soil samples collected from a 14 year old rotation trial at ACRI in Narrabri investigating the role of vetch as a break crop on cotton and wheat yields were examined for changes in 'rhizosphere' labile P using a novel fractionation scheme. The aim was to investigate if legumes in the rotation increased solution ($CaCl_2$-P); dilute organic acid (citrate-P) or organic P availability (enzyme labile-P) over time. Reserve P status was also monitored through a 1M HCl extract to track Ca-P pools.

Methods

Archived soil was collected from the ACRI long-term rotation trial managed by Dr Nilantha Hulugalle from 2002, 2006, 2009 and 2011. This rotation trial is minimum tilled, oriented in plots that are 165m long and 20 (1m) rows wide and constitutes a randomized complete block design with 6 treatments. The rotation included a cotton-fallow-cotton, and a cotton-vetch-cotton rotation, then variations on those that included wheat in the rotation with the stubble incorporated or left standing. Soil was sampled from 0-10, 10-30 and 30-60cm depths allowing investigation of subsoil effects on the lability of P.

The following extractions were undertaken on 1g of air-dried soil.

A) 0.01M $CaCl_2$
B) 0.1M citric acid
C) 0.02 EU phosphatase and phytase
D) 1M HCl

A. 1g of air-dried soil (2mm ground) was added to a 50 mL centrifuge tube with 20 mL of 0.01M $CaCl_2$ solution. Tubes were sealed and shaken end-over-end for 3 hours before centrifuging to clear the supernatant (15 minutes at 5000g). P in extract was measured using malachite green.

B. 1g of air dried soil (2mm ground) was added to a 50 mL centrifuge tube with 20 mL of 0.1M citric acid solution. Tubes were sealed and shaken end-over-end for 3 hours before centrifuging to clear the supernatant (15 minutes at 5000g). P in extracts was measured using malachite green.

C. 1g of air-dried soil (2mm ground) was added to three 50 mL centrifuge tubes.
One tube received 20 mL of a 0.02 EU solution of phytase and phosphatase buffer solution. The enzyme solution is a **15mM MES buffer with 2mM $MgCl_2$ and 1mM EDTA adjusted to pH 5.5**. A second tube received 20 mL of the enzyme (phosphatase and phytase) enriched buffer solution spiked with a 20 µg P/g of soil addition of Na phytate and Na glycerophosphate (10 µg P in each form).
The third tube received 20mL of buffer solution alone, to allow determination of enzyme labile organic P in contrast to buffer hydrolysed P. All tubes were sealed and shaken end-over-end for 3 hours before centrifuging to clear the supernatant. A 5 mL aliquot of supernatant was removed

and treated with 5 mL of 10% tri-chloro-acetic acid (TCA) solution to terminate the reaction. P in extracts was measured using malachite green.
NB: A spike of P to account for sorption of P released through enzyme action will be tested in preliminary trials was tested but was not necessary due to the wide soil:solution ratio. A spike of reagents was undertaken on all samples to ensure the method captured a consistent proportion of enzyme labile P. $MgCl_2$ was added to the buffer to stimulate activation of phosphorylating enzymes.

D. 1g of air dried soil (2mm ground) was added to a 50mL centrifuge tube with 20 mL of 1M hydrochloric acid solution. Tubes were sealed and shaken end-over-end for 3 hours before centrifuging to clear the supernatant (15 minutes at 5000g). P in extracts was measured using malachite green (following 1:5 dilution with DI water).

Results were analysed using JMP preliminarily using years as a nominal variable. Future alaysis will examine the power of each analysis

Results

Inclusion of vetch in the rotation had no effect on the availability of CaCl2-P (Table 1). Surface labile P was significantly higher than at depth, as expected, and labile P decreased slightly in 2006, but not agronomically significantly. Labile P values were consistently low.

Table 1. Effect of vetch in a range of cotton rotations on labile, $CaCl_2$-extractable P over 10 years in a Black Vertosol at ACRI, Narrabri, NSW. Values are the means of three replicates for each treatment, year and depth.

		Year							
		2002		**2006**		**2009**		**2011**	
		0.01M $CaCl_2$-P (mg/kg)		**0.01M $CaCl_2$-P (mg/kg)**		**0.01M $CaCl_2$-P (mg/kg)**		**0.01M $CaCl_2$-P (mg/kg)**	
Treatment	**Depth**	**Mean**	***Std Err***	**Mean**	***Std Err***	**Mean**	***Std Err***	**Mean**	***Std Err***
Cot-vet-cot	0-10	0.53	*0.06*	0.41	*0.05*	0.40	*0.07*	0.40	*0.12*
	10-30	0.19	*0.06*	0.11	*0.03*	0.23	*0.07*	0.16	*0.04*
	30-60	0.16	*0.03*	0.21	*0.07*	0.16	*0.06*	0.37	*0.13*
Cot-wfa-cot	0-10	1.19	*0.25*	0.53	*0.24*	1.06	*0.32*	0.32	*0.08*
	10-30	0.17	*0.09*	0.16	*0.07*	0.22	*0.11*	0.19	*0.05*
	30-60	0.18	*0.07*	0.19	*0.10*	0.18	*0.05*	0.26	*0.08*
Cot-whe-lfa-cot (wh inc)	0-10	1.50	*0.52*	0.50	*0.11*	0.83	*0.23*	0.39	*0.24*
	10-30	0.16	*0.07*	0.15	*0.03*	0.21	*0.08*	0.18	*0.01*
	30-60	0.12	*0.06*	0.08	*0.04*	0.19	*0.06*	0.21	*0.04*
Lfa-cot-whe (wh inc)	0-10	2.40	*1.58*	0.35	*0.15*	1.56	*0.70*	0.67	*0.32*
	10-	0.15	*0.08*	0.17	*0.09*	0.23	*0.08*	0.23	*0.02*

		Year							
		2002		**2006**		**2009**		**2011**	
		0.01M $CaCl_2$-P (mg/kg)		**0.01M $CaCl_2$-P (mg/kg)**		**0.01M $CaCl_2$-P (mg/kg)**		**0.01M $CaCl_2$-P (mg/kg)**	
Treatment	**Depth**	**Mean**	***Std Err***	**Mean**	***Std Err***	**Mean**	***Std Err***	**Mean**	***Std Err***
	30								
	30-60	0.23	*0.08*	0.29	*0.20*	0.17	*0.03*	0.31	*0.09*
Cot-whe-sfa-vet-cot	0-10	1.16	*0.65*	0.87	*0.54*	1.06	*0.50*	1.28	*0.72*
(wh sta)	10-30	0.08	*0.06*	0.18	*0.08*	0.18	*0.09*	0.18	*0.04*
	30-60	0.17	*0.04*	0.10	*0.01*	0.26	*0.10*	0.25	*0.01*
Lfa-cot-whe-sfa-vet	0-10	0.95	*0.22*	0.56	*0.16*	1.06	*0.40*	0.55	*0.16*
(wh sta)	10-30	0.16	*0.06*	0.24	*0.07*	0.22	*0.08*	0.20	*0.01*
	30-60	0.21	*0.10*	0.15	*0.03*	0.17	*0.04*	0.29	*0.06*

Where Cot (cotton); vet (vetch); whe (wheat); wfa (winter fallow); lfa (long fallow (summer and winter)); sfa (summer fallow); wh inc (wheat stubble incorporated); wh sta (wheat stubble left standing).

Inclusion of vetch also had no effect on citrate extractable P (Table 2). No significant treatment effects were observed. After rising by 10% over the first 4 years, citrate extractable P then fell by 20-30% from the beginning of the rotation trial, suggesting that plant extraction was occurring. There was slightly higher extraction from the 10-30cm depth, but citrate extractable P was reasonably uniformly distributed down the profile. Overall, citrate removed 45% of the total acid extractable P in these samples (r^2= 0.49).

Table 2. Effect of vetch in a range of cotton rotations on labile, citrate-extractable P over 10 years in a Black Vertosol at ACRI, Narrabri, NSW. Values are the means of three replicates for each treatment, year and depth.

		Year							
		2002		**2006**		**2009**		**2011**	
		Citric acid (mg/kg)		**Citric acid (mg/kg)**		**Citric acid (mg/kg)**		**Citric acid (mg/kg)**	
Treatment	**Depth**	**Mean**	***Std Err***	**Mean**	***Std Err***	**Mean**	***Std Err***	**Mean**	***Std Err***
Cot-vet-cot	0-10	93.3	*8.9*	102.1	*5.1*	59.8	*2.2*	64.8	*6.4*
	10-30	77.7	*3.3*	81.6	*4.7*	60.6	*2.9*	52.4	*2.8*
	30-60	75.3	*4.1*	87.9	*6.9*	77.1	*3.4*	57.7	*3.4*
Cot-wfa-cot	0-10	88.1	*8.5*	115.8	*21.9*	92.2	*17.5*	79.7	*30.8*
	10-30	88.0	*16.5*	99.4	*21.8*	67.7	*18.5*	63.9	*11.7*
	30-60	76.0	*9.5*	119.4	*22.0*	74.9	*18.7*	67.9	*12.2*
Cot-whe-lfa-	0-10	79.5	*20.8*	112.9	*9.5*	78.8	*14.1*	69.0	*17.0*

		Year							
		2002		**2006**		**2009**		**2011**	
		Citric acid (mg/kg)		**Citric acid (mg/kg)**		**Citric acid (mg/kg)**		**Citric acid (mg/kg)**	
Treatment	**Depth**	**Mean**	***Std Err***	**Mean**	***Std Err***	**Mean**	***Std Err***	**Mean**	***Std Err***
cot									
(wh inc)	10-30	79.7	*17.3*	94.8	*16.1*	65.5	*18.9*	60.5	*14.0*
	30-60	85.4	*21.9*	79.8	*3.9*	74.6	*15.7*	64.5	*11.3*
Lfa-cot-whe	0-10	92.3	*10.8*	87.1	*16.9*	90.5	*18.2*	75.3	*15.3*
(wh inc)	10-30	81.3	*12.3*	102.4	*8.6*	68.1	*15.5*	60.3	*3.5*
	30-60	83.8	*14.6*	85.4	*10.2*	70.9	*9.1*	59.3	*3.1*
Cot-whe-sfa-vet-cot	0-10	96.2	*16.0*	120.0	*30.1*	88.0	*30.3*	73.6	*11.8*
(wh sta)	10-30	92.0	*20.7*	95.9	*23.5*	72.0	*16.6*	63.6	*16.4*
	30-60	96.7	*17.2*	75.7	*14.3*	87.0	*21.2*	71.9	*20.6*
Lfa-cot-whe-sfa-vet	0-10	94.3	*15.4*	124.3	*25.1*	84.3	*17.4*	80.4	*14.5*
(wh sta)	10-30	89.5	*15.8*	102.1	*17.7*	68.6	*13.5*	67.2	*14.7*
	30-60	91.6	*21.2*	111.7	*27.1*	77.7	*11.4*	75.9	*16.9*

Where Cot (cotton); vet (vetch); whe (wheat); wfa (winter fallow); lfa (long fallow (summer and winter)); sfa (summer fallow); wh inc (wheat stubble incorporated); wh sta (wheat stubble left standing).

Enzyme labile P was low throughout all depths and treatments, reflecting the low organic matter present in most Vertosols and sample storage effects (Table 3). As expected, enzyme labile P was highest in the surface, but other than a slight, significant increase in enzyme-labile P in 2009, there was otherwise no difference due to time or treatment.

Table 3. Effect of vetch in a range of cotton rotations on enzyme-labile P over 10 years in a Black Vertosol at ACRI, Narrabri, NSW. Values are the means of three replicates for each treatment, year and depth.

		Year							
		2002		**2006**		**2009**		**2011**	
		Enzyme labile P		**Enzyme labile P**		**Enzyme labile P**		**Enzyme labile P**	
Treatment	**Depth**	**Mean**	***Std Err***	**Mean**	***Std Err***	**Mean**	***Std Err***	**Mean**	***Std Err***
Cot-vet-cot	0-10	1.39	*0.05*	1.35	*0.11*	0.59	*0.05*	1.16	*0.25*
	10-30	0.91	*0.04*	0.55	*0.04*	0.35	*0.02*	0.40	*0.04*
	30-60	0.59	*0.10*	0.72	*0.02*	0.39	*0.11*	0.48	*0.02*
Cot-wfa-cot	0-10	1.15	*0.08*	1.55	*0.22*	1.10	*0.20*	1.01	*0.09*
	10-30	0.91	*0.07*	0.77	*0.08*	0.43	*0.02*	0.65	*0.08*
	30-60	0.58	*0.10*	0.56	*0.22*	0.44	*0.01*	0.55	*0.08*
Cot-whe-lfa-cot	0-10	1.16	*0.18*	1.34	*0.19*	0.73	*0.43*	1.01	*0.09*
(wh inc)	10-30	0.64	*0.04*	0.71	*0.10*	0.38	*0.07*	0.53	*0.10*
	30-60	0.66	*0.08*	0.63	*0.06*	0.42	*0.05*	0.50	*0.02*
Lfa-cot-whe	0-10	1.25	*0.06*	0.85	*0.18*	1.02	*0.15*	1.42	*0.36*
(wh inc)	10-30	0.74	*0.18*	0.65	*0.14*	1.09	*0.60*	0.60	*0.16*
	30-60	0.62	*0.26*	0.75	*0.14*	0.31	*0.10*	0.54	*0.05*

		Year							
		2002		2006		2009		2011	
		Enzyme labile P		**Enzyme labile P**		**Enzyme labile P**		**Enzyme labile P**	
Treatment	**Depth**	**Mean**	***Std Err***	**Mean**	***Std Err***	**Mean**	***Std Err***	**Mean**	***Std Err***
Cot-whe-sfa-vet-cot	0-10	1.18	*0.10*	1.53	*0.41*	0.73	*0.05*	1.57	*0.40*
(wh sta)	10-30	0.74	*0.03*	0.63	*0.12*	0.29	*0.01*	0.43	*0.09*
	30-60	0.52	*0.03*	0.71	*0.12*	0.48	*0.09*	0.47	*0.07*
Lfa-cot-whe-sfa-vet	0-10	1.20	*0.17*	1.35	*0.21*	1.10	*0.13*	1.39	*0.02*
(wh sta)	10-30	0.91	*0.14*	0.77	*0.17*	0.22	*0.04*	0.58	*0.13*
	30-60	0.53	*0.11*	0.60	*0.04*	0.39	*0.01*	0.60	*0.10*

Where Cot (cotton); vet (vetch); whe (wheat); wfa (winter fallow); lfa (long fallow (summer and winter)); sfa (summer fallow); wh inc (wheat stubble incorporated); wh sta (wheat stubble left standing).

There no effect over 10 years in the various rotations, or with crop removal, on reserve P status in this Vertosol. Overall, reserve P was 4% higher at depth than in the surface 30 cm, but did not change otherwise (Table 4).

Table 4. Effect of vetch in a range of cotton rotations on reserve P over 10 years in a Black Vertosol at ACRI, Narrabri, NSW. Values are the means of three replicates for each treatment, year and depth.

		Year							
		2002		2006		2009		2011	
		HCl-P (mg/kg)		**HCl-P (mg/kg)**		**HCl-P (mg/kg)**		**HCl-P (mg/kg)**	
Treatment	**Depth**	**Mean**	***Std Err***	**Mean**	***Std Err***	**Mean**	***Std Err***	**Mean**	***Std Err***
Cot-vet-cot	0-10	182	*24*	163	*13*	150	*17*	188	*23*
	10-30	167	*15*	161	*16*	156	*11*	175	*16*
	30-60	184	*20*	194	*18*	184	*18*	185	*15*
Cot-wfa-cot	0-10	178	*24*	171	*32*	169	*32*	177	*30*
	10-30	168	*28*	173	*28*	155	*25*	180	*25*
	30-60	187	*36*	194	*27*	174	*24*	185	*21*
Cot-whe-lfa-cot	0-10	169	*27*	167	*18*	160	*31*	186	*47*
(wh inc)	10-30	161	*27*	171	*31*	145	*27*	171	*29*
	30-60	182	*41*	185	*23*	172	*27*	180	*30*
Lfa-cot-whe	0-10	179	*30*	156	*22*	169	*25*	197	*28*
(wh inc)	10-30	156	*19*	158	*20*	153	*22*	160	*20*
	30-60	176	*26*	186	*27*	165	*20*	175	*9*
Cot-whe-sfa-vet-cot	0-10	177	*29*	175	*36*	171	*42*	211	*54*
(wh sta)	10-30	152	*13*	162	*32*	150	*31*	170	*34*
	30-60	194	*37*	188	*31*	189	*29*	171	*29*
Lfa-cot-whe-sfa-vet	0-10	179	*26*	188	*29*	173	*31*	202	*33*
(wh sta)	10-30	178	*28*	183	*28*	160	*25*	182	*29*
	30-60	197	*39*	219	*37*	184	*24*	198	*30*

Where Cot (cotton); vet (vetch); whe (wheat); wfa (winter fallow); lfa (long fallow (summer and winter)); sfa (summer fallow); wh inc (wheat stubble incorporated); wh sta (wheat stubble left standing).

Discussion

Use of a ‘rhizosphere’ P fractionation scheme to measure changes in P availability over long time periods in a Black Vertosol from Narrabri was unable to detect any effect of inclusion of vetch in the rotation. The likely reasons for this include: a) there was no effect of rotation variation, or inclusion of legume on the lability of P pools; b) changes in these pools were transient, and soil collection in the fallow periods resulted in P concentrations falling back to their equilibrium values (precipitating out in the acid extractable fractions); c) buffering of labile pools from pools not measured in this fractionation scheme (pools other than reserve P, perhaps residual or sorbed fractions) prevented changes at the ‘pointy’ end of the P lability continuum from accumulating or d) the site itself had high enough background (reserve) P values, that detecting small changes in P in transient labile pools was unlikely.

On reflection, without the availability of long-term stable P isotopes to track changes between P pools in soils, it is difficult to detect and measure short-term changes in labile P in soils with considerable reserves of acid-extractable P. The observed benefits of vetch in the rotations observed at this trial site may have nothing to do with P dynamics at all, and may in fact be driven by changes in soil structure (which would affect root penetration and uptake of P); changes in labile N associated with N fixation, or improved aggregation and structure in the surface and at depth following brown manuring of vetch and the concomitant breakdown and mineralization of the residues.

Appendix 3: Assessment of long-term experiments at ACRI

By Dr. M. Braunack, CSIRO, Narrabri

Introduction

There are many benefits to be derived from long-term field experiments. Trends in crop yields and changes in soil conditions can be assessed which is not possible from short-term experiments. Long-term experiments can be more expensive due to cost of monitoring and analysis so the cotton industry is to be applauded for maintaining such experiments at the Australian Cotton Research Institute, Narrabri, NSW since 1985.

The long-term experiments are being conducted in fields C1 and D1 by NSW I&I (NSW DPI) and in field 6 east and west by CSIRO.

The objective of the first experiment is to determine the long-term effects of tillage and stubble management on soil quality, while the second experiment is to determine the effect of crop rotation on soil quality, deep drainage and nutrient leaching; and growth, yield and profitability of succeeding cotton crops on grey vertosols (Isbell, 1996).

The objective of the third is to diagnose nutritional problems, improve soil health and to determine the nutritional requirements of high yielding cotton crops, again on vertosol soils.

It is not possible to directly compare or contrast the long-term experiments as they were established with different objectives and although they are located on the same soil type; self mulching grey clay (Vertosol), as there are inherent differences between the soils at each site.

Hulugalle et al.. (2002-2005) state '….many cotton growers had shown an interest in utilising rotation crops and their management as an aid in maintaining soil quality cotton-based farming systems. As a consequence, several long-term experiments were conducted between 1993 and 2005 to evaluate the effect of rotation crops, their residual effects and retention of their stubble (i.e. standing stubble) on soil quality, field management, deep drainage and profitability.

These experiments showed that yield reduction with continuous cotton was related to a combination of structural degradation, sodicity, reduced nutrient uptake and increased disease incidence, all of which strongly interacted with soil conditions at the start of the trial, and management practices. Other issues such as higher profitability and ease of management of cereal rotations when compared with leguminous rotation crops, the poor performance of leguminous rotation crops under saline-sodic soil conditions, the potential for allelopathy following legumes (off station observation), potentially better nutrient cycling with deeper rooted cereal rotation crops, nitrogen benefits of legumes and differential soil quality, mainly soil physical changes, due to legumes and cereals were also identified.'

Hulugalle et al. (2005-2008) state '…..many cotton growers had shown an interest in utilising rotation crops and their management as an aid in maintaining sustainability of cotton-based farming systems. As a consequence, a research program on cotton rotations was initiated during the early 1990's with the main objective of identifying sustainable cotton-rotation crop sequences; viz. crop sequences which maintained and improved soil quality, minimised disease incidence, facilitated soil organic carbon sequestration, and maximised economic returns and cotton water use efficiency in the major commercial cotton growing regions of Australia. Several long-term experiments were conducted between 1993 and 2005 to evaluate the effects of the rotation crops, their residual effects and retention of their stubble (i.e. standing stubble) on soil quality, field management, deep drainage and profitability.'

Other issues identified included deep drainage and nutrient leaching and a decrease in soil organic carbon under the rotation system. Also, hairy vetch was identified as a possible control for black root rot in cotton.

The third long-term experiment was established in 1995 to determine the nutritional constraints to efficient cotton production. The broad objectives of the project are to diagnose nutritional problems of cotton crops, to improve soil health by including legumes as rotations with cotton and to determine the nutritional requirements of high yielding cotton crops.

2. Materials and methods

2.1 Field C1 (Tillage/rotation experiment)

Experiment commenced in 1985 with the following treatments (1) continuous cotton planted with conventional tillage (CC-MXT), (2) continuous cotton planted with minimum tillage (CC-MNT) and (3) cotton wheat rotation with cotton planted after minimal tillage and wheat stubble incorporation (CW-MNT) (Constable et al. 1992). After 2000 treatment (3) was altered in that the cotton was planted into standing wheat stubble. After harvest of the trial in 2002 the beds in the CC-MNT and CW-MNT were re-aligned and reformed after chiselling and discing as soil compaction was observed in some areas and rows were no longer parallel. In 2005 the plots were split to incorporate two irrigation regimes; a standard irrigation cycle of 7-14 days (frequent) and an extended irrigation cycle of 14-21 days (infrequent) (Hulugalle et al. 2005-2008).

Soil was sampled from 2002-2005 using 100 mm diam. cores with clods and bulk samples being collected from 0-0.1, 0.1-0.3, 0.3-0.6 and 0.6-1.2 m depths. Parameters assessed on < 2mm soil; plastic limit (hand & drop cone, Weaver and Hulugalle, 2001), coarse SOM (soil organic matter), EC (1:5 soil: water), $CaCO_3$ equivalent, exchangeable Ca, Mg, K and Na, ESP (exchangeable sodium percent), $EC_{1.5}$/ESC (sodicity index), total SOC (soil organic carbon) and nitrate nitrogen (nitrate electrode calibrated against Kjehldahl prior to 2007 and using Kjehldahl post 2007). Bulk density was determined on the collected clods using saran coat technique and the bulk density of the hills (0-0.15 m) (beds) was assessed on air-dry aggregates (1-10 mm) with kerosene saturation and using a weighted mean of the clods and aggregates. A dispersion index was measured by the ratio of the mass of particles <20um in suspension on immersion in water to the mass of particles <20 um in suspension on complete dispersion expressed as a percentage. Soil strength was measured using a recording penetrometer at regular intervals (not specified).

Soil was sampled again in 2006 and assessed as above. Additional soil sampling took place to assess the effect of wheel traffic and no-wheel traffic on soil conditions in furrows where cotton was planted conventionally or with minimum tillage.

2.2 Field D1 (Cotton/wheat/vetch rotation experiment)

Full details of the experiment are provided in (Hulugalle et al. 2009). Briefly four rotations were implemented with minimal tillage after harvesting cotton. Rotations consisted of (T1) Cotton-vetch (green manured)-cotton, (T2) Cotton-fallow-cotton, (T3a) Cotton-wheat- fallow (wheat stubble incorporated)-cotton, (T3b) Fallow-cotton-wheat- fallow (wheat stubble incorporated)-cotton, (T4a) Cotton-wheat-fallow (wheat stubble standing)-vetch (wheat stubble standing)-cotton-wheat and (T4b) Fallow-cotton-wheat-fallow (wheat stubble standing)-vetch (wheat stubble standing)-cotton-wheat (Table 1).

Soil was sampled initially in 2002 to establish a baseline and again in 2004 using 50 mm diam. core sample tube. Samples were collected at 0-0.1, 0.1-0.3, 0.3-0.6 and 0.6-1.2 m depths. The same soil parameters were assessed as for field C1 (see above).

No statistical analysis has been undertaken, only visual trends are considered.

2.3 Field 6

Details of rotations and methods are provided in Rochester et al. (2001). Briefly, five rotations were instigated on 1 m permanent hills using minimum tillage. Tillage was 0.1 m to pupae bust and to incorporate herbicide and stubble. The rotations included; continuous cotton every summer either with green-manured vetch each winter (CVCV) or winter fallow (C~C~C), and three rotations that included cotton every second year either with wheat then fallow (CW~C), wheat then vetch (CWVC) or faba bean then fallow (CFb~C), where ~ represents the fallow of 5-10 months. Cotton was fully irrigated and provided with adequate fertiliser, with all other rotation crops being rain-fed. Cotton, wheat and faba bean was harvested, while the vetch was incorporated four weeks prior to planting cotton. The full sequence of rotations is shown in Table 2.

Soil samples were collected, using a 52 mm diam. core tube, from 0-0.3 m in September prior to planting cotton and analysed for nitrate nitrogen (using a nitrate electrode). Soil organic carbon was measured from the same depth and also from 0.3-0.6 in 2004, 2006 and 2008 and from 0.6-0.9 m in 2006 and 2008. The large tap root from the previous cotton crop was removed from the sample, with all other organic material included in the analysis. Soil organic carbon was measured using a spectrophotometer at 600 nm after digestion with potassium dichromate and sulphuric acid.

3. Results

3.1 Soils

Soil physical and chemical properties of a site in close proximity to field C1 from the soil survey conducted on ACRI is shown in Table 3 (Ward et al.. 1999). For comparison soil chemical properties sampled in 2002 from field C1 are shown in Table 4. Similarly soil chemical properties for a site in close proximity to field D1 (Ward et al.. 1999) and for field D1 sampled in 2002 are shown in Table 5 and Table 6 respectively, while soil chemical properties for a site close to field 6 are shown in Table 7 (Ward et al.. 1999). Samples were not collected from the same depths between sampling times which makes a direct comparison problematic.

Australian soils are considered to be non-sodic, marginal to moderately sodic and strongly sodic if the ESP (exchangeable sodium percentage) is in the range 0-6, 6-14 and >14 respectively, while it has been proposed the equivalent values for New South Wales soils is 0-5, 5-10 and >10 respectively (Hazelton and Murphy, 2007).

The soils at sites near field C1 and D1 are similar in that they are sodic at depth (Table 3, 4) however the textures are slightly different. This is confirmed from the measurement of the same parameters in field C1 and D1 in 2002 (Table 4, 6).

Unfortunately soil chemical properties were not assessed on field 6 at the commencement of the experiment. However, measures made in 1999 at a site located close to field 6 indicate that in contrast to the soils in field C1 and D1, this soil is not sodic at depth (Table 7). Few soil chemical properties have been measured on field 6 (Table 8) and do not include any which indicate sodicity or salinity. Soil properties have not been assessed by depth or time on field 6.

Table 1 Rotation sequence for Field D1

Rotation	2002-03 summer	2003 winter	2003-04 summer	2004 winter	2004-05 summer	2005 winter	2005-06 summer	2006 winter	2006-07 summer	2007 winter	2007-08 winter
1	Cotton	Vetch$_{gm}$	Cotton	Vetch$_{gm}$	Cotton	Vetch$_{gm}$	Cotton	Vetch$_{gm}$	Cotton	Vetch$_{gm}$	Cotton
2	Cotton	Fallow	Cotton	Fallow	Cotton	Fallow	Cotton	Fallow	Cotton	Fallow	
3a	Cotton	Wheat	Wheat stubble incorp/fallow		Cotton	Wheat	Wheat stubble incorp/fallow		Cotton	Wheat	Wheat stubble incorp/fallow
3b	Fallow		Cotton	Wheat	Wheat stubble incorp/fallow		Cotton	Wheat	Wheat stubble incorp/fallow		Cotton
4a	Cotton	Wheat	Standing wheat stubble/fallow	Standing stubble/ Vetch$_{gm}$	Cotton	Wheat	Standing wheat stubble/fallow	Standing stubble/ Vetch$_{gm}$	Cotton	Wheat	Standing wheat stubble/fallow
4b	Fallow		Cotton	Wheat	Standing wheat stubble/fallow	Standing stubble/ Vetch$_{gm}$	Cotton	Wheat	Standing wheat stubble/fallow	Standing stubble/ Vetch$_{gm}$	Cotton

gm = Green manured

Table 2 Rotation sequence for field 6 west and field 6 east

West

Year ending	1	2	3	4	5	6
1995	~C~C	~C~C	~C~C	~C~C	~C~C	~C~C
1997	W~C	Pea~C	~C~C	Fb~C	~Soy~C	LL~C
1999	~C~C	Pea~C	W~C	Fb~C	~Soy~C	LL~C
2001	~C~C	VCVC	W~C	WVC	Fb~C	VCVC
2003	~C~C	VCVC	W~C	WVC	Fb~C	VCVC
2005	~C~C	VCVC	W~C	WVC	Fb~C	VCVC
2007	~C~C	VCVC	Oat~C	OatVC	Fb~C	V~C
2009	~C~C	VCVC	Oat~C	OatVC	Fb~C	V~C
2011	~C~C	VCVC	W~C	WVC	Fb~C	V~C

Where C=Cotton, W=Wheat, V=Vetch, Fb=Faba bean, Soy=Soybean, Oat=Oats, Pea=Field peas, LL=Lablab, ~=5-10 month fallow

1=0, 2=25, 3=50, 4=75, 5=100, 6=125 kg N/ha

East

Year ending	1	2	3
1994	~C~C	~C~C	~C~C
1996	~C~C	~LL~C	~Soy~C
1998	W~C	Pea~C	Fb~C
2000	W~C	Pea~C	~Soy~C
2002	W~C	WVC	VCVC
2004	Oat~C	OatVC	VCVC
2006	Oat~C	OatVC	VCVC
2008	Oat~C	OatVC	VCVC
2010	W~C	V~C	Fb~C
2012	W~C	V~C	Fb~C

1= 150, 2=175, 3=200 kg N/ha

Table 3 Soil profile properties 1992 (site 217) near Field C1 from Ward et al. (1999)

Depth cm	pH	EC mSm^{-1}	OC %	CaCO$_3$ %	Sand %	Silt %	Clay %
0-10	8.2	15.1	0.99	< 0.1	13	18	67
10-20	8.4	12.9	0.93	< 0.1	13	18	67
30-40	9.1	11.8	0.55	< 0.1	19	12	67
70-80	9.1	19.4	0.55	0.2	10	20	69
120-130	9.1	28.2	0.39	0.1	12	22	65
190-200	9.2	30.7	0.41	0.9	10	22	66
250-260	9.1	20.1	0.14	< 0.1	30	26	44

Depth cm	Cl mg kg^{-1}	NO$_3$-N mg kg^{-1}	P mg kg^{-1}	Ca$^{+}_{0.5}$ cmol kg^{-1}	Mg$^{+}_{0.5}$ cmol kg^{-1}	K^{+} cmol kg^{-1}	Na^{+} cmol kg^{-1}	Al$^{+}_{0.33}$ cmol kg^{-1}	Σcations cmol kg^{-1}	ESP %
0-10	44	3.2	52	26.0	15.5	1.8	1.5	<0.01	44.9	3.4
10-20	34	4.7	48	25.3	14.9	1.6	1.7	<0.01	43.5	4.0
30-40	15	1.6	40	24.2	16.0	1.0	3.4	<0.01	44.7	7.6
70-80	46	0.5	66	20.4	16.5	1.1	5.7	<0.01	43.6	13.0
120-130	190	0.5	48	17.8	13.9	0.9	7.7	<0.01	40.4	19.2
190-200	136	0.5	50	18.1	14.2	0.9	7.0	<0.01	40.2	17.5
250-260	223	0.5	30	14.4	8.3	0.4	5.5	<0.01	28.5	19.1

Table 4 Soil properties measured in Field C1 in 2002.

Depth (cm)	Ca^{++} cmol/kg	Mg^{++} cmol/kg	K^{+} cmol/kg	Na^{+} cmol/kg	ESP (%)	OC (%)	pH	EC$_{1:5}$ dS/m
0-15	19.7	9.4	1.7	0.6	1.9	0.9	6.5	0.36
15-30	22.0	11.1	1.1	0.9	2.6	0.7	6.9	0.23
30-45	22.5	12.2	0.9	1.5	4.0	0.6	7.1	0.19
45-60	21.8	12.5	0.8	1.9	5.1	0.6	7.0	0.16
60-120	19.9	13.3	0.9	2.6	10.9	0.5	7.1	0.20

Table 5 Soil profile properties 1992 (site 218) near Field D1 from Ward et al. (1999)

Depth cm	pH	EC mSm^{-1}	OC %	$CaCO_3$ %	Sand %	Silt %	Clay %
0-10	8.2	21.9	1.03	0.2	20	21	57
10-20	8.4	17.0	0.89	0.2	19	21	58
30-40	8.6	15.2	0.63	0.6	20	21	58
70-80	8.9	22.2	0.54	0.9	18	22	59
120-130	9.0	31.7	0.36	0.6	15	24	60
250-260	8.9	27.9	0.23	0.4	18	23	58

Depth cm	Cl mg kg^{-1}	NO_3-N mg kg^{-1}	P mg kg^{-1}	$Ca^{+}_{0.5}$ cmol kg^{-1}	$Mg^{+}_{0.5}$ cmol kg^{-1}	K^{+} cmol kg^{-1}	Na^{+} cmol kg^{-1}	$Al^{+}_{0.33}$ cmol kg^{-1}	Σcations cmol kg^{-1}	ESP %
0-10	105	1.1	45	25.5	11.0	1.5	0.9	< 0.1	38.9	2.4
10-20	65	1.1	39	24.6	12.1	1.5	1.0	< 0.1	39.2	2.5
30-40	27	0.6	10	23.4	12.4	0.9	1.6	< 0.1	38.1	4.1
70-80	20	0.5	24	19.9	14.2	0.8	4.3	< 0.1	39.3	11.0
120-130	88	0.6	35	16.8	13.8	0.8	6.5	< 0.1	37.9	17.1
250-260	141	0.8	26	16.5	12.8	0.8	5.5	< 0.1	35.6	15.4

Table 6 Soil properties measured in Field D1 in 2002

Depth (cm)	Ca^{++}	Mg^{++}	K^{+}	Na^{+}	ESP	OC (%)	pH	$EC_{1:5}$ dS/m	CEC	Clay, %	Silt, %	Sand, %	DI,%
0-10	23.8	12.8	1.6	0.9	2.3	0.8	6.8	0.4	39.0	62	13	25	3.4
10-30	21.5	13.3	1.2	1.1	3.0	0.6	7.0	0.3	37.1	64	9	27	3.1
30-60	19.8	14.6	0.8	2.2	5.9	0.5	6.9	0.2	37.4	65	10	25	3.2
60-120	15.8	15.2	0.8	3.9	10.9	0.5	7.3	0.3	35.6	65	12	24	3.8

Table 7 Soil profile properties 1992 (site 216) near Field 6 from Ward et al. (1999)

Depth cm	pH	EC mSm^{-1}	OC %	$CaCO_3$ %	Sand %	Silt %	Clay %
0-10	7.8	22.2	1.59	0.2	19	22	56
10-20	8.2	12.6	1.17	0.2	20	22	56
30-40	8.5	14.0	0.87	1.1	16	24	58
70-80	8.5	15.5	0.78	1.3	15	24	58
120-130	8.6	16.6	0.51	0.7	13	27	59

250-260	8.6	13.9	0.25	< 0.1	19	25	55

Depth cm	Cl mg kg^{-1}	NO$_3$-N mg kg^{-1}	P mg kg^{-1}	Ca$^{+}_{0.5}$ cmol kg^{-1}	Mg$^{+}_{0.5}$ cmol kg^{-1}	K^{+} cmol kg^{-1}	Na^{+} cmol kg^{-1}	Al$^{+}_{0.33}$ cmol kg^{-1}	Σcations cmol kg^{-1}	ESP %
0-10	69	1.6	58	23.1	7.2	2.1	0.3	< 0.1	32.7	0.8
10-20	47	1.3	10	23.8	7.1	1.3	0.4	< 0.1	32.6	1.3
30-40	32	0.8	16	25.5	7.8	0.6	0.6	< 0.1	34.5	1.8
70-80	29	1.1	29	21.7	11.0	0.7	0.9	< 0.1	34.3	2.6
120-130	14	0.6	25	19.4	11.8	0.6	1.7	< 0.1	33.5	5.0
250-260	10	8.7	30	19.7	11.5	0.5	2.4	< 0.1	34.1	7.0

Table 8 Soil properties from field 6

Depth cm	pH	OC %	Ca cmol kg^{-1}	Mg cmol kg^{-1}	K cmol kg^{-1}	Na cmol kg^{-1}	P mg kg^{-1}	S mg kg^{-1}	Cl mg kg^{-1}	NO$_3$ mg kg^{-1}	CEC cmol kg^{-1}
0-30	8.1	1.1	24.5	8.8	1.5	0.6	52.8	14.0	30.0	19.9	35.5

The difference in soil profile properties may reflect crop performance between the sites as cereals and legumes differ in their response to sodicity (Anon, 2009).

3.2 Fields C1 & D1

Calcium (Figure 1)

The levels of exchangeable calcium are in the very high range (> 20 cmol (+)/kg) for both sites (Hazelton and Murphy 2007). Calcium deficiency would not be an issue with respect to cotton growth. In field C1 the level of exchangeable calcium is more consistent over time and with depth in the profile, whereas in field D1 the level is consistent over time and decreases with depth down the profile. In field C1 conventional tillage continuous cotton (MXT_CC) contains more calcium than the minimum till continuous cotton (MNT_CC) or minimum till cotton wheat rotation (MNT_CW) treatments. There is little differentiation between treatments in field D1.

Potassium (Figure 2)

The level of exchangeable potassium is in the high range (0.7-2 cmol (+)/kg) for both sites (Hazelton and Murphy 2007). Potassium deficiency in cotton is unlikely at both sites. Exchangeable potassium decreases with depth in the profile at both sites with a slight trend of decreasing levels over time as well. Exchangeable potassium levels reflect seasonal conditions. There is little differentiation between treatments at both sites.

Magnesium (Figure 3)

For both sites the level of exchangeable magnesium is in the very high range (>8 cmol (+)/kg) (Hazelton and Murphy 2007). The level of exchangeable magnesium increased with depth down the profile and over time at both experimental sites. There was some variability over time which would be in response to seasonal conditions.

Sodium (Figure 4)

Exchangeable sodium levels range from high to very high (0.7-2, >2 cmol (+)/kg) at both sites (Hazelton and Murphy 2007). The level of exchangeable sodium increased with depth at both sites with higher levels occurring in field D1 compared with field C1. The response in sodium was consistent over time on field D1 whereas the level increased with time on field C1. There was little difference between treatments in D1 while the MXT_CC had slightly greater levels of sodium compared with the other treatments in C1.

Exchangeable Sodium Percentage (ESP) (Figure 5)

The ESP ranges from non-sodic (0-5) in the soil surface to marginally to moderately sodic (5-10) at depth on field C1 and from non-sodic (0-5) to strongly sodic (>10) at depth on field D1 (Pope and Abbott, 1989). The ESP increased with depth and over time on field C1 and remained relatively constant on field D1. The MXT_CC tended to have higher ESP than the other treatments while there was little separation between treatments on field D1.

Dispersion Index (Figure 6)

The dispersion index (%) was calculated as the mass of soil less than 20μm after immersion in water divided by the mass of soil less than 20μm after complete dispersion expressed as a percentage. In simple terms the bigger the percentage the greater the soil dispersion. The test provides an indication of soil dispersion for earthworks and formation of tunnelling. It also provides an indication for water turbidity due to soil dispersing and being entrained in runoff.

Soil at both sites fell into the category for slight dispersion (6-30 %) with the exception of 2002 in D1 where the category was negligible (< 6 %) through the soil profile. There was little differentiation between treatments at both sites.

Electrical conductivity ($EC_{1:5}$) (Figure 7)

The EC (dS/m) of the soils at both sites falls into the medium range (0.24-0.56 dS/m) of salinity; at this level moderately tolerant (to salinity) crops are affected (Hazelton and Murphy 2007). Cotton being tolerant (1-1.7 dS/m) to salinity and would not be affected at this level. In field C1 the EC decreased down the profile except for 1999 when there was a slight increase with depth. The overall trend was for EC to increase in the surface (0-10 cm) over time. There was little difference between treatments; however, MXT_CC was slightly higher than the other treatments. The EC was more variable in field D1 with some treatment differentiation in the surface soil with a decrease in EC to 30 cm and then an increase to 120cm. The treatments which included a legume and stubble incorporation had lower EC in the surface compared with the other treatments. The cotton-fallow rotation was consistently greater than the other treatments. The EC tended to decrease with time in field D1. The EC was variable down the profile and over time.

pH (Figure 8)

Soil pH affects the availability of plant nutrients and whether deficiency or toxicity may occur. The optimum range of pH for cotton is 5.5 to 7.0 (McKenzie, 1998). The major plant nutrients are readily available over this range. The pH has increased slightly with depth and time in field C1. In field D1 the pH increased both with depth and time under all treatments. There was little difference between treatments at both sites.

Soil Organic Carbon (SOC) (Figure 9)

Soil organic matter is associated with a soils physical and chemical fertility (Charman and Roper, 2007). Soil organic matter is calculated from the level of soil organic carbon by multiplying by the factor 1.72, so SOM (g/kg soil) = SOC (g/kg soil) * 1.72. It is recommended that only soil carbon levels (SI unit g C/kg soil: to convert to % values divide by 10) be reported. The levels of organic carbon can be considered as being in the range from moderate (1-1.8 %) in the soil surface to low 0.6-1 %) in the subsoil in both fields. The level of soil carbon will be largely determined by climatic conditions (rainfall/irrigation, temperature), soil type (clay, loam, sand) and land use (cropping/tillage, pasture, forestry). Soil organic carbon decreased with depth in both fields. In field C1 the level of organic carbon also decreased over time in the surface soil and subsoil with the MXT_CC treatment having lower levels of SOC than the MNT_CC and MNT_CW treatments. On field D1 the level of SOC also decreased with depth in the soil profile. However, the SOC of surface layer increased over time while the subsoil remained relatively constant with little separation between treatments. Seasonal variation was observed in both fields.

Profile water (Figure 10)

Profile water varied over the season in both field C1 and D1 reflecting conditions and possibly water management. For the earlier seasons there was little separation between treatments, however, as time progressed the MNT_CW treatment profile contained more water throughout the season. All treatments dried to about the same level at the end of the season with the exception of MNT_CC profile which was the driest at season end. There was greater variability between treatments over the season in field D1 with the stubble standing and stubble incorporated treatments being wetter than the cotton – vetch or cotton – fallow treatments. The stubble incorporated treatments were wetter than the stubble standing treatments in three out of the seven seasons for the experiment to date.

Cotton lint yield (Figure 11)

Lint yield varied with season and tended to increase over time in field C1. The MNT_CW treatment (standing stubble) consistently yielded higher than the other treatments although the MNT_CC (standing stubble) did out yield MNT_CW on one occasion. Lint yield varied with season and tended to increase over time in field D1. The stubble incorporated (T3a, T3b) and stubble standing (T4a, T4b) treatments consistently out-yielded the cotton-vetch (T1) and cotton-fallow (T2) rotations.

3.3 Field 6

Very few soil measurements have been made on this experimental field to quantify changes in soil physical or chemical properties over time as the experiment was established to look at cotton nutrition..

pH (Figure 12)

The surface soil (0-30 cm) pH has increased with time with the greatest increase under wheat-fallow-cotton followed by faba bean-fallow-cotton. Changes in pH reflect seasonal conditions with the smallest change occurring under systems which include a legume. Continuous cotton, wheat-fallow-cotton and faba bean-fallow-cotton had greater pH than rotations which included vetch. The soils under all treatments were more alkaline than the range of pH 5.5 to 7.0 which is suggested as being optimum for cotton (McKenzie, 1998).

Soil bulk density (Figure 12)

Soil bulk density increased with depth under all rotations and with time. There was little differentiation between rotations in the soil surface density (0.15 m) and greater separation at depth (0.45-0.75 m).

Soil organic carbon (Figure 13)

Soil organic carbon levels can be considered to be moderate in the surface soil and low in the subsoil and decreased with depth. Data by depth over time is only available for 2004, 2006 and 2008. The trend was for a slight decrease in soil organic carbon under all rotations except for faba bean-fallow-cotton which did not decrease as much compared with the other rotations. The wheat-vetch-cotton and cotton-vetch rotations had the highest level of soil organic carbon in the surface soil and for all seasons compared with all other rotations. Soil carbon increased slightly in the 30-60 cm depth between 2004 and 2008 for all rotations except for the wheat-fallow-cotton rotation.

Lint yield (Figure 14)

Lint yield increased over time under all rotations from 2005 to 2010. Continual cotton and the cotton-vetch rotation produced the least yield over time compared with the other rotations. There was little difference between Faba bean-fallow-cotton, vetch-fallow-cotton, wheat-fallow-cotton and wheat-vetch-cotton rotations in the season where planted.

Soil cone resistance (Figures 15, 16 17)

Soil cone resistance was measured at various times during the experiments. On all fields the maximum cone resistance was below 2000 kPa the value suggested as limiting root growth (Greacen et al. 1969). There is some indication of soil compaction in field C1 at 20-30 cm in the profile where the soil cone resistance peaks and then weakens below this depth.

Trend in soil organic carbon (Figure 18)

The trend in soil organic carbon is reported for the 0-30 cm depth as it is the only common measure across all experiments. Soil organic carbon varied between tillage treatment and rotations with a decline over time under all rotations in field C1. However, the minimum till cotton wheat rotation contained a greater amount of soil carbon compared with the other rotations. Soil organic carbon varied with time in field D1 with no one rotation having consistently greater soil organic carbon. The overall trend is for soil organic carbon to increase with time under all rotations in field D1; it is not obvious why the large spike in soil organic carbon occurred in 2007, it may be a seasonal effect where better water management resulted in greater crop productivity. In field 6 the overall trend in soil organic carbon was an increase over time under all rotations except for vetch-fallow-cotton where soil organic carbon decreased. There was greater differentiation between rotations in field 6 with wheat-vetch-cotton being consistently greater than all other rotations. Soil organic carbon under the rotation with faba bean was lower than all other legume rotations.

4 Discussion

The level of soil organic carbon (%) can vary from 0.6 % (1% SOM, soil organic matter) in sandy soil to 3 % (5% SOM) under fertile grassland (Rasmussen and Collins, 1991). The level of soil organic carbon in soils is influenced by climate (temperature, water), topography, parent material, vegetation and organisms and time, and varies spatially (Rasmussen and Collins, 1991). Changes in soil organic carbon are difficult to assess against the large background of soil carbon until sufficient time has passed for differences to be greater than analytical variability (Rasmussen and Collins, 1991). Changes over time require that levels of soil organic carbon need to be determined at the start of an experiment. If measurements of soil organic carbon have been made over time the same analytical technique needs to be used or if different method or a change in method has occurred some adjustment should be applied to the results to ensure consistency between times. Also, changes in soil bulk density over time will influence the amount of soil organic carbon reported in the profile.

Soil organic carbon is important to maintain soil fertility from a physical, chemical and biological perspective with respect to agricultural productivity. To maintain or improve soil carbon levels it is necessary to maintain or increase organic matter in soils. Soil organic carbon content is a major determinant of a soils physical condition, which affects water infiltration and permeability through the profile, nutrient supply and ultimately crop productivity. Changing land use from permanent pasture to arable agriculture results in a run down in soil organic carbon over time.

There are limited studies that have monitored/measured changes in soil organic carbon (Entry et al. 1996, Conteh et al. 1997, Mitchell and Entry, 1998, Hubbs et al. 1998, Mitchell et al. 2008, Hulugalle and Scott, 2008, Kaiyong et al. 2011, Rochester 2011) or soil fertility (le Mare, 1972) over time in cotton systems. On Alabama’s ‘Old Rotation’ (established circa 1896) soil organic carbon was greater in the soil surface (varying depth of sampling 0-10, 0-15 or 0-20 cm) under rotations that included a legume rotation crop and applied nitrogen (Entry et al. 1996, Hubbs et al.

1998, Mitchell and Entry 1998, Mitchell et al. 2008), with values ranging of 1 %, 1.3 % and 1.3 % for each depth respectively. These values are lower than values from the long-term experiments in Australia, however, the different soil type, environment and management would explain this variation. Conteh et al.(1997) assessed total soil carbon levels in the 0-20 cm depth from fields which had been under cultivation (including cotton) for varying lengths of time across the Australian cotton industry (Table 9). At all sites the surface soil (0-20 cm) organic carbon has decreased over time with the magnitude varying with soil type and starting level, which contrasts the results from the long-term experiments where the level of soil organic carbon has tended to increase with time or has remained static. The soil was sampled prior to going back into cotton, however, it is not known if a rotation crop was included in the system, whereas rotation crops were included in the long-term experiments and samples were collected from the 0-30 cm depth, which would result in greater amounts of soil organic carbon being reported. Similar to the long-term experiments reported, Kaiyong et al. (2011) reported that soil organic carbon increased in the 0-20 cm depth and decreased with depth down the profile to 1 m over a 20 year period. The greatest increase occurred in the 20-40 cm layer, which corresponded to the depth of incorporation of cotton stalks. This is contrary to the results of Rochester (2010) who found that while soil organic carbon increased in the surface soil (0-30 cm) it also increased at depth (60-90 cm) over a considerably shorter period of time compared with the study of Kaiyong et al. (2011). A direct comparison is not possible as the experiments occurred under different climatic conditions, on different soils and management (drip v furrow flood irrigation) and over varying time periods. It is speculated that the levels of soil organic carbon are probably closer to equilibrium in the Chinese study compared with the Australian study. It is difficult to determine the length of time required for soil organic carbon to reach a new level of equilibrium after perturbation as many factors (crop rotation, residue handling, tillage and so on) influence the outcome (Rasmussen and Collins, 1991). Given the relative short time that the reported experiments have been in place (Field C1: 27 yr, Field D1: 18 yr and Field 6: 10yr) soil organic carbon level may not have stabilised or it may reflect that new treatments have been superimposed over the original experiment. The study by le Mare (1972) highlights the importance of maintaining soil fertility and the interaction between nitrogen, phosphorus and potassium in maintaining cotton yield. Cotton yield was maintained using compost or ammonium sulphate for six years, however, both were required with triple super phosphate to maintain yield over a nine year period, after which yield declined and lime was required to correct soil pH. In the experiments reported, the only nutrient applied was nitrogen, and it was noted that phosphorus was in adequate supply in field 6 and only applied to all plots in field D1 on one occasion and none being applied to field C1. It is not possible to ascertain whether crop nutrition or interactions between nutrients influenced crop growth and hence biomass returned to the system. The fact that crop residues were initially incorporated and then retained as standing stubble (Field C1) or in a rotation system both incorporated or left standing (Field D1) will affect the amount of soil organic carbon in the system.

The general trend in soil organic carbon varied over time across all experiments with no rotation or treatment being consistently greater than any other. With the data plotted along the appropriate time line it can be seen that the soil organic levels in field 6 were greater at the commencement of the experiment that those in field C1 and D1. Soil organic carbon levels peaked in the year following establishment of the tillage-rotation experiment and have declined from then on, with the MXT_CC treatment having the least soil organic carbon over time. Soil organic carbon levels were the least on establishment of the rotation experiment in field D1 and have gradually increased over time with no clear differentiation between rotations. There was a spike in levels in 2007 the cause for this is not known. Starting soil organic carbon levels were greatest in field 6 and have gradually increased with time with the rotations that include a legume maintaining greater levels compared with continuous cotton or rotations including wheat. These trends tend to concur with that reported by Rasmussen and Collins (1991).

Measurement of soil strength was used as an indication in the improvement of soil quality under the different treatments at varying intervals. It was suggested that rotations including a legume resulted in lower soil strength; however, although profile water content did not differ between treatments at the time of measurement (when it was reported) it appears that it probably differed between times of assessment. This is illustrated in field C1 where the strength profiles for 2005 are greater than for the other two years of measurement. Also, when comparing vetch incorporated and vetch no-till in field D1 the response may only be due to soil disturbance. Measurements of soil strength in field 6 also suggest greater difference in yearly profile soil moisture rather than between treatments. The strength values rarely exceed 2000 kPa, the value which starts to limit root growth. It is assumed that the measurements were made in the crop row as it is usually not indicated. Differences between rotations and continuous cotton were measured at 10 cm and increasing strength below 10 cm indicated compaction (Hubbs et al. 1998), however soil moistures at the time of measurement were not reported and the strength profiles were highly variable. The strength profiles can only compared within years and not over time.

Table 9 Total soil organic carbon (%) in 0-20 cm depth from Australian cotton soils

Site	Time (yrs cult)	Red clay	Brown clay	Grey clay			Red brown earth		Alluvlial	Black earth	
				1	2	3	1	2		1	2
Gwydir	0	0.99	2.17	2.24							
	5	0.96	1.11	0.98							
	14	0.77	0.83								
	18			0.94							
Namoi	0			2.8	1.17	1.34					
	1				0.72						
	10					0.85					
	30					0.72					
	40			1.46			1.49	1.14			
Macquarie	0			1.08					1.17		
	2								0.6		
	4			1.07							
	10						1.1		1.09		
	12			0.78							
	50							0.82			
Bourke	0	0.65		0.39	0.36	0.47					
	1				0.31						
	5			0.38							
	16				0.32						
	25	0.48									
	27					0.28					
Mcintyre	0	1.01		1.51						1.61	
	6									1.28	
	8			0.65							

	20	0.87									
Darling downs	0			1.36	1.0	1.88				1.32	1.41
	40			0.93							
	50				0.81	1.12					1.07
	60									0.88	
Central Qld	0			3.31					1.22	1.34	
	10								1.07		
	12								0.87		
	15									1.13	
	21			0.88							
	22			1.07							

Allelopathy of grain legumes on cotton has been observed in an on farm trial and subsequently confirmed in laboratory and glasshouse assays (Hulugalle et al. 1998).

Lower field emergence of cotton occurred where legume grain (chickpea or faba bean) had been incorporated in the soil (self mulching grey clay, Vertosol) in an on-farm study near Wee Waa. This has not been observed in any of the on-station long-term rotations. Verticillium wilt was present in one season only.

Pot studies using cold water extract from crushed seed from wheat, chickpea, faba bean, cow pea, sorghum and dolichos was added to petri dishes to test cotton seed germination. Crushed seed from the same crops was added to soil in pots and cotton seeds planted. Germination and emergence was reduced in order of faba bean, chick pea < sorghum, wheat < control (water only). Dry matter and root length density of cotton was reduced in the same order.

Stubble from sorghum, barley and wheat, dolichos (2 varieties), soybean, faba bean, cow pea, lupin and lucerne was applied as a surface mulch or incorporated (equivalent to 4 t/ha) and 10 pre-germinated cotton plants were transplanted into pots.

Incorporated residues significantly reduced cotton height, nodes and dry weight compared with surface applied mulch. There was no difference between crop species, which suggests that differences exist between stubble and seeds in the allelopathic response. It was suggest that stubble be left on surface as a mulch and not be incorporated.

No allelopathy has been observed (Field 6) in the nutrition work which used faba bean or vetch to fix nitrogen. The stubble was incorporated which contrasts the recommendation of the above study.

Studies in the USA determined that cotton seedling development was inhibited by aqueous extracts from wheat straw and that subsequent laboratory bioassay identified cultivars that were tolerant or susceptible to the extract (Hicks et al. 1989), which agrees with the results above. When the cultivars were tested in field experiments emergence of cotton was affected only when the wheat straw was incorporated in the seedbed and in contact with the seed (Hicks et al. 1989).

Contrasts

Soils at all experimental sites differ with the greatest difference occurring between fields C1/D1 and field 6. Field C1 and D1 have greater sodicity at depth compared with field 6. Also, soil texture differs between fields which will affect soil water. The differences between soils do not allow direct comparisons between experiments.

Another problem is to account for differences in management of each site, were irrigations done at the appropriate time, were weeds and insects adequately controlled? Were soil borne diseases present in the fields, if so was there an impact on crop growth?

The time of soil sampling in relation to stubble incorporation is generally not recorded. Also, the sampling position is not specified, was it always in the crop row?

Field C1

Wheat stubble incorporated initially (from 1985 to 2000) and then since 2000 wheat stubble retained as standing stubble. This experiment has had several treatments imposed over the original design; hills were renovated after traffic caused compaction and realignment of rows occurred and an irrigation treatment has been in place since 2005 as sub-plots. These will affect the long-term crop response and carbon levels.

Field D1

Vetch stubble retained as surface mulch and following cotton planted through it. Land preparation was minimum tillage restricted to the hill after cotton was harvested.

No depth of tillage was recorded for either field but may be assumed to be 0.1 m, the depth for pupae busting.

Field 6

Legume stubble incorporated or green manured before being incorporated with shallow tillage. No depth of tillage/incorporation recorded but is assumed to be 0.1 m the depth of pupae busting.

The same rotations have not been in place since the experiment was initiated in 1995.

No soil measurements undertaken on field 6 to determine changes in soil physical or chemical properties with depth to enable benchmarking.

No soil water profiles have been measured during the conduct of the experiment.

It is well known that soil temperature and water contribute to carbon turn-over.

It is not certain that the minimum tillage for stubble incorporation in each experiment is similar. The fallow period for each experiment is not the same with a summer and winter fallow being in place in one experiment compared with a winter fallow in the other. This would affect the amount of potential carbon input into each system.

Soil samples have been collected at different depths on each field which makes direct comparison between rotations difficult. No soil moistures were sampled when soil cone resistance measurement occurred on field 6. Soil moisture influences soil cone resistance; as the soil dries soil strength increases. The reported benefit by including a legume in the rotation in reducing soil strength is difficult to substantiate from the data as the differences may be due to soil moisture. The variation in soil resistance over time is due to seasonal differences in soil moisture or possibly measuring in a row which had traffic either side.

Suggestions for improvement

Coordinate planting dates and sampling times could be instigated so each rotation is exposed to similar environmental conditions. A common cotton cultivar could be planted at each site. A standard suite of measurements should be made to enable comparison between rotations. The only common rotation at each site is continual cotton. The cotton-vetch-cotton rotation is common to field D1 and field 6. Soil samples should be collected from the same depths to enable comparison between experiments. Very few soil physical parameters have been measured in the experiments. Soil bulk density is critical for the determination of volumetric soil water and establishing the amount of carbon and nutrient in soils. To this end cores of 7.5 cm diameter and 5 cm long should be utilised. The current practice of using core tubes 5 cm diameter and 120 cm long can contribute to errors in bulk density due to compression and sample loss. It is understood why the technique is used for ease in sampling and time; however is it worth compromising the result?

Notwithstanding the above, each experiment was initially established with a different objective which makes it difficult to compare results. However, the results indicate that under certain rotations soil organic carbon is increasing slightly (on a percent carbon basis) while under other rotations it is declining. This probably reflects seasonal conditions, management and soil type. These experiments provide some indication for the cotton industry for carbon sequestration. However, greater care needs to be taken in sampling procedures especially in soil bulk density as this can vary widely over relatively small areas.

Conclusions

In the 0-30 cm depth the results from field C1 demonstrate that soil organic carbon decreases over time under conventional tillage, whereas under minimum tillage the decrease is not as great, especially when wheat is included in the rotation. Differences between treatments are greater when viewed on a seasonal basis. The rotation experiment in field D1 demonstrates that while starting from an initial low base of soil organic carbon it is possible to increase the level over time by utilising rotations with cotton. When wheat stubble is left standing or incorporated the increase is greater, and when a legume is included in the rotation as a green manure (not incorporated) a further increase in soil organic carbon occurs, this however, varies between seasons with no one rotation being consistently high or low. It is uncertain why the spike in soil organic carbon occurred in 2007 in field D1 as no corresponding spike occurred in field C1. Soil organic carbon was not assessed in field 6 in 2007. Soil organic carbon was at a greater level in field 6 at the beginning of the experiment compared with that in fields C1 and D1, and has maintained greater levels for the duration of the experiment so far. Rotations that include a legume also had greater levels of soil organic carbon than the continuous cotton and wheat fallow rotation. All rotations have increased the soil organic carbon level in the 0-30 cm depth, except for the vetch fallow cotton rotation which has decreased over time.

The messages coming from the long-term experiments should be similar with respect to the use of rotations in the cotton system. There is a difference in philosophy in handling stubble/residues between the experiments, however pupae busting, which involves tillage to 10 cm occurs in all experiments. It is not apparent that this is the only tillage operation that occurs as pupae busting would not result in complete incorporation of stubble. The main differences between the long-term experiments are the soils; field C1 and D1 are sodic at depth, while field 6 is not. This will affect cotton and rotation crop growth and resulting stubble load and hence soil organic matter returned to the system. Also, the sites commenced with different levels of soil organic carbon. This will affect the magnitude and rate of change in soil organic carbon over time. It may be not be appropriate to place great emphasis on change in soil organic carbon over short periods of time, especially with respect to sequestration as measurements at depth down the profile have only been done on two occasions in field 6. The use of small soil cores (50 mm) for bulk density determination can cause compression of the sample resulting in greater bulk density than naturally occurring in the profile (McKenzie et al. 2002). This will inflate the estimate of soil organic carbon reported.

Changes in treatments may impact on soil organic carbon dynamics and it will take time before a new equilibrium is established.

Field C1 & D1

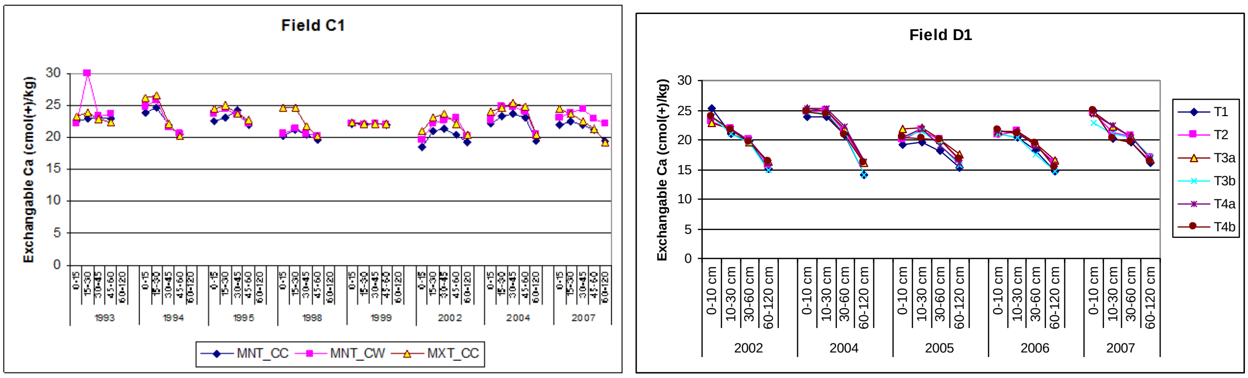

Figure 1 Exchangeable calcium Field C1 and D1

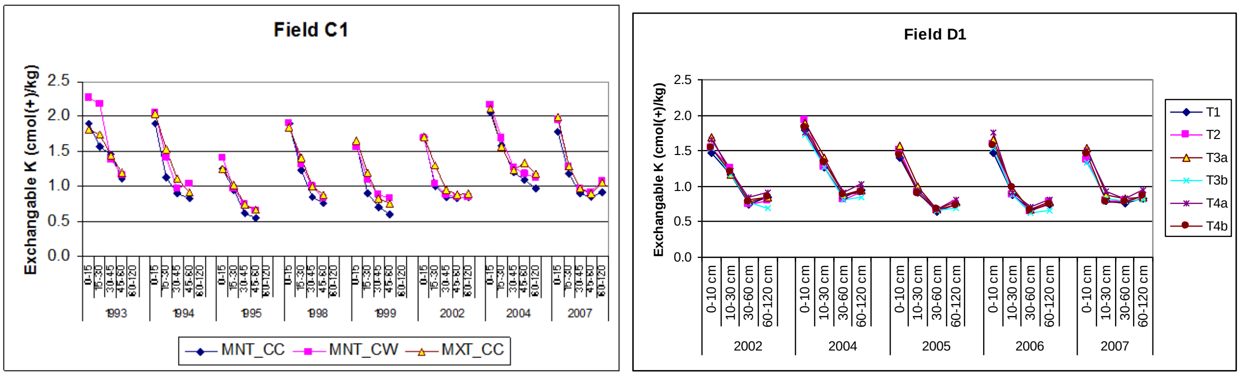

Figure 2 Exchangeable potassium Field C1 and D1

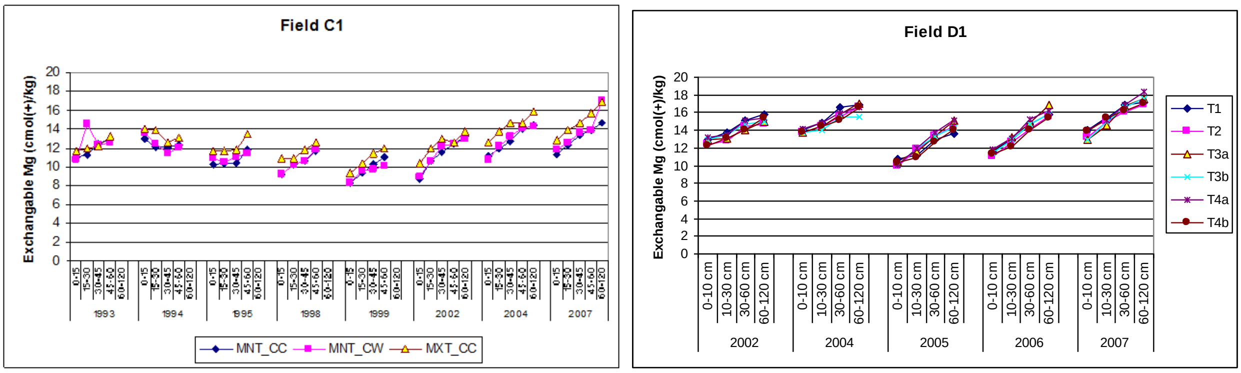

Figure 3 Exchangeable magnesium Field C1 and D1

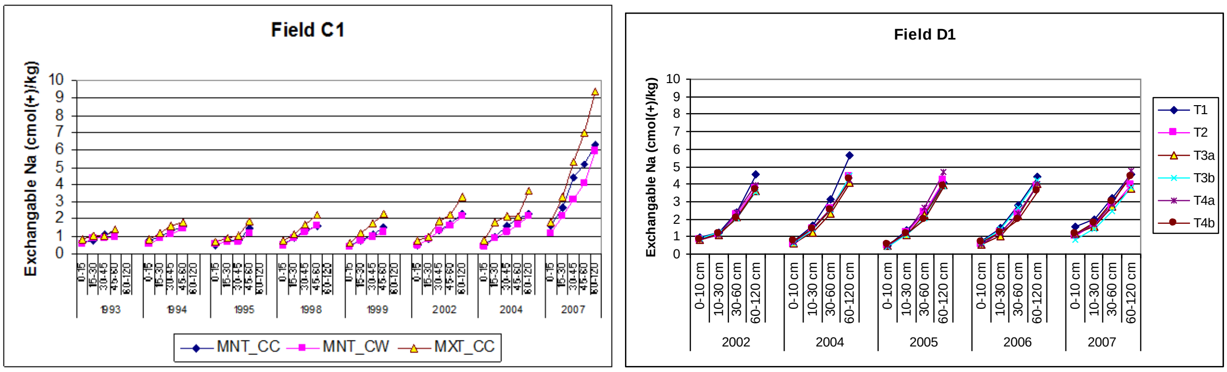

Figure 4 Exchangeable sodium Field C1 and D1

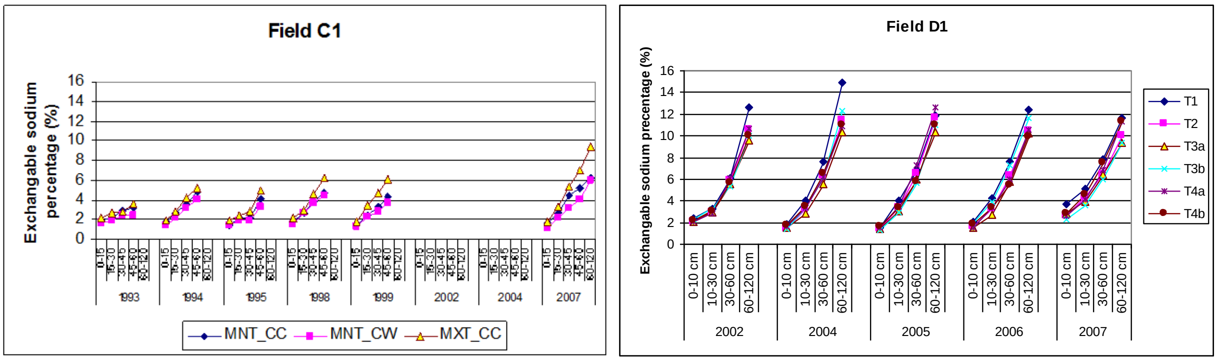

Figure 5 Exchangeable sodium percentage Field C1 and D1

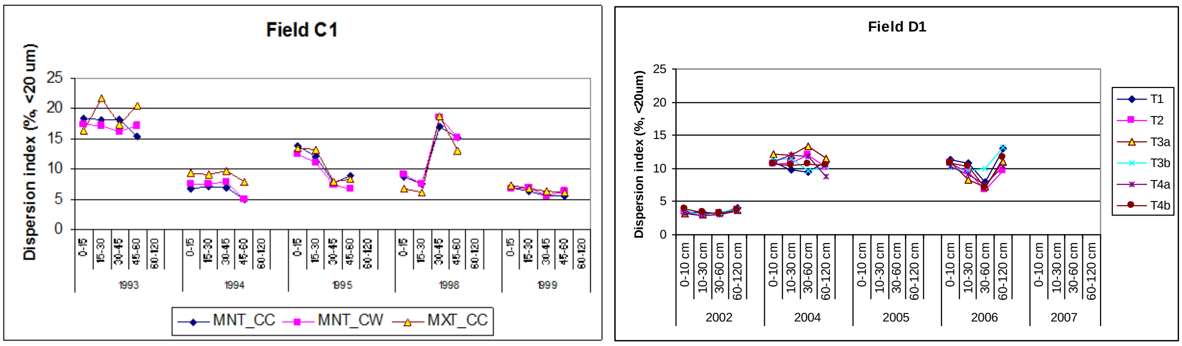

Figure 6 Dispersion index Field C1 and D1

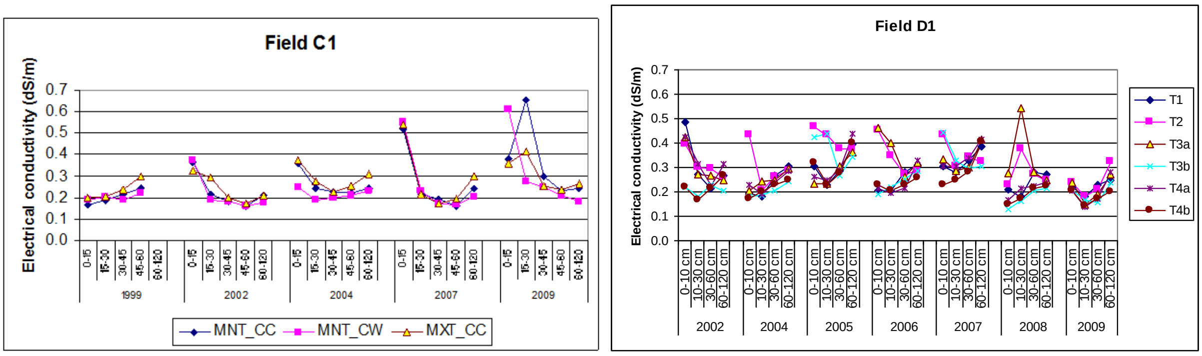

Figure 7 Electrical conductivity Field C1 and D1

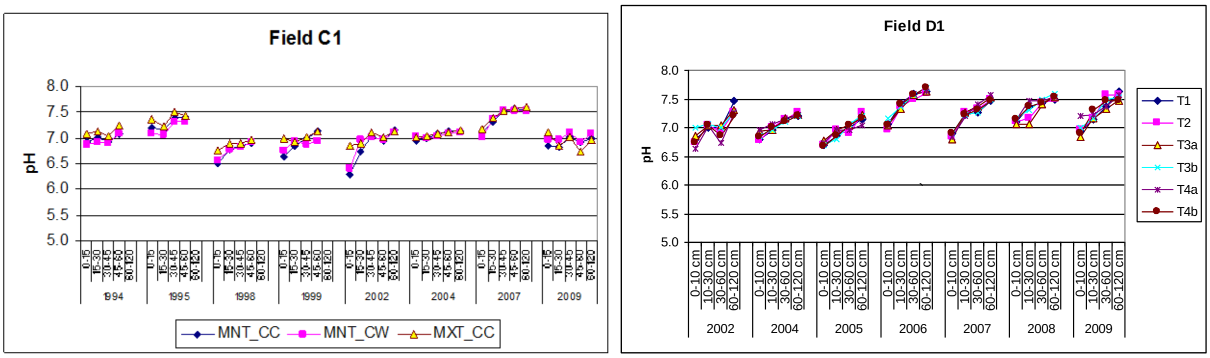

Figure 8 pH Field C1 and D1

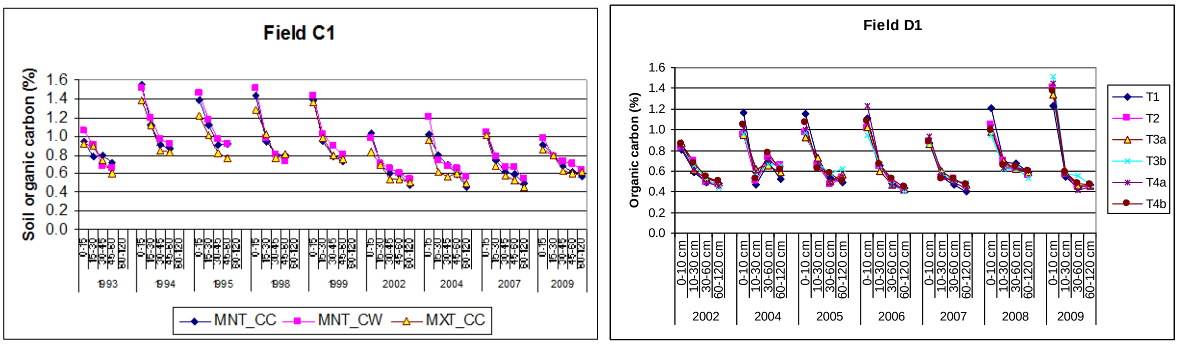

Figure 9 Soil organic carbon Field C1 and D1

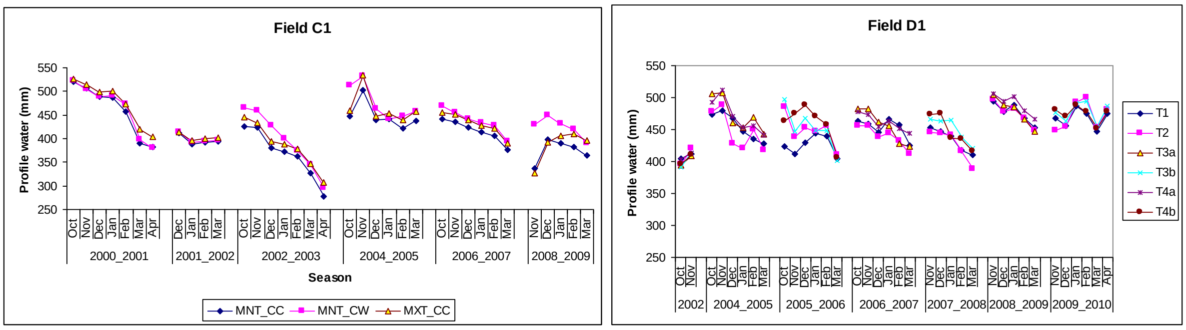

Figure 10 Season soil profile water Field C1 and D1

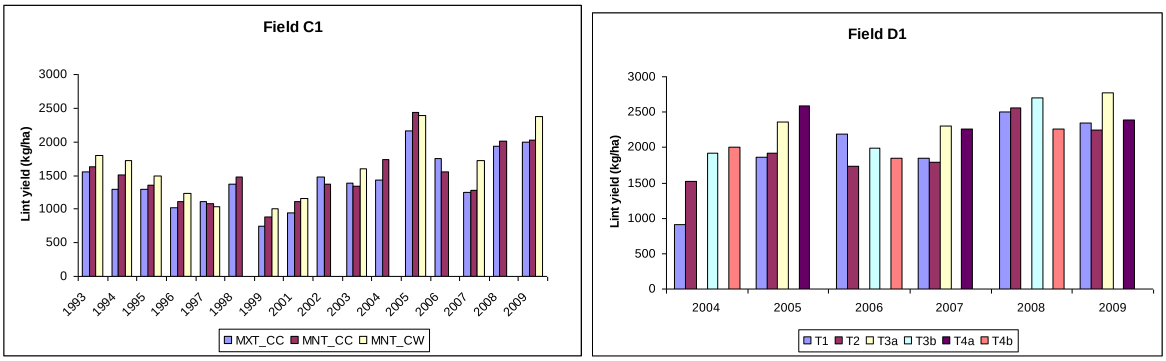

Figure 11 Lint yield Field C1 and D1

Field 6

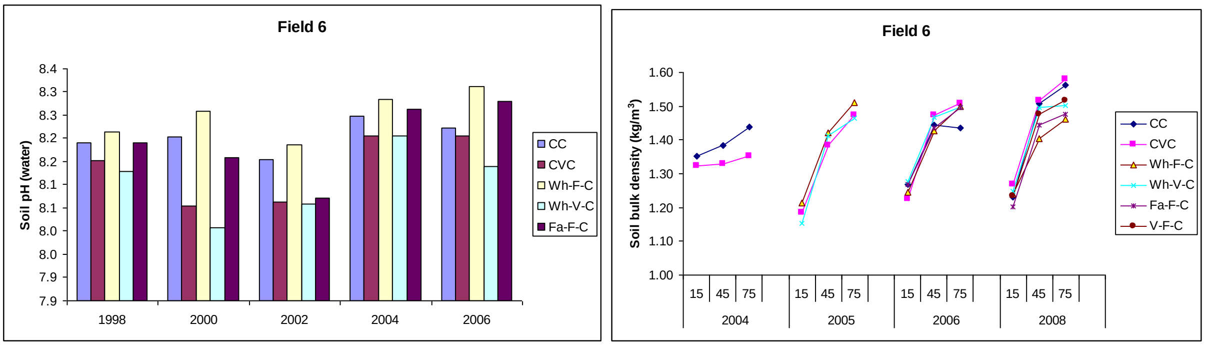

Figure 12 Soil pH and bulk density Field 6

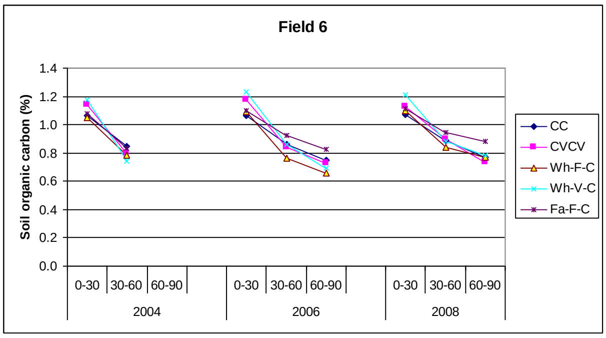

Figure 13 Soil organic carbon Field 6

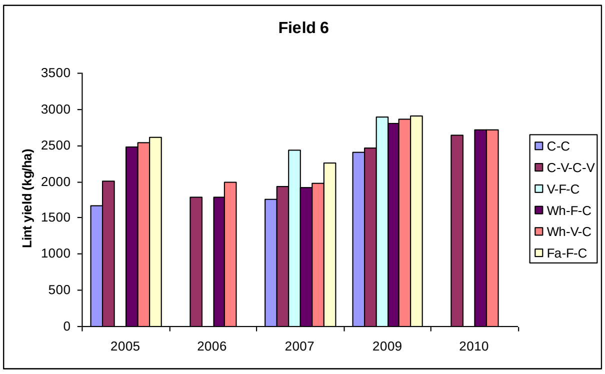

Figure 14 Lint yield Field 6

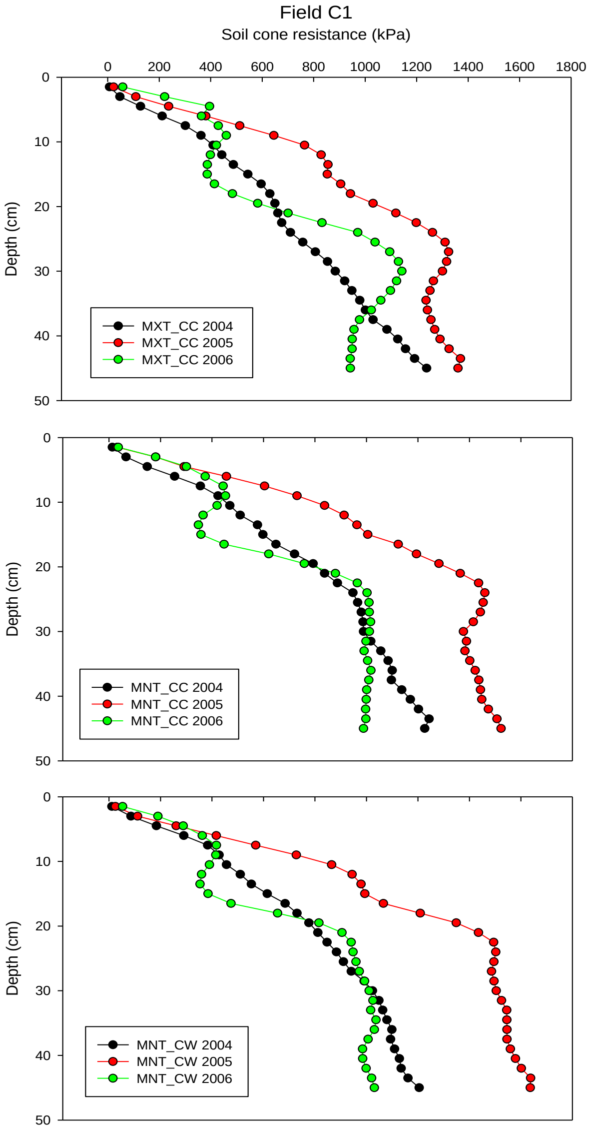

Figure 15 Profile soil cone resistance Field C1

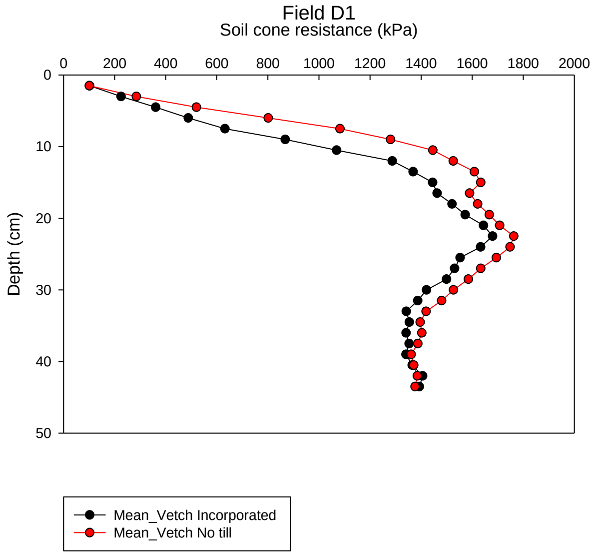

Figure 16 Profile soil cone resistance Field D1

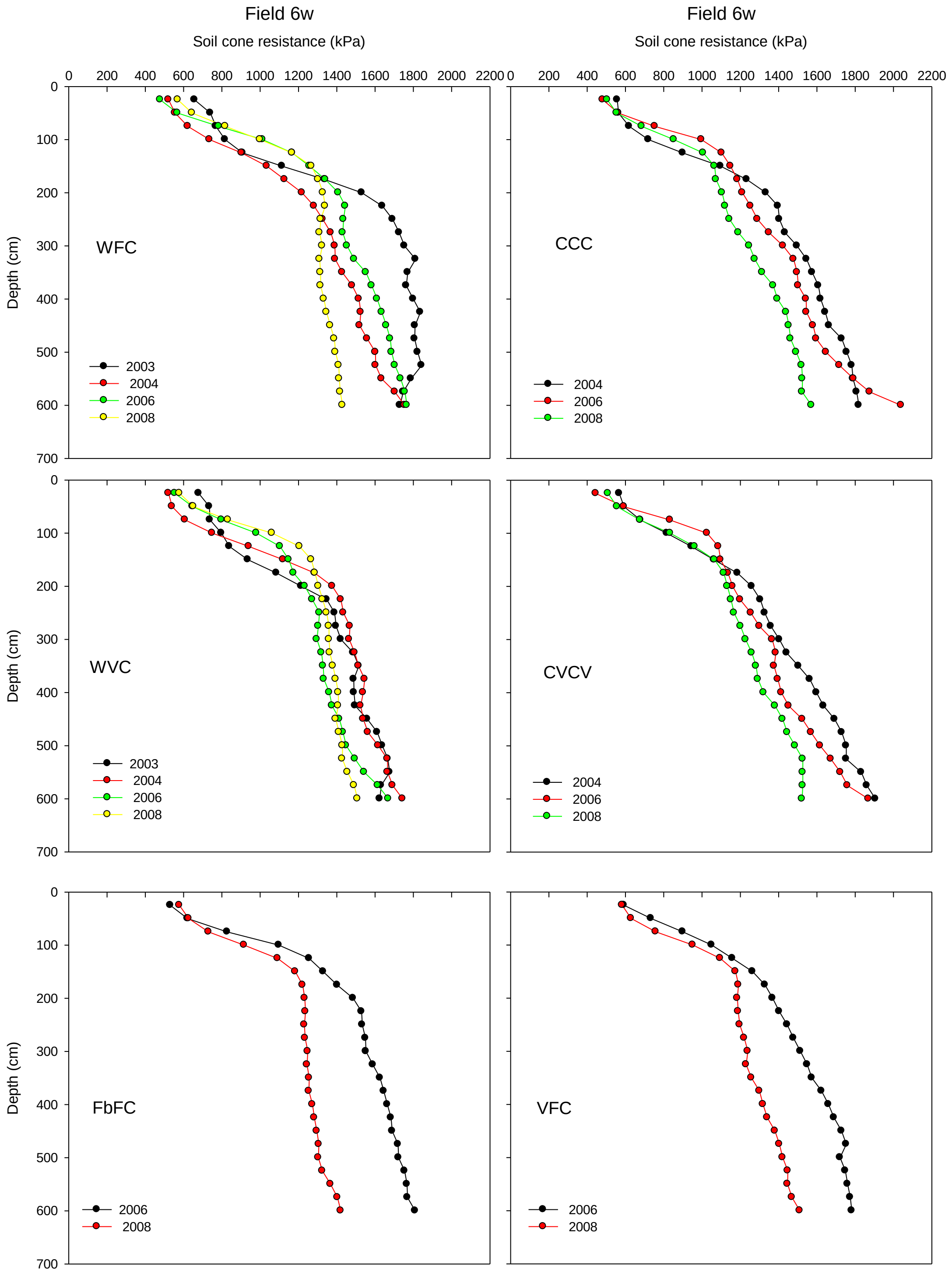

Figure 17 Profile soil cone resistance Field 6

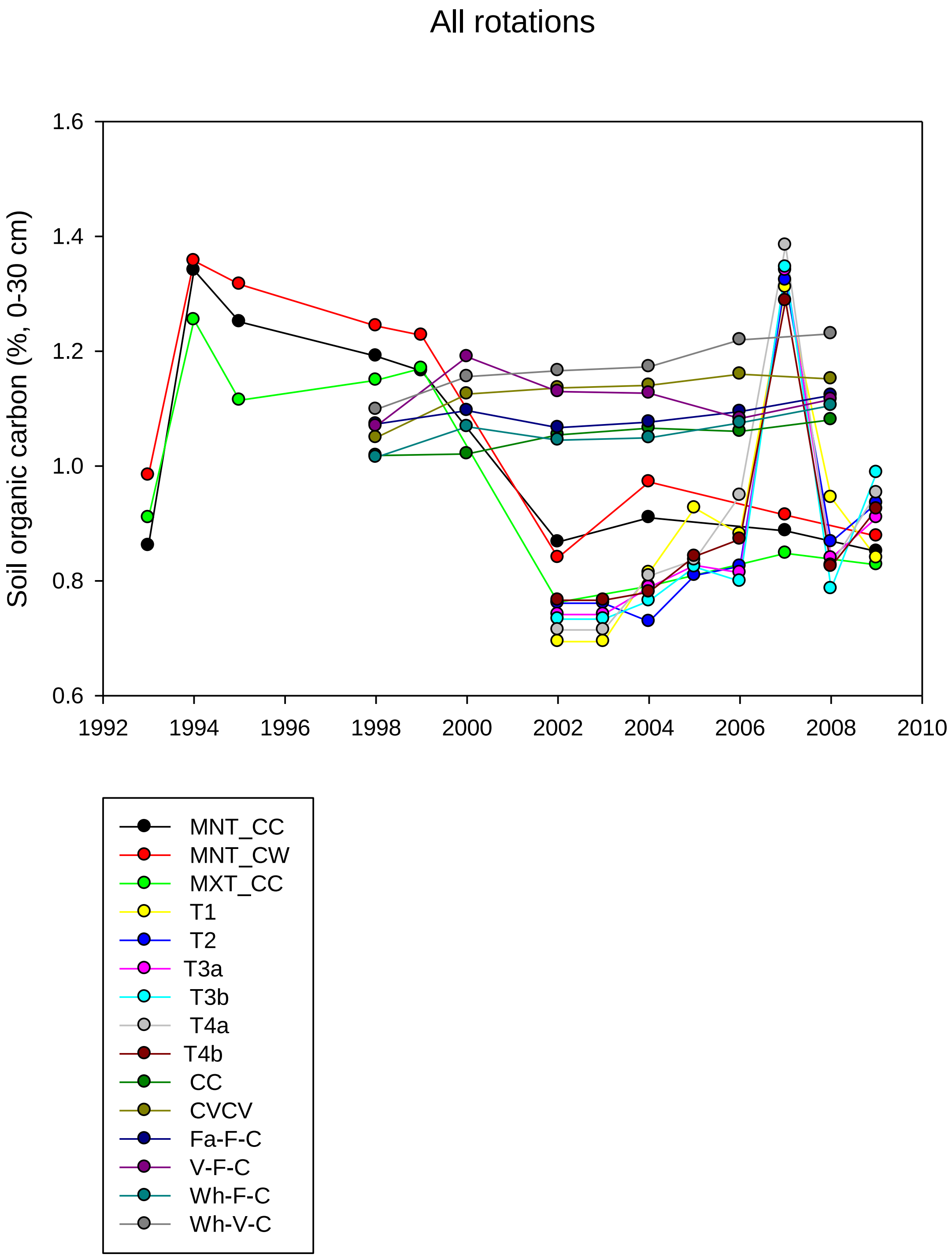

Figure 18 Change in soil organic carbon over time under all rotations (Fields C1, D1 and 6)

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Appendix 4: Details of long-term experimental sites in Warren, Wee Waa, Merah North, Warra and Emerald.

Site details of the experiments at the ACRI and Federation Farm have been described in the main text of this report. The soils in all sites were Vertosols.

- *Warren, NSW (1993-2010)*: Irrigated. All crops (cotton and rotation crops) were sown on 1-m permanent beds following 3 years of continuous cotton with intensive tillage practices (disc and chisel ploughing, and ridging every year; deep ripping every 2-5 years) and burning of crop residues. The experimental treatments (rotations) sown at Warren were: (1) continuous cotton ; (2) long-fallow cotton; (3) cotton-high input, in which wheat was sown at a rate of 100 kg/ha and fertilised with 85 kg/ha of di-ammonium phosphate and 180 kg/ha of urea at sowing; (4) cotton-low input wheat, in which wheat was sown at a rate of 40 kg/ha and did not receive any N fertiliser; (5) cotton-green manured field pea (*Pisum sativum* L.); (6) cotton-wheat-lablab (*Lablab purpureus* L.) (1993-1997) fb. (followed by). cotton-wheat (1997-1998); and (7) cotton-wheat-lablab (1993-1995) fb. cotton-faba bean (*Vicia faba* L.)-lablab (1995-1997) fb. cotton-faba bean (1997-1998). After the rotation crop phase, beds were renovated with a disc-hiller and furrows deepened by direct listing, followed by bed cultivation to a depth of 0.075 m with a Lilliston cultivator. A secondary cultivation of the beds occurred about 6 months later, and involved centre-busting and re-formation of ridges before sowing cotton. The experimental treatments were terminated in 1998, and a cotton-wheat-summer/winter fallow-cotton sequence was sown thereafter in all plots.
- *Wee Waa, NSW (1993-2001)*: Irrigated. The cropping sequences were cotton followed by N fertilised wheat (urea at 140 kg N/ha in 1993; 120 kg N/ha thereafter), unfertilised wheat, unfertilised grain legumes (chickpea in 1993; faba bean thereafter) which were either harvested or the grain incorporated during land preparation. Land preparation after cotton consisted of minimum tillage with an aer-way cultivator and residue incorporation into the beds. Land preparation for cotton consisted of incorporating rotation crops residues with a disc-plough followed by ridging. The site had been deep-ripped to a depth of approximately 50 cm 12 months before the experiment commenced.
- *Merah North, NSW (1994-2005)*: Irrigated. The experimental treatments (rotations) sown on 1-m beds between 1993 and 2000 were: (1) continuous cotton; (2) long-fallow cotton; (3) cotton-green manured faba bean until 1999 when a sorghum crop was sown during the 1999-2000 growing season; (4) cotton-dolichos-green manured faba bean (1993-1994) fb. cotton-unfertilised wheat (1994-2000) (5) cotton-dolichos; and (6) cotton-fertilised dolichos with P and K removed by cotton replaced as fertiliser. From 1993 until 1997 slashing of cotton was followed by incorporation of cotton stubble with a disc-plough into the beds. Depth of incorporation did not exceed 0.10 m. The beds were renovated as described above and all mechanised traffic restricted to the furrows. From 1998 onwards, due to increasing weed numbers, an additional cultivation took place with a disc-plough to a depth of 0.10 m, and the beds were re-formed before sowing cotton. The experimental treatments were terminated in 2000 and a cotton (2000-01)-wheat (2001)-sorghum (2001-02)-winter fallow (2002)-cotton (2002-03)-wheat (2003)-summer and winter fallow (2003-04)-cotton (2004-05) sequence was sown in all plots
- *Warra, Qld (1994-2005)*: Rainfed. The experimental treatments sown on the flat between 1996 and 2005 (rotations) were: (1) continuous cotton; (2) cotton-sorghum (*Sorghum bicolor* (L.) Moench.); (3) double-cropped cotton-wheat; (4) double-cropped cotton-chickpea (*Cicer arietinum* L.)-summer fallow-wheat; and (5) cotton-fallow-wheat-fallow.

From 1993 to 1996 land preparation was by chisel ploughing to about 0.2 m followed by 2-4 cultivations with a Gyral tyne cultivator. Thereafter all crops were sown with zero tillage except for cultivation with a chisel plough to about 0.07-0.1 m after cotton picking to control heliothis moth pupae.

- *Emerald, Qld (1995-2003)*: Rainfed. After beds and furrows were established with a combination of intensive tillage practices, they were managed as permanent beds (cotton stalk pulling and mulching followed by bed renovation).Weeds were controlled by herbicides except for cotton and sorghum regrowth, which was controlled with shallow (~0.05 m) cultivation when required. Traffic was restricted to the furrows between the beds. The experimental treatments (rotations) implemented from 1996 to 2000 were: (1) early cotton sown at the start of the rainy season on 1-m and 2-m beds; (2) wheat (sprayed out)-early cotton on 2-m beds; (3) wheat allowed to mature and harvested followed by late cotton sown mid-way through the rainy season on 1-m and 2-m beds; and (4) cotton-sorghum sown in 2-m beds. The site was deep ripped in during 2000 and all plots sown with a cotton-wheat sequence.

Appendix 5: Mean values of soil properties at on-farm locations in MIA, Namoi and Macquarie valleys, Border Rivers and Darling Downs regions after corn and cotton crops

Table 1. Average soil properties in the 0-30 cm of corn and cotton fields at given locations. EC1:5. Electrical conductivity of a 1:5 soil:water suspension; ESP, exchangeable sodium percentage; SOC, soil organic carbon; ESI, electrochemical stability index

Site	Rotation	Clay (g/100g)	pH (0.01 $CaCl_2$)	$EC_{1:5}$ (dS/m)	SOC (g/100g)	Ca (cmol/kg)	K (cmol/kg)	Mg (cmol/kg)	Na (cmol/kg)	ESP	ESI	SOC (t/ha)
“Breeza Station”, Breeza, NSW	Corn	76	7.4	0.16	1.11	35.1	2.0	18.7	0.6	1.0	0.17	20.3
	Cotton	75	7.2	0.14	1.03	32.2	1.7	19.6	0.9	1.6	0.09	17.5
“Malanganee”, Gurley, NSW	Corn	51	7.0	0.08	0.92	25.1	1.0	4.1	0.8	2.7	0.03	15.3
	Cotton	67	7.2	0.11	0.85	48.9	1.2	3.7	1.2	2.1	0.19	13.5
“Auscott/Togo”, Narrabri, NSW	Corn	58	6.8	0.17	0.77	21.3	1.4	9.6	1.1	3.3	0.05	13.3
	Cotton	63	6.9	0.64	0.70	21.3	1.4	11.5	2.1	5.9	0.11	13.4
“Rossmar Park”, Quirindi, NSW	Corn	84	6.7	0.09	0.94	28.5	1.7	31.1	1.9	3.0	0.03	14.7
	Cotton	85	6.9	0.18	1.05	26.9	2.0	32.2	1.9	3.1	0.06	16.3
“Breeza Station”, Breeza, NSW	Corn	80	7.4	0.17	0.95	34.6	1.3	22.3	1.4	2.3	0.08	40.7
	Cotton	77	7.3	0.14	0.75	31.0	1.1	21.6	1.6	2.9	0.05	28.0
“Malanganee”, Gurley, NSW	Corn	55	7.3	0.12	0.77	26.3	0.5	5.2	1.5	4.6	0.03	28.5
	Cotton	65	7.3	0.15	0.70	47.7	0.7	4.2	2.5	4.4	0.13	24.8
“Auscott/Togo”, Narrabri, NSW	Corn	58	6.9	0.16	0.70	21.2	1.1	9.7	1.7	5.0	0.03	26.2
	Cotton	63	7.0	0.65	0.59	22.1	1.2	11.8	2.6	6.8	0.10	25.1
“Rossmar Park”, Quirindi, NSW	Corn	87	7.3	0.15	0.70	27.9	1.1	33.1	3.6	5.5	0.03	24.7
	Cotton	87	7.2	0.17	0.86	26.7	1.4	33.4	2.8	4.3	0.04	32.1
“Kooba Station”, Darlington Point, NSW	Corn	60	6.0	0.09	0.86	8.8	0.8	7.9	1.0	5.3	0.02	12.7
	Cotton	67	5.9	0.10	0.75	11.9	1.2	9.0	1.0	4.2	0.02	10.9
“Akoonah”, Narromine, NSW	Corn	27	6.0	0.07	1.47	4.1	0.5	1.9	0.3	4.5	0.02	20.1
	Cotton	27	5.5	0.11	1.28	3.3	0.7	1.5	0.3	4.5	0.03	17.8
“Riverdale”, Darlington Point, NSW	Corn	68	6.2	0.10	1.13	13.2	1.1	9.6	0.7	2.7	0.04	16.1
	Cotton	67	6.3	0.20	1.05	12.8	1.2	9.1	0.5	2.0	0.10	15.8
“Farm 536”, Coleambally, NSW	Corn	53	4.8	0.11	1.22	7.2	1.0	5.0	0.3	2.3	0.05	17.4
	Cotton	52	5.3	0.12	1.23	6.4	1.2	5.2	0.6	3.9	0.04	17.6
“Farm 511”, Coleambally, NSW	Corn	52	4.5	0.16	1.22	13.3	1.0	6.8	0.2	0.9	0.20	17.3
	Cotton	49	6.0	0.12	1.02	16.3	1.1	8.6	0.3	1.0	0.13	15.6

"Farm 8", Coleambally, NSW	Corn	62	5.6	0.14	1.24	13.4	1.0	6.8	0.2	0.9	0.18	17.6
	Cotton	70	6.0	0.11	1.05	16.5	1.1	8.6	0.3	1.0	0.12	15.9
"Maroondah", Trangie, NSW	Corn	53	6.9	0.15	1.07	17.8	1.2	5.9	0.3	1.2	0.16	15.7
	Cotton	56	6.9	0.17	1.09	19.1	1.6	5.1	0.2	0.6	0.31	16.4
"Ringwood", Darlington Point, NSW	Corn	59	6.4	0.12	1.37	11.3	1.5	8.3	0.3	1.3	0.10	20.6
	Cotton	64	6.0	0.13	1.52	11.2	1.7	8.0	0.3	1.5	0.09	22.7
"Alderton", Condamine, Qld	Corn	45	7.2	0.28	0.92	14.9	0.9	5.7	0.3	1.5	0.18	22.6
	Cotton	46	7.2	0.26	0.78	15.2	0.8	4.8	0.4	2.1	0.16	18.9
"Eschol1" and "Eschol2", Warra, Qld	Corn	66	7.2	0.14	0.70	24.6	0.7	11.1	1.1	3.0	0.05	17.8
	Cotton	68	7.3	0.16	0.73	25.0	0.7	11.0	1.3	3.3	0.06	19.4
"Benalla", Dalby, Qld	Corn	71	6.8	0.32	1.17	20.0	1.0	24.2	2.5	5.3	0.07	31.4
	Cotton	75	7.1	0.29	1.03	19.9	0.8	26.5	3.8	7.5	0.04	27.0
"Loch Eaton", Dalby, Qld	Corn	67	7.0	0.27	1.34	22.4	1.0	13.1	3.0	7.5	0.04	34.4
	Cotton	69	6.8	0.19	1.23	22.6	1.4	13.6	2.2	5.5	0.03	32.7
"Mayfield", Dalby, Qld	Corn	65	7.1	0.22	0.99	21.7	0.9	12.9	1.3	3.5	0.07	26.7
	Cotton	71	6.8	0.21	1.11	20.3	1.2	15.0	1.9	4.9	0.05	28.9
"Morella", Goondiwindi, Qld	Corn	60	6.3	0.18	0.96	13.8	0.9	9.1	0.6	2.4	0.08	26.8
	Cotton	58	6.5	0.20	0.89	14.8	0.9	8.4	0.6	2.3	0.09	23.7

Appendix 6: Influence of crop management on wolf spider assemblages (*Araneae: Lycosidae)* in an Australian cotton cropping system

By Miss Dalila Rendon, Macquarie University, North Ryde; and CSIRO, Narrabri

Wolf spiders (*Lycosidae*) are the most abundant ground hunting spiders in Australian cotton) agro-ecosystems. These spiders have the potential to play an important role in controlling pest bollworms, *Helicoverpa* spp. (*Lepidoptera: Noctuidae*) especially in minimum-tilled fields. A study was carried out during the 2011-12 growing season in Narrabri, NSW, Australia, to determine how different crop rotations under minimum tillage affect wolf spider assemblages in cotton fields. Spider abundance and species richness did not differ significantly between simple plots (no winter crop) and complex plots (cotton-wheat-vetch rotation). However, wolf spider biodiversity, as expressed by the Shannon-Weaver and Simpson’s indices, was significantly higher in complex plots. Higher biodiversity reflected a more even distribution of the most dominant species (*Venatrix konei*, *Hogna crispipes*, *Tasmanicosa leuckartii*) and the presence of more rare species in complex plots. *Tasmanicosa leuckartii* was more abundant in complex plots and appears to be sensitive to farming disturbances, whereas *V. konei* and *H. crispipes* were similarly abundant in the two plot types, suggesting higher resilience or recolonizing abilities. The demographic structure of these three species varied through the season, but not between plot types. Environmental variables had a significant effect on spider assemblage, but environmental effects and plot treatment were overshadowed by the seasonal progression of cotton stages. Maintaining a high density and even distribution of wolf spiders that prey on *Helicoverpa* spp. should be considered as a conservation biological control element when implementing agronomic and pest-management strategies.