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Minimising yield variability to maximise yield in a cotton farming system- Technical Report

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Minimising yield variability to maximise yield in a cotton farming system

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Executive summary

The objectives of this project were to (i) identify the causal factors for yield variability and (ii) develop strategic soil and crop management options to address yield variability and improve soil health and sustainability in cotton farming systems. The project conducted a paired field comparison during the 2018-19 season to identify the causes of yield variability between cotton fields in close proximity and of the same soil type. As drought impacted the number of cotton fields under cotton in that year, the investigation focused on soil property-induced yield differences at paired fields within five farms. The paired fields at each farm recorded an average yield difference of >284 kg/ha (1.25 bales/ha). Despite being the same soil type, several soil properties differed between the paired fields at each farm comparison. The soil organic carbon stocks were higher in the higher-yielding fields (five-year average yield) at all the farm comparisons and the normalised lint yield percentage was positively correlated with soil organic carbon stocks. Soil sodicity was higher in the lower-yielding fields at 3 of the 5 farms. Soil compaction was a potential causal factor for lower yield at one paired-field comparison in the Macquarie region. Results for most soil nutrient tests were above the critical concentrations recommended for Australian cotton production. Visual soil assessment (VSA) using the FAO method was carried out across paired sites, multiple CSD ambassador sites and within ACRI across multiple cropping systems. No earthworms were detected at any site during visual soil assessment or soil sampling across all the sites. The visual soil quality index using FAO method was not a sensitive predictor of cotton crop performance. However, future investigation into individual components such as scoring for soil structure, surface crusting etc. will improve the understanding of soil conditions and subsequent management decisions.

Comparing soil properties using a paired-field approach identified compaction, sodicity and soil organic carbon levels among casual factors of yield differences. To assess the relative contributions of selected soil constraints and strategic management to address the yield differences, further investigations were carried out at Australian Cotton Research Institute, including,

1. Assessing the effect of soil compaction on cotton lint yield and its legacy effect on subsequent cotton and wheat crop
2. Assessing the effect of winter cereal cover crop, chickpea and wheat stubble management on soil strength and cotton and wheat yield performance
3. Assessing the cotton lint yield response to applied P and its legacy effect in subsequent crops
4. Assessing the legacy effect of maize rotation on cotton lint yield, disease incidence and soil organic carbon under maximum and minimum tillage
5. Assessing the cotton crop response to foliar sprays after a flooding event
6. Assessing the effect of simulated hail damage on lint yield penalty for cotton crop
7. Assessing the long-term changes in soil micro-nutrients and their implications for the cotton cropping system
8. Assessing the ability of cotton strip assay to detect soil management-induced differences in microbial activity

1. To assess the effect of compaction induced by in-field traffic, a novel investigation was carried out by continuously monitoring crop canopy temperature and soil profile moisture and measuring crop yield by comparing compacted and non-compacted areas within fields. Traffic by a tractor weighing 19.2 tonnes on either side of the plant row reduced lint yield by 27% due to lower crop height and reduced leaf area, biomass, and fruit number. Water recharge in the soil profile from irrigation and rainfall was reduced by 16% due to compaction with the highest reduction being 86% at 0.3–0.5m depth. Further assessments were carried out to assess the legacy effect of soil compaction. The results suggest there was no further legacy effect of soil compaction on cotton lint yield and wheat yield in subsequent seasons beyond the season when compaction occurred. The self-repair potential of Vertosols with a clay content of 62% likely assisted the natural and wheat rotation-mediated alleviation of soil compaction. Future investigation needs to repeat this research on a greater range of soils typically used for irrigated cotton production, focusing on the time required to repair the soil compaction induced by heavy round-bale pickers using natural and rotation crop tactics.

2. Long-term continuous cropping research showed the benefits of leaving wheat as standing stubble after harvest compared to stubble incorporation by tillage. The benefits included less tillage and fuel use and better wheat yields during dry winter years. Introducing a chickpea rotation increased the disease risk in subsequent cotton compared to wheat rotation. Assessing other benefits of chickpeas requires long-term investigation. A winter oat cover crop may not be a suitable break crop for a system planted with cotton every summer. The gross margin/ML of water was always higher for the cotton-wheat system; however, the gross margin/ha was higher for cotton monoculture over the long term. Future research needs to focus on additional rotation crops that can alleviate soil compaction and improve the soil organic carbon and productivity of the cropping systems

3. The response to phosphorus application was investigated by subdividing the selected cropping systems (cotton-wheat and cotton-oats cover crop systems) within the long-term experiments. P fertiliser application before an oats cover crop increased cotton lint yield compared to P applied when planting the cotton. The results suggest there was a lint yield response to applied P in the season of application but there was no legacy effect of applied P beyond the season of application. To better understand the response of cotton plants to applied P fertiliser, future research needs to quantify the movement of applied P into the slowly available BSES P pool in the soil.

4. There was no legacy of the effect of maize rotation on cotton lint yield in the four years since its last planting in 2017–18. Maize is a good break crop for managing Verticillium disease and there was a maize legacy effect on microbial catabolic diversity. Soil organic carbon concentration started declining after the last planting of maize in 2017-18.

5. Flooding decreased the alkaline soil pH towards neutral. The application of foliar nutrient spray products after a significant flooding event on a Vertosol did not improve cotton lint yield, biomass or fibre quality, however previous studies indicated foliar nutrient sprays applied prior to flooding may improve crop performance. Improved soil structural properties

through minimum tillage practices (higher bed height) is more likely to assist cotton recovery from floods than applying foliar nutrients. The water use efficiency of the minimum tilled cotton wheat system is higher than cotton monoculture system.

6. The hail simulation investigation indicated there was no influence of hail damage simulation on cotton lint yield across three experiments. The results suggested that, if the growers don't have appropriate crop insurance, continuing with a December-hailed crop could result in average lint yield provided other factors are not limiting the cotton crop growth and maturity.

7. There was no evidence of decline or changes in stratification of total micronutrients in intensively managed Vertosols. Apart from Zinc, other micronutrients (manganese, iron, copper) were not observed to be nearing critical deficiency concentrations, and therefore micronutrient stratification and decline in irrigated cotton-growing Vertisols are unlikely to be yield limiting, provided that surface soil properties are well managed. The findings of this study will be useful for benchmarking the micronutrient status after an extended period of cropping in the future and also for the soil management decisions (such as pH and SOC).

8. The investigation on cotton strip assay (CSA) using loss of tensile strength measurements suggested that CSA can be an effective indicator of microbial activity, soil organic carbon or crop biomass as influenced by agricultural practices in cotton fields. The CSA weight-loss method was found to be a simpler and cheaper means of assessing the loss of tensile strength of a standard cotton strip after burial in the soil, compared to breaking the strip with a tensometer. Assessing the soil biology status in Australian cotton-growing soils does not require specialised laboratory equipment, just attention to detail when preparing and a reliable balance for weighing, thus increasing the potential for wider adoption of the CSA.

Identifying and addressing causal factors of yield variability requires a multi-year effort across a variety of seasonal conditions (normal, wetter and drier than normal). Multi-year and multi-location grower-driven strip trials with the involvement of researchers to document the key data will build the dataset required to interpret and improve the understanding of yield variability. Building a dataset is the first key step in addressing variability. However, the development of a centrally-managed database (e.g. CRDC or CSD or a common cotton industry body similar to GRDC's Better Fertiliser Decision for Cropping (BFDC) or grains on-farm trial database (https://www.farmtrials.com.au/) or Soil CRC's Visualising Australasia's soils database (https://data.soilcrc.com.au/map/about)) could enable the data capture from all the on-farm trials and support the efforts to understand and address the cotton yield variability. The data needs to be screened to make sure it has proper quality assurance protocols and has enough supporting meta-data for it to be useful for future interpretation. Such effort should be accompanied by ongoing maintenance of the database.

Chapter 1: Soil property differences and irrigated-cotton lint yield—cause and effect? An on-farm case study across three cotton-growing regions in Australia

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Abstract

The average lint yield of irrigated cotton in Australia ranges from 2270–3700 kg ha^{-1}, but yields vary significantly between farms and between fields on the same farm. Differences in soil properties may cause these yield variations. Identifying which factors are causal and what management can be implemented to mitigate the impacts should optimise inputs and improve profits. During the 2018–19 summer cotton-growing season, a paired-field comparison approach was used to investigate and improve the understanding of soil property-induced yield differences within 5 farms. The paired fields at each farm recorded an average yield difference of >284 kg/ha (1.25 bales/ha). Several soil properties differed between the paired fields at each farm comparison. The soil organic carbon stocks were higher in the higher-yielding fields (five-year average yield) at all the farm comparisons and the normalised lint yield percentage was positively correlated with soil organic carbon stocks. Soil sodicity was higher in the lower-yielding fields at 3 of the 5 farms. Soil compaction was a potential causal factor for lower yield at one of the Macquarie comparisons. Results for most soil nutrient tests were above the recommended critical concentrations for Australian cotton production. No earthworms were detected during visual soil assessment or soil sampling across all the sites. Visual soil assessment may not be a sensitive predictor of cotton crop performance. Comparing soil properties using a paired field approach may assist cotton growers in understanding the factors behind yield differences. A similar approach could be adopted for within-field variability by dividing the fields into performance zones and assessing the soil properties of each zone separately.

Key words: Paired field, cotton, soil, lint yield

1 Introduction

Cotton is an important fibre crop grown across numerous countries with a wide variation in yield both between and within countries. In Australia, the average cotton lint yield (2500 kg/ha) is higher than the world's average lint yield (800 kg/ha) (CRDC and Cotton Australia, 2020). However, there is a significant yield variability across the various regions in the industry. Cotton yields can vary substantially within the same field despite having the same management and weather conditions. This is understood to be due to cotton yields being impacted by a range of diverse factors including water, soil health, climate, nutrition, pests, diseases, and weeds (Constable and Bange, 2015). In-field variation of these factors, both individually and via complex interactions, are known to affect cotton lint yield potential. While long-term experiments can improve the understanding of the causal factors for yield differences, significant resources and time are often constraints to establishing and maintaining such experiments in sufficient numbers across distinct climatic regions. Simulations of varying climate scenarios, crop management practices and soil characteristics is one approach to investigating the relative impact of these factors, but actual field data is essential to validate models and improve their predictive capabilities.

In Australia, cotton has been traditionally grown on highly fertile Vertosols (Isbell and National Committee on Soil and Terrain, 2021). The cotton-growing regions in Australia are currently located across four states (New South Wales, Queensland, Northern Territory and Western Australia). Recent studies indicate a decline in soil fertility under cotton cropping systems (Nachimuthu *et al.*, 2022c; Palmer *et al.*, 2023) which could result in additional limitations for realising the yield potential. Many of the newer areas being brought into intensive cotton production often include soils that are not as fertile and feature one or more inherent constraints to plant growth.

Investigating soil properties could be the first step to assist growers to improve their understanding of soil property induced yield differences. Previous research in USA compared the soil property differences (0-20 cm) between high and average yielding soybean areas (Adams *et al.*, 2017; Adams *et al.*, 2018) and identified properties such as soil organic carbon and extractable phosphorus levels were higher in selected high yielding soybean fields. There have been no such comparative studies on cotton fields in Australia.

Understanding the soil physical, chemical and biological properties and their contributions to yield variability is important. Soil test based nutrient recommendations are part of commercial agronomic services that is prevalent in cropping industries including cotton in Australia and elsewhere across the world. This test predominantly covers the chemical properties. Soil physical properties are not measured regularly inspite of the use of heavy machinery that induces soil compaction (Jamali *et al.*, 2021). Soil biological properties are often perceived as time consuming and difficult to measure, although recent commercial test are emerging to fill the gap (Predicta B, 2023). A visual soil assessment was proposed by United Nations Food and Agriculture Organisation (Shepherd *et al.*, 2008) as an universal assessment for soil health indicator. This assessment incorporates a range of soil physical, hydrological and biological indicators to provide an aggregate score and could potentially be used for assessment and comparison of fields with yield differences. However, the ability of visual soil assessment to delineate the field with yield differences are yet to be investigated.

To investigate the soil property induced yield differences a case study was undertaken comparing five paired fields (10 fields) spread across three cotton growing regions. Five paired fields (10 fields) across three cotton growing regions were investigated to determine if soil properties identified through routine laboratory testing could be linked to yield differences. To establish if addition of the Visual Soil Assessment added any further insight to the yield differences, a sub sample three of the paired sites (six fields) were assessed. In this on-farm study across the Australian cotton industry, we hypothesised the yield differences were related to soil properties and initially focussed on between field yield differences.

2 Materials and methods

2.1 Study location and site selection

The farms were located in the Gwydir Valley, Macquarie and Riverina cotton growing regions of New South Wales, Australia. The sites were selected in discussion with the CottonInfo team (Australian Cotton Industry's extension wing), cotton growers and agronomists. The locations of each farm (Figure 1.1, Table 1.1) are described in section 2.2. The soils in Gwydir Valley irrigation area are relatively uniform and were mostly formed from alluvial sediments (NSWDOI, 2018; Aus Gov, 2023). The soils in the Macquarie irrigation area are part of the clay plains of the Warren-Trangie region and may include patches of aeolian deposits (parna) (McKenzie, 1992). The soils in the Riverina cotton-growing area are highly variable with most being a mixture of parna (Cattle and Smith, 2018) and several riverine deposition layers. Natural fluvial pathways through parna depositions and the use of laser levelling to improve irrigation efficiency have produced additional variability in these fields. The soil texture of all the fields under investigation is clay ranging from light (Riverina) to heavy clay (Gwydir).

Figure 1.1. Location of cotton farms selected for investigation in this study

The annual average rainfall of the case study regions varied from 395 mm in Riverina to 569 in Gwydir regions (Table A1.1, supplementary data). The average monthly mean maximum and minimum temperatures declined from Gwydir to Riverina region as expected from Northern to Southern latitudes (Table A1.2, supplementary data).

2.2 Field comparisons

A total of 10 fields were investigated with five within-farm paired comparisons made. Historical yield records (five-year field average) were collected from growers. The paired fields recorded an average yield difference of at least 284 kg lint/ha (or 1.25 bales/ha, 1 bale= 227 kg lint) or higher, mostly according to the growers' average historical yield records. For those fields where the historical yield information was not available, yield assessment in the 2018–19 season was used for the study. Soil sampling of all fields occurred in November and December 2018. Soil chemical properties were analysed using methods described in Rayment and Lyons (2010) (Table 1.2). In comparisons Gwydir, Macquarie 1 and Macquarie 2, visual soil assessment using the FAO method (Shepherd *et al.*, 2008) was also undertaken to compare the soil quality (section 2.4).

Table 1.1. Details of paired field comparisons and basic management information

Comparison	Field	GPS coordinates		Rainfall (mm)	Tillage depth	Irrigation type	Laser levelling
Gwydir	1	-29.298°	149.761°	140	>20 cm	Furrow-siphon	Details NA#
	2	-29.301°	149.749°	140	>20 cm	Furrow-siphon	Details NA#
Macquarie-A	3	-31.769°	147.708°	219	10-20 cm	Furrow-siphon	2005
	4	-31.803°	147.704°	219	10-20 cm	Furrow-siphon	2005
Macquarie-B	5	-31.750°	147.710°	219	10-20 cm	Furrow-siphon	2005
	6	-31.713°	147.717°	219	10-20 cm	Furrow-siphon	2000
Riverina-A	7	-34.536°	146.216°	181	>20 cm	Bankless	2017
	8	-34.539°	146.211°	181	>20 cm	Bankless	2017
Riverina-B	9	-34.539°	146.189°	181	>20 cm	Bankless	Details NA#
	10	-34.539°	146.186°	181	>20 cm	Bankless	Details NA#

*-Seasonal rainfall from October 2018 to April 2019, #-Details not available indicates current grower not aware of the year the fields were laser levelled.

2.2.1 Comparison -Gwydir Valley

Two fields located in the Gwydir valley in Northwest NSW were selected for comparative analysis. The basal fertiliser application in the 2018-19 season included 290, 32.5 and 50 kg of N, P and K, respectively. The soil type in this valley is predominantly cracking clay with >50% clay. Both the fields had been harvested with round bale module pickers since 2011 and have been under similar management. Laser levelling details were not available from the farm manager.

2.2.2 Comparisons Macquarie Valley A and B

Two pairs of adjacent fields within the Macquarie valley in Central West NSW were selected for two comparative analyses. The soil type in this field is described as fine, thermic, smectitic, *typic haplustert* and soil texture on this farm was classified as 52, 16 and 32 g/100g of clay, silt and sand (Hulugalle *et al.*, 2017). The basal fertiliser application for the first pair (Macquarie Valley A) in the 2018-19 season included 150, 44 and 25 kg/ha of N, P and K respectively. Both fields had been harvested using round bale module pickers since 2011 and were under similar management. Macquarie Valley B was between the second pair of adjacent fields located in Macquarie valley in Central West NSW. The basal fertiliser application in the 2018-19 season included 150, 44 and 25 kg/ha of N, P and K respectively. An additional 160–200 kg N/ha of N was applied in-crop N as a water-run fertiliser application for both the pairs. Both fields have been harvested using round bale module pickers since 2011 and were under similar management.

2.2.3 Comparisons Riverina A and B

Two pairs of adjacent fields within the Riverina region in Southern NSW were selected for two comparative analyses. No yield records were available for both the pairs. In 2018–19, lint yields were measured by hand harvesting at each of the soil sampling locations. Both the pairs had a bankless channel irrigation system. Soil properties in the two fields were highly variable as a result of fluvial and aeolian deposition and earthworks for constructing the irrigation system. The soil texture of both fields was heavy clay however, there was increasing clay content at the deeper depths. The soil texture of both the fields at 0-15 cm were 40, 9 and 51 g/100 g of clay, silt and sand. The soil texture of both the fields at 15-30 cm were 55, 6 and 39 g/100 of clay, silt and sand. The soil texture of 30-90 cm was 62, 8 and 30 g/100 g of clay, silt and sand.

The second pair in the Riverina region were laser levelled in 2017, one year before sampling. Yield measurements were undertaken at each of the sampling locations. Half of the 300 kg N/ha nitrogen applied was as urea, with the rest supplied in a blend with other nutrients (N-46.2%, P-11.4%, S-7.8%).

2.3 Yield estimation

Cotton was handpicked from 1 m^2 per sampling core point for yield estimation (A total of 9 m^2 per field). Seed cotton was weighed. A <500 g seed cotton subsample was ginned using a 20-saw gin with a pre-cleaner (Continental Eagle, Prattville, AL, USA) to determine the gin turnout (i.e., the percentages of seed and lint by mass). The lint turnout (% lint) was used to estimate the lint yield from seed cotton and the results were reported as bales lint/ha. For each comparison, the grower (5 year average) lint yield or the measured lint yield in 2018-19 was used to derive a normalised lint yield percentage. The low yielding field lint yield percentage was worked out in relation to high yielding field for each comparison.

2.4 Soil sampling and analysis

Soil samples were taken from 0-90 cm depth (0-15, 15-30, 30-45, 45-60 and 60-90 cm depth increments). Nine cores per field were taken (3 cores taken 50 m from the head-ditch end, 3 cores taken 50 m away from the tail drain end and 3 cores from the middle of the field) in all the fields. Soil samples were air dried to constant weight at 40 ^{o}C and samples were weighed. A sub sample of each soil sample were oven dried at 105 ^{o}C to estimate the soil moisture. The bulk density of the soil samples at each depth increment was calculated by dividing the oven-dry mass (105 ^{o}C) of the soil at each depth by the volume of the soil core. Soil samples were ground to < 2 mm then homogenised and sub-sampled using a riffle splitter for each depth increment in every core. The processed samples were analysed for chemical parameters described in Rayment and Lyons (2010). The soil available P is presented as Colwell P (Colwell, 1963). Soil organic carbon and mineral N stocks were calculated by multiplying the soil organic carbon and mineral N concentrations adjusted for soil moisture (105 ^{0}C oven drying) with the bulk density at respective depths. The methods used for soil chemical analysis from are listed in Table 1.2 below

Table 1.2. Soil chemical methods used from Rayment and Lyons (2010)

Soil parameter	Method
Ammonium N (mg/kg)	Rayment and Lyons Method 7C2b
Nitrate N (mg/kg)	Rayment and Lyons Method 7C2b
Colwell P (mg/kg)	Rayment and Lyons Method 9B and 18A1
KCl-40 S (mg/kg)	Rayment and Lyons Method 10D1
SOC (%)	Rayment and Lyons Method 6A1
EC	Rayment and Lyons Method 3A1

pH ($CaCl_2$)	Rayment and Lyons Method 4B4
pH (water)	Rayment and Lyons Method 4A1
DTPA Cu (mg/kg)	Rayment and Lyons Method 12A1
DTPA Fe (mg/kg)	Rayment and Lyons Method 12A1
DTPA Mn (mg/kg)	Rayment and Lyons Method 12A1
DTPA Zn (mg/kg)	Rayment and Lyons Method 12A1
B (mg/kg)	Rayment and Lyons Method 12C2
Exch. Ca (meq/100g)	Rayment and Lyons Method 15E2
Exch. Mg (meq/100g)	Rayment and Lyons Method 15E2
Exch. Na (meq/100g)	Rayment and Lyons Method 15E2
Exch. K (meq/100g)	Rayment and Lyons Method 15E2

2.5 Visual soil assessment

Visual soil assessment (Shepherd *et al.*, 2008) was undertaken for Gwydir, Macquarie A and B. The top 20 cm of soil were scored for soil texture, structure, colour, mottles, earthworms, rooting depth, surface ponding, crusting and surface cover, and soil erosion index. Each indicator was given a visual score of zero (poor), 1 (moderate) and 2 (good) based on the soil quality observed when comparing with the field guide manual provided by Shepherd *et al.* (2008). We also scored 0.5 and 1.5 if the indicators fell between two categories. The score was then multiplied by the weighting factor described in the manual according to the importance of each soil indicator. The soil quality index is an aggregated sum of the adjusted indicators. Soil samples with a quality index of < 15 were classified as poor, 15-30 as moderate and >30 as good.

2.6 Simple interpretation of yield map

Cotton lint yield maps of three fields (2017-18 season) were collected from the DeBortoli farm in the Riverina region of NSW. Management information and soil data were used to interpret the variation in the lint yield.

2.7 Statistical Analysis

All data analysis was carried out using Genstat (21st Edition, VSN International Ltd). For each comparison, the fields were considered as treatments with cores (9) as replicates. Soil parameter data were analysed using Analysis of variance for each pair separately to assess the effect of treatments (fields) and soil depth as two factors and their interactions.

3 Results and discussion

3.1 Cotton lint yield

In the Gwydir comparison, the grower's yield records (5-year average) indicated that the average lint yield difference between the two fields investigated (Fields 1 and 2) was 522 kg/ha (2.3 bales/ha). Similarly for the Macquarie Valley A and B comparisons, the grower's yield records (5-year average) showed an average lint yield difference between the two fields 284 kg/ha (1.25 bales/ha) for the first pair (Fields 3 and 4) and 624 kg/ha (2.75 bales/ha) for the second pair. In addition, the measured yield difference between the fields for the Riverina A comparison was 356 kg lint/ha (1.57 bales/ha) and that of Riverina B comparison was 806 kg lint/ha (3.55 bales) (Table 1.3). The 2018-19 season yield was in a different trend to the 5-year average yield obtained from grower yield records for Gwydir and Macquarie comparisons. The 2018-19 season was one of the driest seasons experienced by the Australian cotton industry and yield for Gwydir and Macquarie comparisons deviated from the 5-year average trend. Due to the extreme climate induced growing conditions, it was proposed that the yield at these sites in this season was influenced by factors other than soil properties. The disease survey indicates the occurrence of fusarium wilt in one field in Gwydir and verticillium wilt in one field in Macquarie valley. Southern NSW paired sites were free of fusarium and verticillium wilt.

Table 1.3. Lint yield (5 year average preceding 2018-19 season) and soil organic carbon and nitrogen stocks for the paired sites

Comparison	Field	Average lint yield (kg/ha)*	Soil organic carbon stocks (0-90 cm) (t/ha)	Mineral N stock (0-90 cm) (kg/ha)
Gwydir	1	3360	60.3	316
	2	2838	48.0	399
Macquarie-A	3	2440	52.3	148
	4	2724	60.4	247
Macquarie-B	5	1816	42.9	303
	6	2440	45.4	589
Riverina-A	7	2801	61.4	535
	8	2445	54.8	665
Riverina-B	9	2874	56.2	175
	10	2068	49.3	201

*-The average lint yields reported are based on the grower survey for fields 1 to 6 and the measured average yield near sampling points for field 7 to 10.

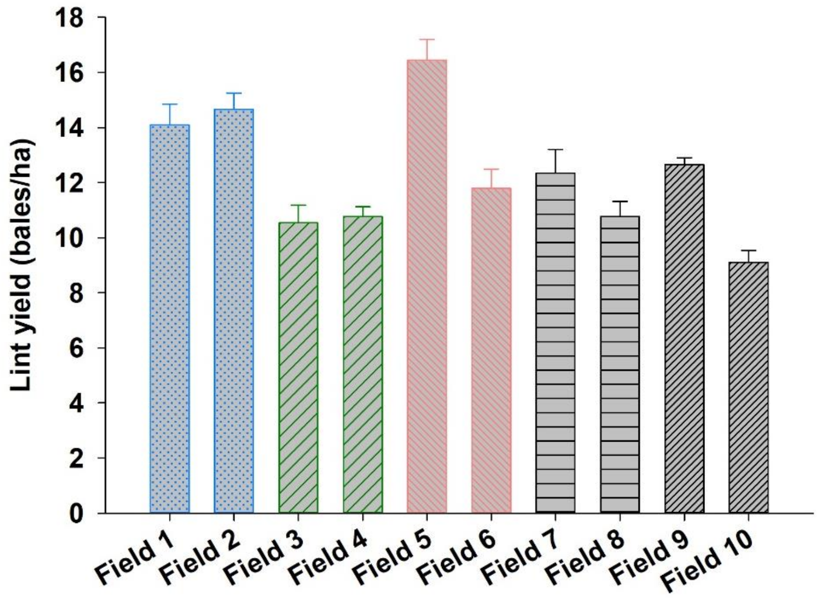


Figure 1.2. Lint yield of paired sites measured during the 2018-19 season. The error bars indicate the standard error of the mean. Each paired site is presented in the same colour and pattern.

3.2 Bulk density and profile soil pH

There were differences in bulk density between the fields in each comparison except Riverina B comparison. However, there was no relationship between average bulk density and average lint yield (r^2= 0.03) across the 10 fields. The bulk density of the soil is related to soil type (Indoria *et al.*, 2020). The soils of southern NSW exhibit texture contrast with Parna (aeolian deposits) and fluvial deposits layered over each other, prior to laser levelling to alter the landscape for irrigation and rice production in the past resulting in a mixture of these layers making drainage characteristics uneven and influencing their bulk density. The irrigated cotton-growing soils of the Gwydir Valley are predominantly cracking clays (Vertosols) with uniform clays upto 1 m depth (Zhao *et al.*, 2019). The soil type and its origin accounted for the variability in bulk density across the regions, with the seasonal traffic or underlying compaction from previous season likely influencing the bulk density differences among the fields in each comparison (Table 1.4). The bulk density of the top 30 cm was within the normal range (~1.3 or lower) expected for Vertosols (Al-Shatib *et al.*, 2021) that usually do not impact plant growth in all the fields expect Macquarie valley (Fields 4 and 6) surveyed in this case study. The bulk density indicates field 4 and field 6 were compacted compared to their pairs- field 3 and field 5. The measured lint yield in field 6 is significantly lower than field 5, however field 3 and 4 recorded similar yield in 2018-19 season (Figure 1.2). The magnitude of bulk density changes between 0-15 cm and 15-30 for fields 3 and 4 is 0.2 g/cm^3. However, the magnitude of bulk density changes for the same depths for fields 5 and 6 are 0.2 and 0.4 g/cm^3 respectively. This higher magnitude of change in bulk density in field 6 indicates subsoil compaction and is a potential causal factor for the lower yield. A recent study reported a 86% reduction in soil water recharge and 72% reduction in crop water use at 30-50 cm soil depth by cotton as a result of compaction (Jamali *et al.*, 2021).

The soil pH was alkaline throughout the profile with increasing alkalinity from the topsoil to 90 cm depth for all the fields (Tables 1.4, 1.5A and 1.5B) except fields 7 to 10 in Riverina where the soil pH was acidic in the top 30 cm and neutral to alkaline from 30-90 cm depth for both fields (Table 1.6A and 1.6B).

Table 1.4. Soil properties for the paired fields measured in Gwydir Valley comparison (Values are mean of 9 replicates)

Field	Field 1	Field 2	Field 1	Field 2	Field 1	Field 2	Field 1	Field 2	Field 1	Field 2
Depth (cm)	0-15	0-15	15-30	15-30	30-45	30-45	45-60	45-60	60-90	60-90
Bulk density (g/cm3)	1.1	1.0	1.3	1.2	1.3	1.3	1.3	1.3	1.4	1.3
Ammonium N (mg/kg)	3.6	5.1	2.9	3.1	2.2	2.4	2.7	2	2.4	1.7
Nitrate N (mg/kg)	60	83	20	30	17	21	15	19	17	24
Colwell P (mg/kg)	31	40	7	7	4	5	4	4	6	6
KCl-40 S (mg/kg)	7	13	7	9	9	8	10	11	20	41
SOC Conc. (%)	0.73	0.57	0.56	0.44	0.49	0.41	0.45	0.37	0.38	0.34
EC	0.160	0.182	0.139	0.122	0.164	0.139	0.194	0.159	0.221	0.268
pH ($CaCl_2$)	7.4	7.2	7.7	7.5	7.8	7.6	7.8	7.7	7.8	7.8
pH (water)	8.3	8.0	8.6	8.6	8.7	8.8	8.8	8.9	8.9	9.0
DTPA Cu (mg/kg)	1.5	1.8	1.6	1.7	1.6	1.7	1.6	1.6	1.5	1.7
DTPA Fe (mg/kg)	20	27	21	27	22	25	21	28	21	25
DTPA Mn (mg/kg)	23	35	10	18	9	14	9	13	8	10
DTPA Zn (mg/kg)	1.9	1.8	0.4	0.7	0.2	0.3	0.3	0.3	0.2	0.3
$CaCl_2$-B (mg/kg)	1.2	1.4	1.4	1.6	1.7	2.0	2.1	2.4	2.3	3.2
Exch. Ca (meq/100g)	20	19	20	20	20	19	19	18	17	17
Exch. Mg (meq/100g)	7.3	10	8.1	11	9.2	11	9.5	11	9.2	11
Exch. Na (meq/100g)	0.20	0.4	0.41	0.90	0.75	1.7	1.2	2.6	1.8	3.5
Exch. K (meq/100g)	1.1	1.2	0.70	0.84	0.62	0.76	0.59	0.76	0.58	0.82
Sodicity (ESP) %	0.70	1.2	1.4	2.7	2.4	5.0	3.9	7.8	6.2	11
Mineral N stock (kg/ha)	106	138	49	65	40	48	38	43	83	106
SOC stock (t/ha)	12	9.1	12	8.6	10	8.3	10	7.5	17	14
Lint yield (kg/ha)	Field 1: 3360					Field 2: 2838				

3.3 Soil organic carbon and Mineral N

Soil organic carbon (SOC) stocks ranged from 43 to 61 t/ha in the 0–90 cm profile depth. There was a clear difference in SOC at Gwydir comparison, where higher SOC was observed in the higher-yielding fields (Figure 1.3). There was also a trend of relatively higher SOC in topsoil (0-15 cm) and also the whole profile SOC stocks of high-yielding fields in all comparisons (Table 1.3, Table 1.4 to 1.6B). There was a positive correlation between SOC stocks and normalised yield ($P<0.05$) (Figure 1.4). The SOC stocks of high-yielding fields were 2.5 to 12.3 t/ha higher than their low-yielding paired fields, which, at a typical C:N ratio of 10:1, means these field also had an additional 250 to 1230 kg/ha of organic N – a benefit for potential nitrogen mineralisation and thus less reliance on mineral fertiliser for crop nutrition. The SOC of all the on-farm sites investigated was typically lower than that reported from three long-term experiments at the Australian Cotton Research Institute (Rochester, 2011; Hulugalle *et al.*, 2013; Nachimuthu *et al.*, 2018; Osanai *et al.*, 2020). The three long-term sites maintained the crop rotation integrity in every rotation cycle. However, commercial fields are often prone to extended fallow due to drought and lack of irrigation water availability. Mineral N levels were relatively higher than recent research studies (Schwenke *et al.*, 2022). This could be a result of timing of soil sampling that occurred after fertiliser application and before crop uptake. There was no relationship between early season mineral N and cotton lint yield (r^2 =0.04). However, Rochester and Bange (2016) reported lint yield was positively correlated with pre-sowing soil nitrate in unfertilised plots. The lack of relationship between cotton lint yield and soil mineral N in our study suggest the combined fertiliser N and soil N measured are higher than soil nitrate N reported by Rochester and Bange (2016) and there is potential to rationalise the nitrogen input. Previous research found that cotton plants often derive more N from soils than from applied fertiliser (Rochester and Bange, 2016; Macdonald *et al.*, 2017). A recent study conducted at the Australian Cotton Research Institute highlighted that higher yields can be achieved with a lower N application rate (<155 kg N/ha) (Schwenke *et al.*, 2022) compared to a higher industry average N application rate (CRDC, 2019). The topsoil SOC of the experimental field in the study by Schwenke *et al.* (2022) was similar (~1%) to the other fields at the Australian Cotton Research Institute (Figure 1.3) and higher than the paired fields investigated in this study. Future studies on nutrient response comparing soils with higher and lower SOC will unravel the capacity of the soil to supply the plant nutrient demand and assist with optimising nutrient inputs.

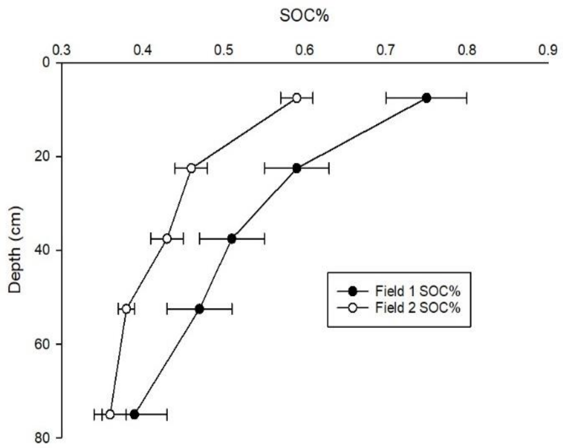


Figure 1.3. Soil organic carbon at different depths of Fields 1 and 2. F1 and F2 are two fields that recorded average lint yield of 14.5 and 12.5 bales/ha over 5 years. The error bars indicate standard error of the mean.

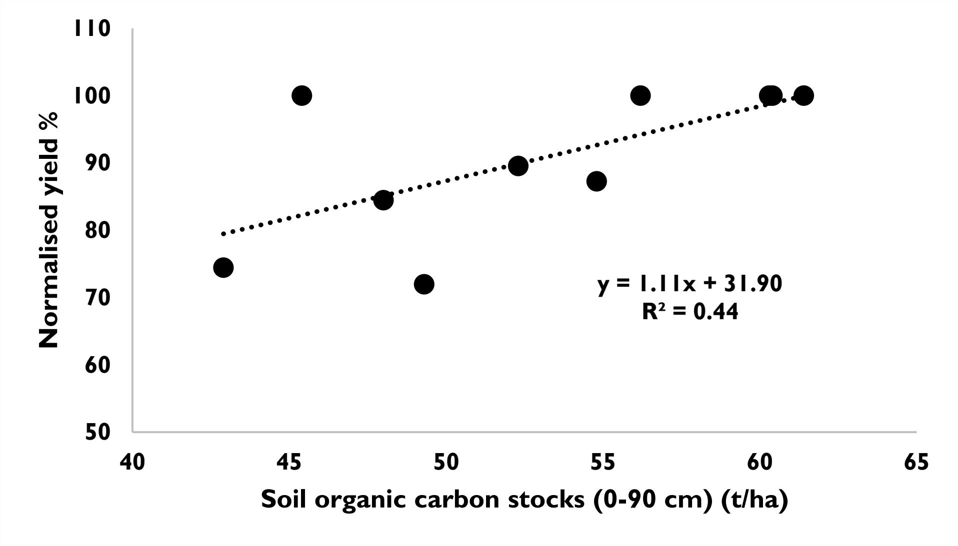


Figure 1.4. Relationship between soil organic carbon stocks (t/ha) and normalised yield across 10 fields.

Table 1.5A. Soil properties for the paired fields measured in Macquarie valley A comparison (Values are mean of 9 replicates)

Field	Field 3	Field 4	Field 3	Field 4	Field 3	Field 4	Field 3	Field 4	Field 3	Field 4
Depth (cm)	0-15	0-15	15-30	15-30	30-45	30-45	45-60	45-60	60-90	60-90
Bulk density (g/cm3)	1.1	1.4	1.3	1.6	1.4	1.7	1.4	1.8	1.5	1.9
Ammonium N (mg/kg)	2.2	2.9	2.0	2.6	1.8	2.0	1.6	1.8	1.2	1.7
Nitrate N (mg/kg)	36	61	6.0	8.6	5.1	7.0	5.1	5.4	7.0	5.3
Colwell P (mg/kg)	34	76	31	18	4	8	3	6	2	10
KCl-40 S (mg/kg)	14	15	6	5	6	5	7	6	21	14
SOC Conc. (%)	0.63	0.71	0.48	0.49	0.42	0.40	0.36	0.32	0.30	0.24
EC	0.171	0.187	0.143	0.090	0.183	0.097	0.215	0.107	0.287	0.128
pH ($CaCl_2$)	7.7	7.3	7.8	7.4	7.9	7.6	8.0	7.5	8.1	7.7
pH (water)	8.6	8.0	8.8	8.3	9.0	8.4	9.1	8.5	9.2	8.5
DTPA Cu (mg/kg)	1.6	1.6	1.8	1.7	1.7	1.5	1.7	1.6	1.7	1.6
DTPA Fe (mg/kg)	25	26	26	28	25	25	24	24	21	22
DTPA Mn (mg/kg)	16	32	14	22	11	15	10	12	9	10
DTPA Zn (mg/kg)	0.5	1.3	1.7	0.6	0.2	0.4	0.3	0.4	0.3	0.4
$CaCl_2$-B (mg/kg)	1.6	1.1	1.4	0.9	1.8	1.0	2.8	1.4	5.2	2.3
Exch. Ca (meq/100g)	18	11	18	11	17	11	16	11	15	11
Exch. Mg (meq/100g)	5.0	4.4	5.8	4.4	6.8	4.9	7.7	5.4	8.3	6.0
Exch. Na (meq/100g)	0.21	0.03	0.38	0.07	0.80	0.11	1.3	0.21	2.4	0.43
Exch. K (meq/100g)	0.85	0.81	0.62	0.50	0.51	0.43	0.47	0.36	0.49	0.39
Sodicity (ESP) %	0.86	0.16	1.5	0.38	3.1	0.63	5.1	1.0	9.0	2.1
Mineral N stock (kg/ha)	64	136	16	27	15	24	14	20	38	40
SOC stock (t/ha)	11	15	9.8	12	9.4	11	8.0	8.9	14	14
Lint yield (kg/ha)	Field 3: 2440					Field 4: 2724				

Table 1.5B. Soil properties for the paired fields measured in Macquarie valley-B (Values are mean of 9 replicates)

Field	Field 5	Field 6	Field 5	Field 6	Field 5	Field 6	Field 5	Field 6	Field 5	Field 6
Depth (cm)	0-15	0-15	15-30	15-30	30-45	30-45	45-60	45-60	60-90	60-90
Bulk density (g/cm3)	1.2	1.1	1.4	1.5	1.4	1.7	1.4	1.7	1.5	1.7
Ammonium N (mg/kg)	2.0	3.1	1.7	2.0	1.3	1.7	0.9	1.2	0.5	1.2
Nitrate N (mg/kg)	76	225	20	11	16	11	12	15	9.9	16
Colwell P (mg/kg)	35	43	6	24	3	7	2	5	2	6
KCl-40 S (mg/kg)	13	20	6	6	6	7	6	7	12	12
SOC (%)	0.56	0.62	0.37	0.43	0.31	0.30	0.29	0.23	0.25	0.20
EC	0.235	0.433	0.158	0.087	0.172	0.104	0.193	0.143	0.244	0.191
pH ($CaCl_2$)	7.6	7.0	7.7	7.2	7.9	7.5	8.0	7.7	8.0	7.8
pH (water)	8.4	7.5	8.6	8.2	8.8	8.6	8.9	8.8	9.1	9.0
DTPA Cu (mg/kg)	1.6	1.7	1.6	1.8	1.7	1.7	1.7	1.5	1.7	1.6
DTPA Fe (mg/kg)	22	28	20	29	22	31	23	30	21	30
DTPA Mn (mg/kg)	16	23	9	14	8	13	9	11	8	11
DTPA Zn (mg/kg)	0.6	1.1	0.2	0.6	0.4	0.3	0.2	0.2	0.2	0.2
$CaCl_2$-B (mg/kg)	1.4	1.3	1.3	1.2	1.6	1.2	2.1	1.4	3.5	1.9
Exch. Ca (meq/100g)	18	13	18	13	17	14	16	12	14	11
Exch. Mg (meq/100g)	6.3	5.8	6.7	6.2	7.4	7.0	7.9	7.0	8.6	7.3
Exch. Na (meq/100g)	0.09	0.16	0.36	0.33	0.82	0.70	1.4	1.2	2.5	2.1
Exch. K (meq/100g)	1.2	0.82	0.73	0.63	0.60	0.45	0.57	0.38	0.60	0.42
Sodicity (ESP) %	0.3	0.8	1.4	1.6	3.1	3.2	5.2	5.8	9.8	9.6
Mineral N stock (kg/ha)	143	395	47	30	36	33	29	43	49	90
SOC stock (t/ha)	11	11	8	10	7	8	6	6	12	11
Lint yield (kg/ha)	Field 5: 1816					Field 6: 2440				

3.4 Soil available P and exchangeable K

Soil available P of all the fields except field 5, was well above the critical soil test value recommended by Dorahy *et al.* (2004). In Macquarie-B comparison, the Colwell P values of the field 5 were significantly lower than the field 6 (Table 1.7B), however, the yield in 2018-19 season (Figure 1.2) was not correlated with the Colwell P values. The Colwell P levels at 15-30 cm of field 5 were lower than the critical Colwell P values (7 mg/kg) derived by Dorahy *et al.* (2004) for 0-30 cm. It is possible, the long-term average lower yield in field 5 could be a combined effect of low native P fertility and P input not matching the demand. The cotton crop in fields with lower Colwell P levels may have been limited for P if P fertiliser was not part of the nutrient management plan. Previous studies on similar soils in the Macquarie Valley found higher lint yield where P had been applied (Nachimuthu *et al.*, 2022c). The Colwell P soil test measures the fraction of soil P that is more readily available to crops. The BSES P soil test includes Colwell P and additional P that is in other forms less available to plants. Once Colwell P is depleted by plant uptake, the P from the BSES P pool will slowly replenish the Colwell P (Moody *et al.*, 2013). This process will depend on various soil factors, such as mineral composition of soil, soil pH changes, root acidification and microbial processes. Sporadic cotton yield responses have been reported to applied P in recent years (Nachimuthu *et al.*, 2022b) and some of the responses occurred in soils where the Colwell P value was above the previously suggested critical level (7 mg P/kg). The original study that derived the critical Colwell P values relied on P response studies that predominantly used banding as the method of P fertiliser application in the soil. However, recent studies indicated that cotton plants utilise P more efficiently if it is dispersed throughout the beds (Bell, 2014). A previous study suggested that the enrichment of soil with regular P fertiliser additions over the long term would better improve the P supply to the cotton plant than an immediate response in the same season of P application (Griffith and Guppy, 2015). This could be a reason for the sporadic yield response to applied P in cotton.

Soil exchangeable K levels in all the paired fields were above the critical values of 0.25 to 0.37 meq K^+/100 g for clay soil (NutriPak 2018) and no interactions with yield and K was evident.

3.5 Sodicity

Sodicity (ESP) was significantly different between paired fields for Gwydir, Macquarie-A and Riverina-B comparisons (Tables 1.4, 1.5A and 1.6B). Those fields with higher ESP (averaged across 0-90 cm depth) had lower yields. The sodicity levels were well below the previously suggested values for chemical toxicity, however, sodicity can result in dispersion and poor drainage (Dodd *et al.*, 2013). This would likely contribute to reduced root exploration, poor nutrient uptake, reduced cotton crop biomass and lower SOC due to less biomass returned to the soil after harvest (Figure 1.5). Sodicity is usually ameliorated by gypsum application and leaching, or else revised inputs to suit the lower yield potential.

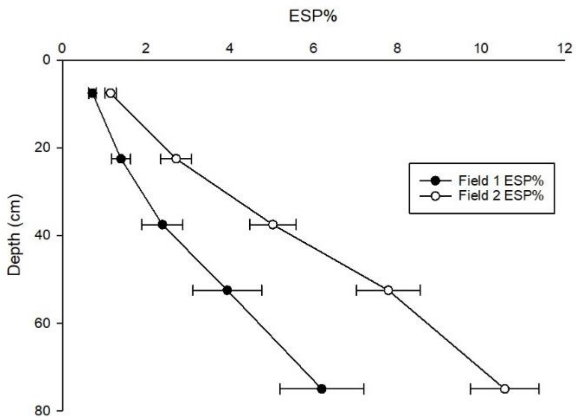


Figure 1.5. Different sodicity levels in paired fields (Average yield of fields 1 and 2 were 14.8 and 12.5 bales/ha respectively). The error bars indicate standard error of the mean.

Table 1.6A. Soil properties for the paired fields measured in Riverina-A comparison (Values are mean of 9 replicates)

Field	Field 7	Field 8	Field 7	Field 8	Field 7	Field 8	Field 7	Field 8	Field 7	Field 8
Depth (cm)	0-15	0-15	15-30	15-30	30-45	30-45	45-60	45-60	60-90	60-90
Bulk density (g/cm3)	1.2	1.4	1.4	1.5	1.6	1.6	1.6	1.5	1.5	1.6
Ammonium N (mg/kg)	7.2	9.8	69.4	91.8	5.8	2.7	2.1	2.2	1.8	2.7
Nitrate N (mg/kg)	32	49	84	83	18	12	6.9	11	7.7	12
Colwell P (mg/kg)	95	77	120	66	22	6	8	4	6	4
KCl-40 S (mg/kg)	11	18	11	24	14	39	17	39	20	32
SOC (%)	0.92	0.92	0.72	0.61	0.47	0.34	0.32	0.24	0.20	0.15
EC	0.104	0.133	0.195	0.187	0.093	0.128	0.116	0.175	0.168	0.211
pH ($CaCl_2$)	6.3	5.9	6.0	6.1	6.7	6.9	7.4	7.7	8.0	7.8
pH (water)	7.1	6.7	6.8	6.8	7.7	7.9	8.4	8.6	8.9	8.7
DTPA Cu (mg/kg)	1.9	2.1	1.9	2.2	1.7	1.8	1.8	1.6	1.4	1.3
DTPA Fe (mg/kg)	54	49	54	42	35	21	27	18	20	15
DTPA Mn (mg/kg)	21	32	27	33	13	7	10	5	5	4
DTPA Zn (mg/kg)	3.6	3.9	1.9	1.6	0.5	0.3	0.6	0.3	0.2	0.2
$CaCl_2$-B (mg/kg)	1.5	1.3	1.5	1.5	1.9	1.9	2.7	2.5	3.9	2.8
Exch. Ca (meq/100g)	7.0	7.4	6.9	8.5	7.9	10	9.3	12	11	13
Exch. Mg (meq/100g)	4.2	4.0	4.5	5.5	5.9	7.9	7.3	8.4	8.4	8.7
Exch. Na (meq/100g)	0.17	0.13	0.16	0.19	0.43	0.48	0.54	0.46	0.60	0.47
Exch. K (meq/100g)	0.76	0.72	0.58	0.54	0.44	0.50	0.51	0.50	0.56	0.55
Sodicity (ESP) %	1.4	1.0	1.2	1.3	2.9	2.6	3.1	2.2	2.8	2.0
Mineral N stock (kg/ha)	72	124	343	405	58	35	22	31	40	70
SOC stock (t/ha)	17	19	16	14	11	8	8	6	9	7
Lint yield (kg/ha)	Field 7: 2801					Field 8: 2445				

Table 1.6B. Soil properties for the paired fields measured in Riverina-B comparison

Field	Field 9	Field 10	Field 9	Field 10	Field 9	Field 10	Field 9	Field 10	Field 9	Field 10
Depth (cm)	0-15	0-15	15-30	15-30	30-45	30-45	45-60	45-60	60-90	60-90
Bulk density (g/cm3)	1.4	1.3	1.5	1.4	1.5	1.5	1.5	1.5	1.6	1.5
Ammonium N (mg/kg)	7.4	5.3	3.1	9.0	2.2	2.1	2.2	2.1	2.3	2.3
Nitrate N (mg/kg)	34	20	12	21	5.9	11	3.0	5.1	2.0	5.0
Colwell P (mg/kg)	55	63	20	19	4	4	3	2	3	4
KCl-40 S (mg/kg)	75	55	30	24	13	12	7	11	6	34
SOC (%)	0.90	0.75	0.58	0.54	0.41	0.39	0.29	0.25	0.16	0.15
EC	0.194	0.128	0.083	0.079	0.061	0.085	0.092	0.14	0.152	0.201
pH ($CaCl_2$)	5.1	5.4	5.0	6.0	6.4	7.0	7.2	7.7	7.7	7.7
pH (water)	5.8	6.3	6.0	7.3	7.4	8.4	8.1	9.0	8.6	8.9
DTPA Cu (mg/kg)	2.5	2.2	2.2	2.1	1.7	1.8	1.7	1.5	1.3	1.3
DTPA Fe (mg/kg)	90	58	64	32	22	15	19	14	15	13
DTPA Mn (mg/kg)	41	37	40	22	12	7	7	5	5	4
DTPA Zn (mg/kg)	3.1	3.8	1.3	1.6	0.3	0.4	0.2	0.3	0.2	0.4
$CaCl_2$-B (mg/kg)	1.0	1.5	1.4	2.5	2.3	3.9	3.1	4.7	3.3	4.4
Exch. Ca (meq/100g)	4.6	5.2	5.7	6.9	9.0	8.5	10	9.4	12	10
Exch. Mg (meq/100g)	2.9	4.0	4.8	6.3	8.3	8.5	8.9	8.9	8.9	8.7
Exch. Na (meq/100g)	0.03	0.21	0.11	0.89	0.41	1.6	0.45	2.0	0.48	2.1
Exch. K (meq/100g)	0.81	0.78	0.68	0.62	0.67	0.63	0.66	0.67	0.68	0.67
Sodicity (ESP) %	0.3	1.8	0.9	5.9	2.1	8.6	2.2	9.5	2.2	10
Mineral N stock (kg/ha)	87	52	35	67	19	31	13	17	21	34
SOC stock (t/ha)	19	15	13	12	10	9	7	6	8	7
Lint yield (kg/ha)	Field 9: 2874					Field 10: 2068				

3.6 DTPA-extractable micronutrients and Boron

All DTPA-extractable micronutrients (Cu, Zn, Fe and Mn) were above recommended critical values for crop response in top soil (NUTRIpak, 2018) across all the sites (Table 1.4 to 1.6B). The lower-yielding fields in both Macquarie-A and B comparisons had lower Zn levels in topsoil (Table 1.4 and 1.5A) than high-yielding fields. Hot $CaCl_2$ extractable Boron levels were above the critical values (0.4 mg/kg) prescribed for a cotton crop response across all the sites in this case study (Table 1.4 to 1.6B). A recent study on micronutrient changes over the long-term suggested that micronutrient availability was not related to the nutrient export associated with crop removal in fertile Vertosols, but noted that variable soils of southern NSW cotton growing regions (e.g. Riverina, Macquarie) required further investigation (Palmer *et al.*, 2023).

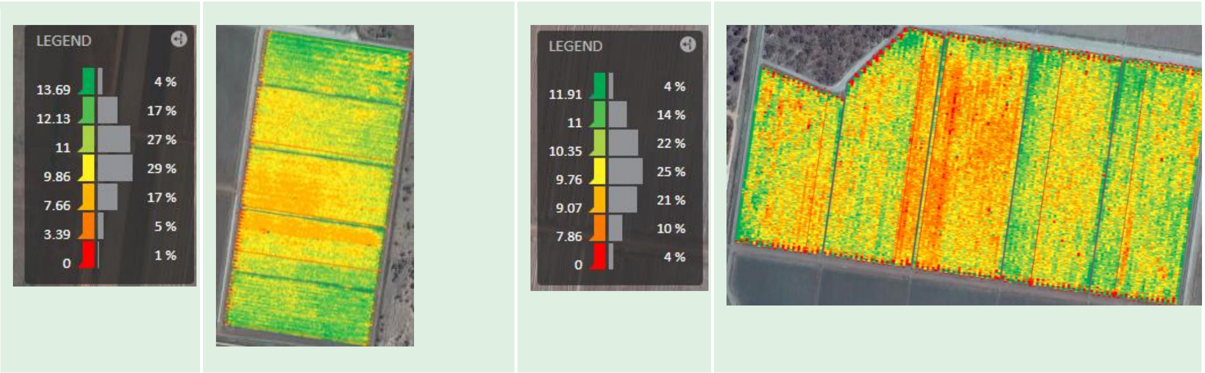
3.7 Visual soil assessment

The soil quality index score of fields 1 to 6 was above 30 and classified as good under this assessment. Many cotton farms in Australia were developed on medium–heavy, cracking clay soils, with the shrink-well properties acting to self-repair physical damage (Pillai-McGarry *et al.*, 1994). In addition, soil management has improved over time by adopting control traffic farming. For example, most Australian cotton farms now practice stubble incorporation into the topsoil, which improves the soil quality compared to the raking and burning practices that existed in the past (NUTRIpak, 2018). The good soil quality index results are indicative of the role soil management provides in achieving the high yield potential expected in Australia, which is currently the highest in the world (Constable and Bange, 2015). The average irrigated yield across the Australian cotton industry ranges from 10 to 12 bales/ha, which is around 50% of the potential theoretical yield of 22 bales/ha (Constable and Bange, 2015). There are other soil constraints, such as subsoil compaction induced by heavy machinery (that may not be assessed in this scoring index), that can significantly impact the cotton yield (Jamali *et al.*, 2021). Crop rotation using cereals and legumes within cotton-based cropping systems is often advocated as a potential solution to improve soil physical properties (Hulugalle and Scott, 2008) and fertility (Rochester *et al.*, 2001; Rochester, 2011). While the soil quality was ‘good’ using the visual soil assessment method, there are still opportunities for improvement with soil management practices.

One of the drawbacks of visual soil assessment is the biological indicator. Earthworms are the only biological indicator assessed in this method and they were not detected during soil sampling across all the sites. This is similar to other visual soil assessments across Australian cotton regions, where earthworms were rarely sighted (out of 205 visual assessments). This is reflective of Eastern Australian hot climatic conditions during cotton production. We suggest the biological indicator assessment for cotton-growing soils in Australia may be modified using other indicators such as cotton fabric degradation (Nachimuthu *et al.*, 2022a), which would represent organic matter degradation under the cotton-growing conditions. The most parameters of the current visual soil assessment method account only top soil except drainage and rooting depth. The current assessment method, providing visual soil quality index may not be sensitive enough to predict cotton crop performance in cotton growing Vertosols of Australia and needs further refinement.

3.8 Simple interpretation of cotton lint yield map

An investigation of the cotton lint yield map (2017-18 season) using management information and soil test from the DeBortoli farm in the Riverina region suggested the zones or bays of the field that had an accidental missing of wheat crop rotation (Figure 1.6A) in the previous winter (due to rain interfering with planting) or the low yield points consisted of soil with higher subsoil sodicity (Figure 1.6B). The yield decline again re-emphasises the benefits of rotation crops, especially in southern NSW, where growers tend to go back-to-back cotton.



A) B)

Figure 1.6 (A) The middle bay missed the wheat crop rotation in the previous winter resulting in lower lint yield in the 2017-18 season. (B) The red and yellow patches in the middle bay showing lower yield are the points matching the higher subsoil sodicity.

4 Conclusion

This case study using the paired field comparison was helpful to identify differences in soil properties that could be potentially causing yield limitations. Soil organic carbon stocks were correlated with normalised lint yield percentage whereas early season soil mineral N or soil organic carbon does not correlate with current season yield. Soil sodicity and lower soil available P and Zn may be limiting production at some sites. The visual soil quality index was not a sensitive predictor of cotton crop performance. This case study focussed on improving the understanding between the two fields at each site. A similar approach could be undertaken to improve the understanding of within-field yield variability by dividing the field into several zones and assessing each zone individually.

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References

Adams, T.C., Brye, K.R., Purcell, L.C., Ross, J., Gbur, E.E., Savin, M.C., 2017. Soil property predictors of soybean yield using yield contest sites. Journal of Crop Improvement 31, 816-829. 10.1080/15427528.2017.1372326

Adams, T.C., Brye, K.R., Purcell, L.C., Ross, W.J., Gbur, E.E., Savin, M.C., 2018. Soil property differences among high- and average-yielding soya bean areas in Arkansas, USA. Soil Use and Management 34, 72-84. https://doi.org/10.1111/sum.12397

Al-Shatib, M.A.M., Chen, G., Bennett, J.M., Jensen, T.A., 2021. Monitoring the behaviour of Australian Vertosols in response to the shrink–swell characteristic and cotton picker traffic. Soil Research 59, 396-405. https://doi.org/10.1071/SR20222

Aus Gov, 2023. Bioregional assessment program. Gwydir subregion: context statement for the Gwydir subregion-Physical Geography.

Bell, M., 2014. Developing soil testing and fertiliser response guidelines to manage P, K and S fertility for irrigated and dryland cotton cropping systems. Final Report. Cotton Research and Development Corporation and The University of Queensland.

Cattle, S.R., Smith, C.M.S., 2018. Fabric of soil derived from parna and the riddle of transported pellets. Soil Research 56, 219-234. https://doi.org/10.1071/SR16343

Colwell, J., 1963. The estimation of the phosphorus fertilizer requirements of wheat in southern New South Wales by soil analysis. Australian Journal of Experimental Agriculture 3, 190-197. https://doi.org/10.1071/EA9630190

Constable, G.A., Bange, M.P., 2015. The yield potential of cotton (Gossypium hirsutum L.). Field Crops Research 182, 98-106. https://doi.org/10.1016/j.fcr.2015.07.017

CRDC, 2019. 2019 Grower Survey, December 2019. Cotton Research and Development Corporation, Narrabri.

CRDC and Cotton Australia, 2020. Australian Cotton Sustainability Report 2019. In: Australian Cotton Industry's Sustainability working group (Ed.). Cotton Research and Development Corporation and Cotton Australia, Narrabri & Sydney.

Dodd, K., Guppy, C.N., Lockwood, P.V., Rochester, I.J., 2013. The effect of sodicity on cotton: does soil chemistry or soil physical condition have the greater role? Crop and Pasture Science 64, 806-815. https://doi.org/10.1071/CP13078

Dorahy, C.G., Rochester, I.J., Blair, G.J., 2004. Response of field-grown cotton (Gossypium hirsutum L.) to phosphorus fertilisation on alkaline soils in eastern Australia. Soil Research 42, 913-920. https://doi.org/10.1071/SR04037

Griffith, B., Guppy, C., 2015. Phosphorus availability in raingrown cotton. Final Report for UNE1501. Cotton Research and Development Corporation, Narrabri, NSW 2390, p. 14.

Hulugalle, N.R., Scott, F., 2008. A review of the changes in soil quality and profitability accomplished by sowing rotation crops after cotton in Australian Vertosols from 1970 to 2006. Soil Research 46, 173-190. https://doi.org/10.1071/SR07077

Hulugalle, N.R., Strong, C., McPherson, K., Nachimuthu, G., 2017. Carbon, nitrogen and phosphorus stoichiometric ratios under cotton cropping systems in Australian Vertisols: a meta-analysis of seven experiments. Nutrient Cycling in Agroecosystems 107, 357-367. 10.1007/s10705-017-9837-y

Hulugalle, N.R., Weaver, T.B., Finlay, L.A., 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 and Pasture Science 64, 799-805. https://doi.org/10.1071/CP12374

Indoria, A.K., Sharma, K.L., Reddy, K.S., 2020. Chapter 18 - Hydraulic properties of soil under warming climate. In: Prasad, M.N.V., Pietrzykowski, M. (Eds.), Climate Change and Soil Interactions. Elsevier, pp. 473-508.

Isbell, R.F., National Committee on Soil and Terrain, 2021. The Australian soil classification. CSIRO Publishing, Melbourne.

Jamali, H., Nachimuthu, G., Palmer, B., Hodgson, D., Hundt, A., Nunn, C., Braunack, M., 2021. Soil compaction in a new light: Know the cost of doing nothing – A cotton case study. Soil and Tillage Research 213, 105158. https://doi.org/10.1016/j.still.2021.105158

Jeffrey, S.J., Carter, J.O., Moodie, K.B., Beswick, A.R., 2001. Using spatial interpolation to construct a comprehensive archive of Australian climate data. Environmental Modelling & Software 16, 309-330. https://doi.org/10.1016/S1364-8152(01)00008-1

Macdonald, B.C.T., Chang, Y.F., Nadelko, A., Tuomi, S., Glover, M., 2017. Tracking fertiliser and soil nitrogen in irrigated cotton: uptake, losses and the soil N stock. Soil Research 55, 264-272. https://doi.org/10.1071/SR16167

McKenzie, N.J., 1992. Soils of the Lower Macquarie Valley, New South Wales,. CSIRO Division of Soils, Canberra, Australia., Canberra, Australia.

Moody, P.W., Speirs, S.D., Scott, B.J., Mason, S.D., 2013. Soil phosphorus tests I: What soil phosphorus pools and processes do they measure? Crop and Pasture Science 64, 461-468. https://doi.org/10.1071/CP13112

Nachimuthu, G., Hulugalle, N.R., Watkins, M.D., Finlay, L.A., McCorkell, B., 2018. Irrigation induced surface carbon flow in a Vertisol under furrow irrigated cotton cropping systems. Soil and Tillage Research 183, 8-18. https://doi.org/10.1016/j.still.2018.05.011

Nachimuthu, G., Hundt, A., Palmer, B., Schwenke, G.D., Knox, O.G.G., 2022a. Cotton strip assay detects soil microbial degradation differences among crop rotation and tillage experiments on Vertisols. Journal of Microbiological Methods 200, 106558. https://doi.org/10.1016/j.mimet.2022.106558

Nachimuthu, G., Schwenke, G., Baird, J., McPherson, A., Mercer, C., Sargent, B., Hundt, A., Macdonald, B., 2022b. Cotton yield response to fertilizer phosphorus under a range of nitrogen management tactics. Crop and Environment 1, 214-219. https://doi.org/10.1016/j.crope.2022.09.004

Nachimuthu, G., Schwenke, G., Mercer, C., Bischof, C., Hulme, P., Bell, M., 2022c. A review of phosphorus nutrition in irrigated cotton farming systems of Australia. Journal of Cotton Research 5, 6. 10.1186/s42397-022-00114-x

NSWDOI, 2018. Gwydir Alluvium Water Resource Plan – Groundwater Resource Description. p. 61.

NUTRIpak, 2018. NUTRIpak: A practical guide to cotton nutrition. CottonInfo and Cotton Research and Development Corporation.

Osanai, Y., Knox, O., Nachimuthu, G., Wilson, B., 2020. Increasing soil organic carbon with maize in cotton-based cropping systems: Mechanisms and potential. Agriculture, Ecosystems & Environment 299, 106985. https://doi.org/10.1016/j.agee.2020.106985

Palmer, B., Guppy, C., Nachimuthu, G., Hulugalle, N., 2023. Changes in micronutrient concentrations under minimum tillage and cotton-based crop rotations in irrigated Vertisols Soil and Tillage Research In Press.

Pillai-McGarry, U., Sarmah, A.J., McGarry, D., 1994. Structure Repair with Wet/Dry Cycles in a Cotton Soil World Cotton Research Conference, Brisbane.

Predicta B, 2023. DNA-based soil testing service. Copyright ©2023 PIRSA, South Australian Research and Development Institute.

Rayment, G.E., Lyons, D.J., 2010. Soil chemical methods - australasia. CSIRO Publishing.

Rochester, I.J., 2011. Sequestering carbon in minimum-tilled clay soils used for irrigated cotton and grain production. Soil and Tillage Research 112, 1-7. https://doi.org/10.1016/j.still.2010.10.012

Rochester, I.J., Bange, M., 2016. Nitrogen fertiliser requirements of high-yielding irrigated transgenic cotton. Crop and Pasture Science 67, 641-648. https://doi.org/10.1071/CP15278

Rochester, I.J., Peoples, M.B., Hulugalle, N.R., Gault, R.R., Constable, G.A., 2001. Using legumes to enhance nitrogen fertility and improve soil condition in cotton cropping systems. Field Crops Research 70, 27-41. https://doi.org/10.1016/S0378-4290(00)00151-9

Schwenke, G., Baird, J., Nachimuthu, G., Macdonald, B., McPherson, A., Mercer, C., Hundt, A., 2022. Dressed for success. Are crop N uptake, N loss and lint yield of irrigated cotton affected by how in-crop N fertiliser is applied? Field Crops Research 287, 108659. https://doi.org/10.1016/j.fcr.2022.108659

Shepherd, G., Stagnari, F., Pisante, M., Benites, J., 2008. Visual Soil Assessments- Annual Crops. Food and Agriculture Organisation of the United Nations, Rome.

Zhao, X., Wang, J., Zhao, D., Li, N., Zare, E., Triantafilis, J., 2019. Digital regolith mapping of clay across the Ashley irrigation area using electromagnetic induction data and inversion modelling. Geoderma 346, 18-29. https://doi.org/10.1016/j.geoderma.2019.01.033

Table 1.4. Summary of Analysis of Variance for the effects of field and soil depth on selected soil properties measured across selected fields in three cotton growing regions in New South Wales, Australia in 2018

	P values														
Region	Gwydir Comparison			Macquarie-A Comparison			Macquarie-B Comparison			Riverina-A Comparison			Riverina-B Comparison		
Soil property	Field	Soil depth	Field* Depth	Field	Soil depth	Field* Depth	Field	Soil depth	Field* Depth	Field	Soil depth	Field* Depth	Field	Soil depth	Field* Depth
Bulk density (g/cm3)	<0.01	<0.001	0.728	<0.001	<0.001	0.154	<0.001	<0.001	<0.001	0.093	<0.001	<0.05	0.311	<0.01	0.839
Ammonium N (mg/kg)	0.723	<0.001	<0.01	<0.01	<0.001	0.470	<0.05	<0.001	0.381	0.667	<0.001	0.936	0.619	0.054	0.331
Nitrate N (mg/kg)	0.156	<0.001	0.116	<0.05	<0.001	<0.001	<0.05	<0.001	<0.001	0.621	<0.001	0.734	0.618	<0.01	<0.01
Colwell P (mg/kg)	0.471	<0.001	0.319	0.135	<0.001	<0.01	<0.05	<0.001	<0.01	<0.05	<0.001	0.128	0.647	<0.001	0.381
KCl-40 S (mg/kg)	0.132	<0.001	0.183	0.475	<0.001	0.713	0.083	<0.001	0.089	<0.001	<0.001	<0.001	0.794	<0.001	<0.01
SOC Conc. (%)	<0.05	<0.001	<0.05	0.839	<0.001	<0.01	1.000	<0.001	<0.01	0.205	<0.001	0.151	0.078	<0.001	<0.001
EC	0.912	<0.001	<0.05	<0.01	<0.001	<0.001	0.680	<0.001	<0.001	0.110	<0.001	0.435	0.482	<0.001	<0.001
pH ($CaCl_2$)	0.296	<0.001	0.152	<0.01	<0.001	0.396	<0.05	<0.001	<0.01	0.948	<0.001	<0.01	<0.05	<0.001	<0.001
pH (water)	0.889	<0.001	<0.05	<0.001	<0.001	0.857	<0.05	<0.001	<0.001	0.514	<0.001	<0.05	<0.001	<0.001	<0.001
DTPA Cu (mg/kg)	<0.05	0.846	0.308	0.202	0.072	0.437	0.707	0.323	<0.01	0.395	<0.001	<0.05	<0.05	<0.001	<0.001
DTPA Fe (mg/kg)	<0.05	0.840	0.196	0.830	<0.001	0.919	<0.05	0.712	0.641	0.113	<0.001	0.724	<0.001	<0.001	<0.001
DTPA Mn (mg/kg)	<0.05	<0.001	NS	0.063	<0.001	<0.001	<0.01	<0.001	0.414	0.512	<0.001	<0.01	<0.01	<0.001	<0.001
DTPA Zn (mg/kg)	0.502	<0.001	0.335	0.919	<0.05	0.102	<0.05	<0.001	<0.001	0.132	<0.001	0.541	0.077	<0.001	0.581
B (mg/kg)	0.243	<0.001	0.250	<0.05	<0.001	<0.01	<0.05	<0.001	<0.001	0.232	<0.001	0.088	<0.01	<0.001	<0.05
Exch. Ca (meq/100g)	0.313	<0.001	0.882	<0.01	<0.01	<0.05	<0.001	<0.001	<0.05	0.134	<0.001	0.222	0.824	<0.001	<0.001
Exch. Mg (meq/100g)	<0.001	<0.001	<0.05	<0.05	<0.001	<0.01	0.074	<0.001	<0.01	0.095	<0.001	<0.001	0.379	<0.001	<0.001
Exch. Na (meq/100g)	<0.001	<0.001	<0.001	<0.01	<0.001	<0.001	0.565	<0.001	0.564	0.684	<0.001	0.565	<0.001	<0.001	<0.001
Exch. K (meq/100g)	<0.01	<0.001	0.110	0.087	<0.001	0.613	<0.01	<0.001	<0.001	0.882	<0.001	0.299	0.312	<0.001	0.556
Sodicity (ESP) %	<0.001	<0.001	<0.001	<0.01	<0.001	<0.001	0.809	<0.001	0.978	0.333	<0.001	0.491	<0.001	<0.001	<0.001
Mineral N stock (kg/ha)	0.240	<0.001	0.449	<0.01	<0.001	<0.001	<0.05	<0.001	<0.001	0.499	<0.001	0.940	0.495	<0.001	<0.05
SOC stock (t/ha)	<0.05	<0.001	0.774	0.125	<0.001	<0.05	0.124	<0.001	<0.05	0.339	<0.001	<0.01	0.064	<0.001	<0.001

Table 1.5 Mean separation values (Least significant differences (LSD)) for the effects of field and soil depth on selected soil properties measured across selected fields in three cotton growing regions in New South Wales, Australia in 2018

	LSD values at α=0.05														
Region	Gwydir Comparison			Macquarie-A Comparison			Macquarie-B Comparison			Riverina-A Comparison			Riverina-B Comparison		
Soil property	Field	Soil depth	Field* Depth	Field	Soil depth	Field* Depth	Field	Soil depth	Field* Depth	Field	Soil depth	Field* Depth	Field	Soil depth	Field* Depth
Bulk density (g/cm3)	0.036	0.049	NS	0.147	0.065	NS	0.064	0.069	0.104	NS	0.072	0.102	NS	0.08	NS
Ammonium N (mg/kg)	NS	0.635	1.013	0.236	0.296	NS	0.463	0.453	NS	NS	31.78	NS	NS	NS	NS
Nitrate N (mg/kg)	NS	7.980	NS	5.498	5.013	8.000	28.45	31.50	46.97	NS	17.55	NS	NS	5.176	7.519
Colwell P (mg/kg)	NS	5.105	NS	NS	12.47	19.00	6.244	4.462	7.987	15.48	21.60	NS	NS	4.843	NS
KCl-40 S (mg/kg)	NS	9.57	NS	NS	5.916	NS	NS	3.218	NS	7.21	4.24	8.53	NS	12.25	17.32
SOC Conc. (%)	0.088	0.040	0.097	NS	0.041	0.087	NS	0.035	0.052	NS	0.057	NS	NS	0.026	0.061
EC	NS	0.027	0.049	0.044	0.028	0.053	NS	0.048	0.074	NS	0.036	NS	NS	0.026	0.043
pH ($CaCl_2$)	NS	0.093	NS	0.260	0.100	NS	0.302	0.124	0.326	NS	0.213	0.337	0.314	0.146	0.348
pH (water)	NS	0.109	0.272	0.296	0.103	NS	0.305	0.134	0.334	NS	0.201	0.299	0.263	0.151	0.309
DTPA Cu (mg/kg)	0.127	NS	NS	NS	NS	NS	NS	NS	0.188	NS	0.150	0.227	0.074	0.086	0.127
DTPA Fe (mg/kg)	4.244	NS	NS	NS	2.662	NS	6.827	NS	NS	NS	6.95	NS	4.809	4.974	7.579
DTPA Mn (mg/kg)	5.711	3.633	NS	NS	2.986	7.475	2.812	2.543	NS	NS	4.929	6.898	3.042	3.331	4.984
DTPA Zn (mg/kg)	NS	0.211	NS	NS	0.660	NS	0.104	0.116	0.173	NS	0.476	NS	NS	0.391	NS
B (mg/kg)	NS	0.342	NS	1.037	0.644	1.252	0.538	0.316	0.637	NS	0.458	NS	0.746	0.382	0.846
Exch. Ca (meq/100g)	NS	0.860	NS	2.586	0.870	2.716	1.263	0.758	1.505	NS	0.981	NS	NS	0.635	1.451
Exch. Mg (meq/100g)	0.540	0.351	0.664	1.497	0.440	1.552	NS	0.250	0.835	NS	0.511	1.162	NS	0.4	1.368
Exch. Na (meq/100g)	0.398	0.273	0.500	0.452	0.193	0.492	NS	0.335	NS	NS	0.115	NS	0.41	0.159	0.439
Exch. K (meq/100g)	0.098	0.053	NS	NS	0.049	NS	0.102	0.044	0.111	NS	0.051	NS	NS	0.041	NS
Sodicity (ESP) %	1.040	0.751	1.337	1.554	0.687	1.703	NS	1.388	NS	NS	0.597	NS	2.102	0.815	2.251
Mineral N stock (kg/ha)	NS	15.98	NS	12.26	11.37	18.03	53.53	55.50	84.50	NS	109.3	NS	16.72	19.53	28.68
SOC stock (t/ha)	2.093	1.249	NS	NS	1.482	2.736	NS	0.970	1.354	NS	1.326	3.280	NS	0.747	1.67

Supplementary data

Table A1.1: Rainfall (mm) for the regions represented in the 2018 soil sampling. Sixty-four-year (1955–2019) average of monthly and annual precipitation

Month	Gwydir	Macquarie	Riverina
Jan	80	58	31
Feb	71	50	32
Mar	50	44	37
Apr	34	39	31
May	37	38	40
Jun	30	34	35
Jul	40	32	38
Aug	30	31	37
Sep	31	33	37
Oct	43	44	41
Nov	60	38	30
Dec	63	43	32
Annual average (mm)	**569**	**483**	**422**

Source: SILO (Jeffrey *et al.*, 2001), https://www.longpaddock.qld.gov.au/

Table A1.2: Air temperature data for the regions represented in the study. Sixty-four-year (1955–2019) average of monthly min. and max air temperatures

	Gwydir		Macquarie		Riverina	
Month	Tmin °C	Tmax °C	Tmin °C	Tmax °C	Tmin °C	Tmax °C
Jan	20.2	34.1	19.4	33.9	17.4	32.8
Feb	19.8	33.3	19.0	33.0	17.3	32.1
Mar	17.3	31.2	16.2	30.1	14.4	28.6
Apr	12.9	27.4	11.8	25.7	10.2	23.8
May	8.6	22.6	7.7	20.5	6.9	18.7
Jun	5.7	19.1	5.0	17.0	4.5	15.3
Jul	4.3	18.3	3.6	16.1	3.5	14.3
Aug	5.3	20.2	4.4	18.0	4.3	16.3
Sep	8.5	24.1	7.2	21.8	6.3	19.6
Oct	12.8	27.9	11.1	26.1	9.4	23.7
Nov	16.1	31.0	14.5	29.6	12.6	27.6
Dec	18.6	33.2	17.4	32.6	15.2	30.5

Source: SILO (Jeffrey *et al.*, 2001), https://www.longpaddock.qld.gov.au/

Chapter 2: Soil compaction in a new light: know the cost of doing nothing – A cotton case study

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Abstract

Increased size of farm machinery has improved farm efficiency but at the risk of soil compaction. Here we present a novel approach investigating the effect of compaction due to in-field traffic by continuously monitoring crop canopy temperature and soil profile moisture and measuring crop yield in individual crop rows to determine the economic impact on cotton farming systems. Traffic by a tractor weighing 19.2 Mg either side of the plant row reduced lint yield by 27% due to lower crop height, leaf area, biomass and fruit number. Elevated canopy temperature (Tc) in the compacted plots resulted in 30% higher stress time (i.e. cumulative time when Tc is higher than the optimum Tc for cotton growth) compared with the non-compacted plots. Higher stress time in compacted plots was correlated with a 72% and 27% reduction in crop water use (estimated from change in soil water) at 0.3 - 0.5m and 0.5 – 0.7m depths, respectively. Water recharge in the soil profile from irrigation and rainfall was reduced by 16% due to compaction with the highest reduction being 86% at 0.3 – 0.5m depth. These results demonstrate that compaction likely reduced root access to water below 0.3m inducing water stress resulting in yield reduction. Tractors used for farm operations only compact one side of the bed, however, both sides are compacted in the absence of permanent wheel tracks. By comparison a dual tyre round module cotton picker weighing ~32 Mg compacts 67% of the rows on both sides and 33% on one side suggesting greater economic loss in the following season compared to that estimated from the current study. Reductions in soil water recharge following irrigation and rainfall events due to compaction will further decrease farm efficiency and profitability. To our knowledge this is the first study related to soil compaction in any crop to show the direct relationship between yield, plant stress time and soil water dynamics at specific depths in profile. It is suggested that short term agronomic decisions (eg irrigation scheduling) need to be considered differently where compaction has been identified as limiting productivity. We recommend case studies be conducted to monitor the effect of compaction on commercial farm productivity and to demonstrate the cost of compaction across agricultural industries to drive practice change. Demonstrating the potential economic consequences of soil compaction by the integrated approach used in this study may encourage practice change to minimize compaction on farms.

Keywords

Soil strength, canopy temperature, water stress, crop water use, soil water recharge

1. Introduction

Mechanization has increased farm productivity by improving efficiency of operations and reducing cost of labour (Kutzbach, 2000). However, larger machinery with higher capacity increases subsoil (>0.4 m depth) compaction due to higher axle loads (Keller and Arvidsson, 2004). A recent Australian cotton industry survey (CCA, 2020) suggested 66 percent of the surveyed cotton farms were impacted by soil compaction. Cotton is mostly grown on Vertisol soils with high clay content and water-holding capacity (Isbell, 2016) and with a history of intensive land preparation posing a greater risk of structural degradation (McGarry, 1990). In Australia, cotton is predominantly grown under irrigation (i.e. >80%

of area and >90% of production) with water applied frequently, resulting in high soil profile water content during the season (Roth et al., 2013) and therefore subject to greater risk of compaction. Australian cotton is grown predominantly in a cotton-wheat-fallow rotation with a range of farm machinery used for different field operations (Table 2.1).

Recent research has largely focussed on the effect of modern pickers on soil compaction (Bennett et al., 2019; Braunack and Johnston, 2014). Operations conducted before and during the cotton season with commonly available tractors can also result in soil compaction. In one example, cultivation conducted on wet soil before sowing resulted in 30% decrease in air-filled porosity and severely affected the crop with many plants falling over at first irrigation, forcing the farmer to manage the crop as dryland causing 70% yield loss (McGarry, 1990). In another case, a field cultivated wet (and hence compacted) required triple the number of irrigations to maintain lint yield due to soil compaction thus significantly reducing water use efficiency and adding to the cost of production associated with increased water use and labour (McGarry, 1995b).

Cotton sowing may occur after an irrigation (pre-irrigation) or on dry soil followed by an irrigation, referred to as watering up (ACPM, 2020). Current industry recommendations for cotton sowing in Australia are based on temperature and do not consider soil moisture per se (CSD, 2020). When rainfall occurs before sowing, farmers try to plant within a few days after rain to take advantage of the soil profile moisture. This strategy results in saving an irrigation which increases farm profitability in the short term albeit at the risk of compacting soil. Most of the operations following sowing are conducted as necessary and often without flexibility to delay if soil is wet because of rain or irrigations.

Fertilizer is mostly applied a few weeks before sowing, however, it is recommended to apply a proportion of fertilizer during the season to match crop demand and reduce nitrogen losses (Schwenke, G, personal communication). In the pre-sowing phase, fertilizer is generally applied using a tractor under drier soil conditions in the fallow season. The in-season fertilizer may be applied using a tractor either as side dressing or surface broadcast, water-run during an irrigation or surface broadcast by air. The operation to apply fertilizer with a tractor during the season can be a source of soil compaction as soil is relatively wet due to frequent irrigations. Inter-row cultivation is used for controlling weeds and Roundup™ ready volunteer cotton in furrows by disturbing the topsoil (up to 15 cm) and, while it loosens soil near surface, it can be a potential source of compaction in subsoil (McGarry, 1990, 1995b). Sprays of pesticides and insecticides are applied using either a ground rig or by air.

Cotton harvesting is performed using dual tyre round bale picker (32 Mg) which has the greatest potential to cause soil compaction due to greater weight of the machine and area under the wheels compared with equipment (15 – 20 Mg) used to carry out other farm operations. In a study in Australia (Braunack and Johnston, 2014), cotton pickers increased soil strength to a depth of 0.6 m, with zones of greater soil strength (>3MPa) observed closer to surface under the round bale picker (0.3 m) compared with the basket picker (0.4 m). In another study (Bennett et al., 2019), the round bale cotton picker compacted soil to 0.8 m depth on 50% of sites.

Soil compaction has occurred in the Australian cotton production systems using the current agronomic practices as explained above (McGarry, 1990, 1995b). Annual tillage to 0.3 m depth does not alleviate compaction in sub-soil. The soils of north western NSW, where most of the cotton is grown, are cracking clays with swelling/shrinking characteristics and have a strong potential to self-repair (Isbell, 2016). However, the self-repairing is limited to soil near the surface and several wetting and drying cycles would be required to alleviate the effect of compaction in that layer (McGarry, 1995b). That is difficult to achieve in furrow irrigated cotton systems as the irrigation cycle is frequent (Roth et al., 2013).

In cotton production systems, the effect of farm traffic on soil physical properties has been well documented through recent research (Antille et al., 2016; Bennett et al., 2017; Bennett et al., 2019; Braunack and Johnston, 2014; Roberton and Bennett, 2017). It is important to understand the effect of compaction on soil water dynamics (crop water use and soil water recharge) and plant water stress to develop a realistic picture of productivity losses from compaction; however, research in this area is lacking. Low soil water availability causes stomatal closure reducing photosynthesis and increasing crop water stress which can be assessed by measuring canopy temperature (Tc) (Idso et al., 1977; Jackson et al., 1981). Plants dissipate canopy heat load through transpiration, however, when access to water is reduced, stomatal closure is induced to conserve water resulting in elevated canopy temperature. Thus, canopy temperature has an inverse relationship with transpiration and stomatal conductance (Jones, 1999). Plant growth is directly related to the cumulative time plants stay within their Thermal Kinetic Window (TKW) which is species specific and is defined as a range of plant temperatures optimal for plant growth (Burke et al., 1988). Strong correlations between canopy temperature and cotton yield have been reported in Australian cotton systems (Conaty et al., 2015).

To assess the impact of soil compaction on cotton productivity, and to develop amelioration strategies it is important to understand the processes through which soil compaction affects farm productivity. For example, compaction can affect water and nutrient use efficiency by restricting root growth (Arvidsson, 1999). Quantifying the effect of compaction on water and nutrient uptake, and yield can also be used to assess the effectiveness of soil amelioration strategies to address soil constraints including soil compaction and soil-borne disease. Such knowledge may also be valuable for farmers in developing strategies to minimize the effects of compaction by changing agronomic practices within a cotton growing season. The loss of productivity caused by soil compaction is long-term and therefore less obvious to farmers than, for example, the effect of water stress. As such, farmers pay attention to immediate agronomic decisions (e.g. water, fertilizer, and crop protection) compared to soil compaction. It is important to demonstrate the link between soil compaction and agronomic factors. For example, farmers are more likely to increase efforts to avoid soil compaction if they see a direct link between soil compaction, water use, plant stress, crop development and yield.

This case study aims to assess the effect of soil compaction on cotton productivity. We hypothesize that soil compaction caused by infield traffic will increase stress time (i.e. cumulative time when Tc is higher than the optimum Tc for cotton growth) by reducing access to soil water leading to negative affects on plant growth and resulting in yield and fibre quality penalties. This study is the first of its kind related to soil compaction in any crop and was aimed at investigating the relationship between yield, plant stress time and changes in soil water at specific depths.

2. Materials and methods

2.1 Site Description

This experiment was conducted at the Australian Cotton Research Institute, Narrabri (149°47′E, 30°13′S), north-western New South Wales, Australia. The site has a semi-arid climate with a mild winter and a very hot summer. Long- term mean annual rainfall, calculated from an on-site weather station, is 568 mm with more than 50 % of rainfall occurring during the cotton growing season (October-March).

The soil at the experimental site is classified as Vertisol (grey cracking clay) according to Australian Soil Classification (Isbell, 2016), and is classified as a fine, thermic, smectitic, Typic Haplustert (Soil Survey Staff, 2010) or Grumic, sodic Vertisol (Pellic) (WRB classification). The soil in the experimental field is alkaline (average pH in 0.01 M $CaCl_2$ is 7.42 in the 0–0.3 m depth), non-saline (average electrical conductivity (EC 1:5) is 0.20 dS m^{-1} in the 0–0.3 m depth). The ESP was 2.9 at 0–0.3 m. Detailed soil characteristics of this site are presented in Hulugalle et al., (2017). Daily rainfall and air temperature (Figure 2.1) were measured using an on-site weather station.

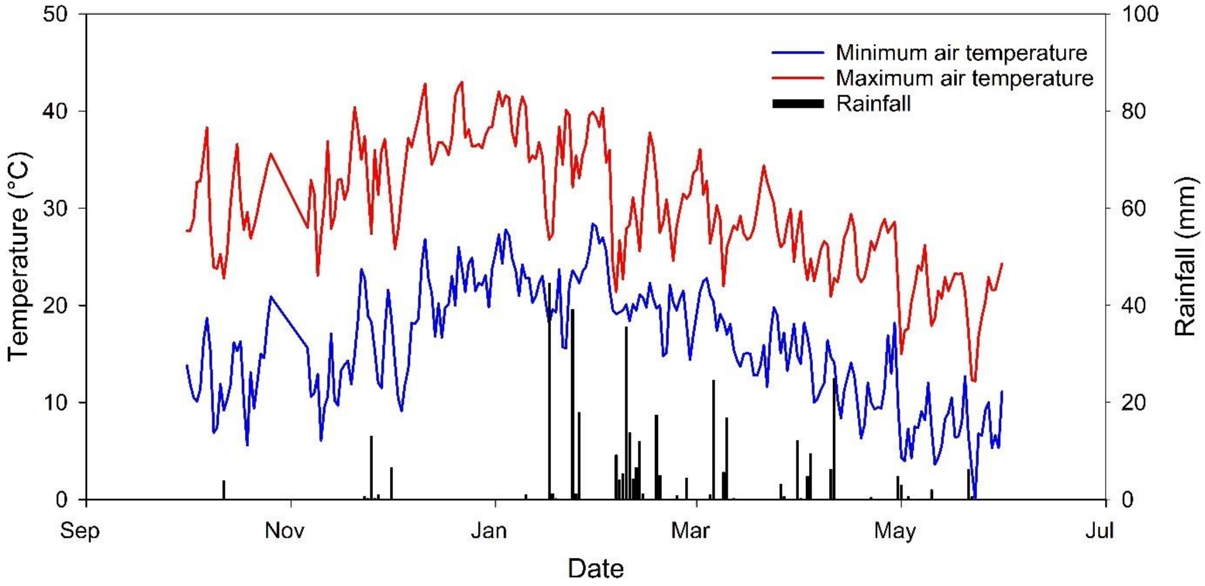

Figure 2.1: Rainfall and air temperature during the 2019-20 cotton season recorded from an on-site weather station

2.2 Experimental layout

The field used for this experiment was managed under a cotton-wheat-fallow or a cotton-sorghum rotation from 2002 until 2014. In 2014-15 all plots were planted with cotton and managed under wheat-long fallow-cotton rotation until the start of this experiment. Standard agronomic practices (ACPM, 2020) were used to manage these crops; however, cotton was harvested using a two-row basket picker from 2002 to 2008 and a four-row basket picker since 2008. This field has had not been exposed to the compaction caused by heavier round bale pickers commonly used on commercial farms in Australia. Field operations of sowing and fertilising were performed with four row implements which results in a higher number of traffic passes than the commercial farms where 8 to 12 row implements are commonly used. Cotton (*Gossypium hirsutum*, cv. Sicot 748 B3F) was planted at a row spacing of 1m on 29 October 2019 and irrigated two days later. The field was divided into eight plots: 4 m wide (4 plant rows) and 30 m long (Figure 2.2). All plots were sprayed with herbicide at sowing (Cotorn^{TM}) and again on 4th December 2020 (Roundup^{TM}) using self-propelled spray coupe.

Table 2.1: List of different farm operations in a cotton-wheat-fallow rotation; the weight of machinery is indicative only

Crop	Operation	Equipment mass (Mg)	Number of passes
Cotton	Land preparation	14-18*	1 -3
	Planting	14-18	1
	Fertilizer application	14-18	1-2
	Inter-row cultivation	14-18	1
	Spraying	15-16	2-7
	Harvesting	28-32	1
	Mulching	14-18	1
	Root cutting	14-18	1

	Pupae busting	14-18	1
Wheat	Land preparation	14-18	1-3
	Planting	14-18	1
	Spraying	15-16	3-4
	Harvesting	20-25**	1

*excluding implement weight which can be 4 to 5 Mg

**excluding weight of grain stored in the bin on the machine

Figure 2.2: Field layout showing position of four replicate plots; rows were in head ditch to tail drain direction

Treatments were a Control (CONT) and Compacted (COMP) with four replicates per treatment. Sowing and two herbicide sprays mentioned above were the only in-field traffic in CONT. In COMP, furrows on either side of the planted row had additional traffic four days after the first in-crop irrigation by a John Deere 8235R on 20 Dec 2019. The tractor was driven the full length of the plot in furrows labelled “1” (Figure 2.3) and then reversed effectively resulting in two traffic passes in those furrows. The same process was repeated in furrows labelled “2” (Figure 2.3). The tractor carried a go-devil implement on rear and a 1200 litre tank of water on the front giving a total weight of 19.2 Mg (Table 2.2). Width of the rear tyres of the tractor while parked on ground was 0.43 m.

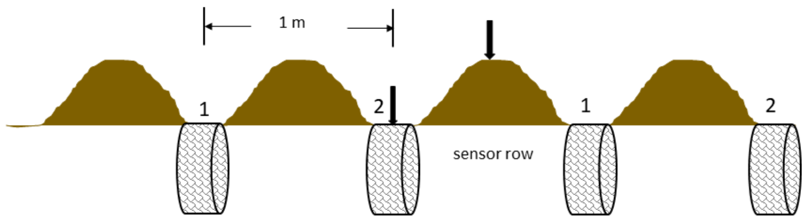

Figure 2.3: An illustration of traffic wheel tracks for applying compaction; furrows 1 were COMP first with two traffic passes (forward and reverse), followed by furrows 2; vertical arrows show the location of soil strength and bulk density measurements in COMP treatment

Table 2.2: Weight of tractor used to apply treatments; tractor was weighed while carrying go-devil implement on rear and the empty water tank in front. The water tank was filled with 1200 litre water at the time of compaction simulation for this experiment

Description	**Mass (Mg)**
Front left wheel	2.38
Front right wheel	2.44
Rear left wheel	6.58
Rear right wheel	6.57
Tractor mass	**17.97**
Water	1.20
Total mass at the time of traffic	**19.17**

2.3 Crop development

Plant density (ie number of plants per meter) was measured in one of the two central rows on six occasions during the season between 13/12/2019 and 01/03/2020. Plants were counted in a subplot of one-metre length that was randomly selected in each plot during the season. Plant growth was monitored by measuring plant height, number of nodes and number of fruit (squares, flowers, bolls) of 10 plants per plot on seven occasions between 13 Dec 2019 and 01 March 2020. At the end of the season or 124 days after sowing (DAS), total dry matter was measured by harvesting plants (cut at ground level) from a randomly allocated one meter in each plot. Three plants were sub-sampled and partitioned into stems, leaves and fruit, and dried in a fan forced oven at 60 °C for 48 hours or until constant weight was achieved. Total dry matter, vegetative dry matter (i.e. stems and leaves) and reproductive dry matter (i.e. fruit) was measured. Fresh leaves from the same three plants were used to determine the leaf area using a planimeter (Model LI-3100 Area Meter, Li-Cor).

2.4 Soil strength and bulk density measurements

Soil strength was measured as cone index (CI) using a cone penetrometer (RIMIK, 12.3 mm diameter cone, 30° included angle) before and after traffic passes on 20th December, 2019 within a 1-2-hour time window (ASAE, 1986). In each plot, soil strength was measured in the centre of a plant row (row) and middle of the furrow (furrow) (Figure 2.2). At each position, soil strength was measured at 0.025 m intervals to a depth of 0.6 m. Treatment mean was calculated for each position and depth before and after compaction. Average volumetric water content (VWC) measured using capacitance probes (see section 2.6) at the time of traffic passes was 43%.

Soil resistance measurements

Trial showing difference in plant height

Non-compacted plot bed height (~15 cm)

Compacted plot bed height (~29 cm)

Plate 2.1: Soil resistance measurements and bed height difference between compacted and control plots

At the end of cotton season, dry bulk density was measured from both the middle of row and the middle of furrow (i.e. one core from each position and plot) before cotton picking operation. Soil cores were collected by inserting a coring tube (diameter = 0.042 m) to 1.2 m depth using a handheld post driver

(Christie Engineering, Australia). The core was divided into 0.1 m sections, dried at 105°C in oven for 48 hours and bulk density calculated using the dry weight and volume of the core.

2.5 Canopy temperature

Canopy temperature was measured using infrared sensors (Goanna Ag, Australia) installed in each plot after the treatment application, however, data from two sensors (both in CONT) was excluded from analyses due to large gaps in data. These sensors use a MLX90614-BCF lens (Melexis, Ypres, Belgium) with a 35° field of view, resolution of 0.02 °C and an accuracy of ±0.5 °C from 0 to 50 °C. Temperature was measured at 5-minute intervals and data transmitted via LoRaWAN to an online platform for visualizing in real-time and downloading. Sensors were installed at an angle of 45° to the horizontal and at a height of 20-30 cm above the canopy. Height of the sensors was adjusted every week to maintain this sensor position relative to the crop canopy. Canopy temperature was converted to stress time or stress hours using the Biologically Identified Optimal Temperature Interactive Console (BIOTIC) approach (Mahan et al., 2005). Briefly, when average Tc in a 15-minute interval was greater than 28°C, which is considered the optimal temperature for cotton (Conaty et al., 2012), 0.25 stress hours are counted. Stress hours were summed to calculate the cumulative stress time from few days after first flower (74 DAS) to when crop stopped accumulating stress (154 DAS), i.e. Tc remained < 28°C.

2.6 Soil water

Soil water was measured using capacitance probes (ODYSSEY®, Dataflow Systems, New Zealand). Capacitance probes were installed 45 days after sowing in the same plant row as canopy temperature sensors in each plot and measured soil moisture every hour at 0.1, 0.2, 0.4, 0.6 and 0.8m depths. The capacitance probe readings were calibrated using neutron moisture meter (CPN 503-DR Hydroprobe®, CPN International, Concord, CA) measurements at the same site to calculate volumetric water content (VWC) at different depths. The VWC was converted to millimetres (mm) of water for different soil depths by multiplying with the length of the soil section. Crop water use (CWU) for different soil depths was calculated by accounting for decrease in soil water (mm) in hourly readings. Total CWU was calculated by summing the hourly CWU values. Soil water recharge (SWR) for different soil depths was calculated by accounting for increase in soil water (mm) in hourly readings. Total SWR was calculated by summing the hourly SWR values.

2.7 Yield and fibre quality

Seed cotton was harvested with a single row spindle picker and weighed immediately. A 10 m section in each plot was harvested from the same row where canopy temperature sensors and soil moisture probes were installed. A 300-gram seed cotton subsample was ginned using a 20 saw gin with a pre-cleaner (Continental Eagle, Prattville, AL, USA) to determine the gin turnout (i.e. the percentage weight of seed and lint). Cotton lint samples were analysed for fibre length (mm), strength (KN Tex^{-1}) and micronaire (unitless) using a spinlab High Volume Instrument (HVI) model Classing 900 (Uster Technologies AG, Uster, Switzerland).

2.8 Statistical analysis

Data were processed using R software and statistical analyses were performed using GenStat 19th ed. (VSN International, Hemel Hempstead, UK). Differences in treatments were determined using t-tests expressed at the 95% confidence level ($P < 0.05$) unless stated otherwise. Simple linear regression was used to analyse the relationship between yield, stress hours and soil water use. As cone index measurements taken early in the season showed large variability in background soil strength due to historical farm traffic, a multiple regression analysis was fitted to soil strength after traffic to account for background soil strength and profile depth.

3. Results

3.1 Soil strength and bulk density

The soil strength results presented in this section were measured immediately before and after traffic in the COMP treatment on the 20th December 2019. The vertical distance between top of row and base of furrow was 0.14 m. The soil strength results are presented using the top of row as starting point which means measurements in furrow start at 0.14 m (Figure 2.4). Soil strength measured before traffic increased with depth and ranged between 0.5 MPa and 3 MPa (data not shown). Soil strength did not change in rows, however soil strength in furrows (ie under the wheels) increased by 0.1 – 0.2 MPa in top 0.2 m with the highest strength occurring between 0.4 – 0.7 m depth with average soil strength increasing up to ~0.6 MPa (Figure 2.4). Multiple regression analysis showed that soil strength post traffic was significantly affected by soil depth and soil strength measured before traffic (Table S2.1). This model accounted for 97% of the variability in soil strength measured after traffic in both the rows and the furrows. Soil strength measured before traffic had the greatest effect on soil strength measured after traffic in both furrows and rows reflecting compaction from historic farm traffic. Bulk density was higher in rows in COMP at 0 - 0.1 m depth compared with CONT, while in furrows, bulk density was higher in COMP at 0 - 0.3 m depth with no change deeper in the profile compared to CONT (Figure S2.2).

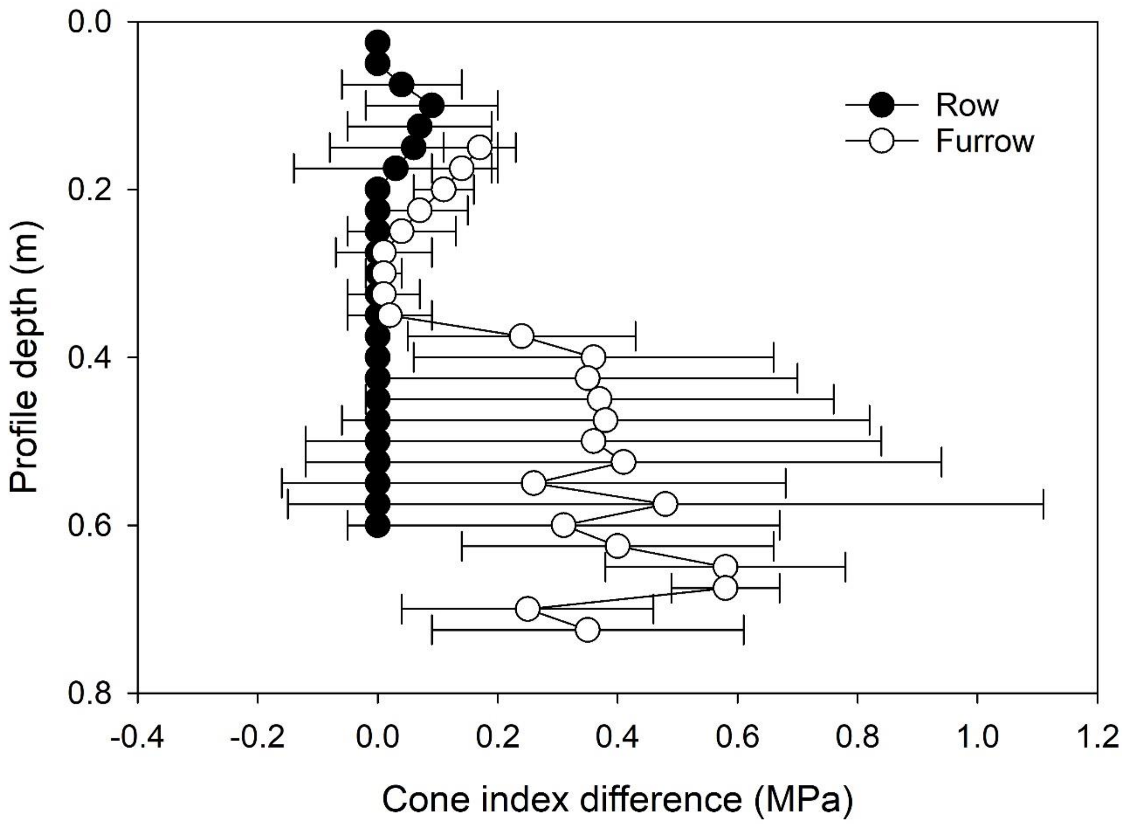

Figure 2.4: Difference in soil strength profiles measured before and after traffic in rows and furrows; error bars indicate the standard error of the mean

3.2 Soil water

In addition to six supplemental irrigations, there was 362 mm of in-crop rainfall during cotton season of which >80% fell between January and March 2020 (Figure 2.1). The soil volumetric water content (VWC) varied with depth. At 0.1 m depth, water extraction was similar between treatments, however, irrigation and rainfall events resulted in greater increase in VWC in CONT (Figure 2.5). At 0.2 m depth, the VWC was similar between the treatments. The greatest effect of compaction on VWC was observed at 0.4 m depth where water extraction by plants was less in COMP resulting in a lower water deficit between irrigation and rainfall. In the first six weeks, the VWC in COMP gradually decreased from 45% to 40%. In contrast, the VWC in CONT decreased to <35% between irrigation and rainfall events in the same period. The increase in VWC following irrigation and rainfall events was less pronounced in COMP compared with the CONT (Figure 2.5). From 90 DAS onwards, both the water extraction and recharge increased gradually in COMP albeit still less pronounced than in CONT (Figure 2.5). Water extraction at 0.6 m and 0.8 m depth was minimal but marginally higher in CONT than COMP, likely because of better soil structure in the soil profile above this depth in CONT allowing water infiltration and root development deeper in the profile.

Crop water use (CWU) in CONT (846 ± 75 mm) was 16% higher than COMP (726 ± 87 mm). At individual depths, the highest and statistically significant difference (CONT – COMP) of 72% between treatments was observed at 0.3m – 0.5m depth (Figure 2.6). The treatment effect on CWU at other depths was not significant. Soil water recharge (SWR) as a result of irrigation and rainfall mirrored the CWU pattern (Figure 2.6) and was 16% higher in CONT (746 ± 60 mm) compared with COMP (657 ± 76 mm) for full soil profile (0 – 1m). At individual depths, the highest and statistically significant difference (CONT – COMP) of 86% between treatments was observed at 0.3m – 0.5m depth (Figure 2.6). The treatment effect on SWR at other depths was not significant. The similar pattern in CWU and SWR was further confirmed by a significant linear relationship (R^2 = 0.99) between CWU and SWR (Figure 2.7).

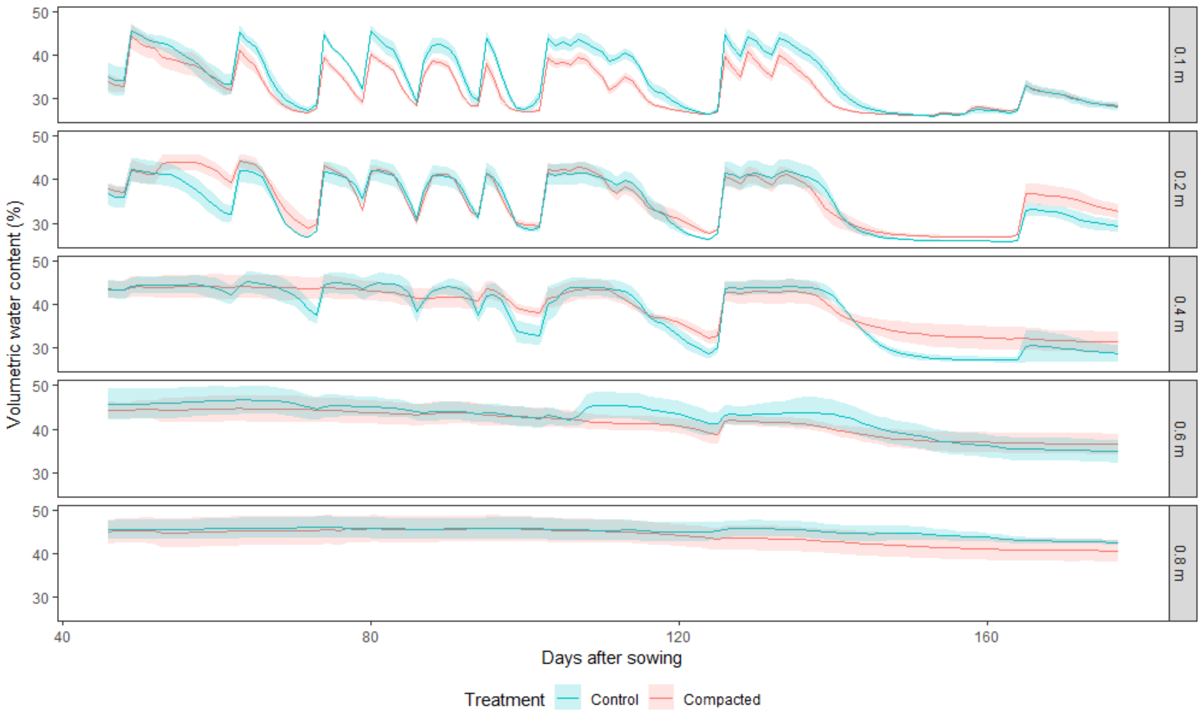

Figure 2.5: Average volumetric water content at different soil depths measured using capacitance probes; shade is showing the standard error of the mean

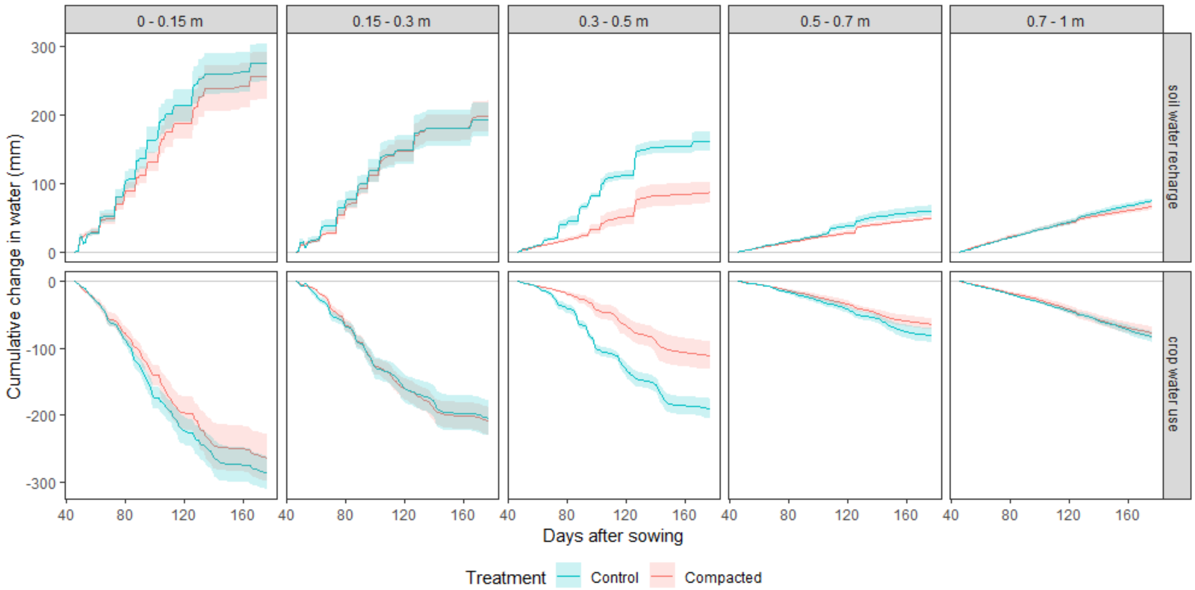

Figure 2.6: Average cumulative crop water use and average cumulative soil water recharge at different depths in soil profile; treatment effect was significant at 0.3 – 0.5m depth in both crop water use ($p < 0.05$) and soil water recharge ($p < 0.01$)

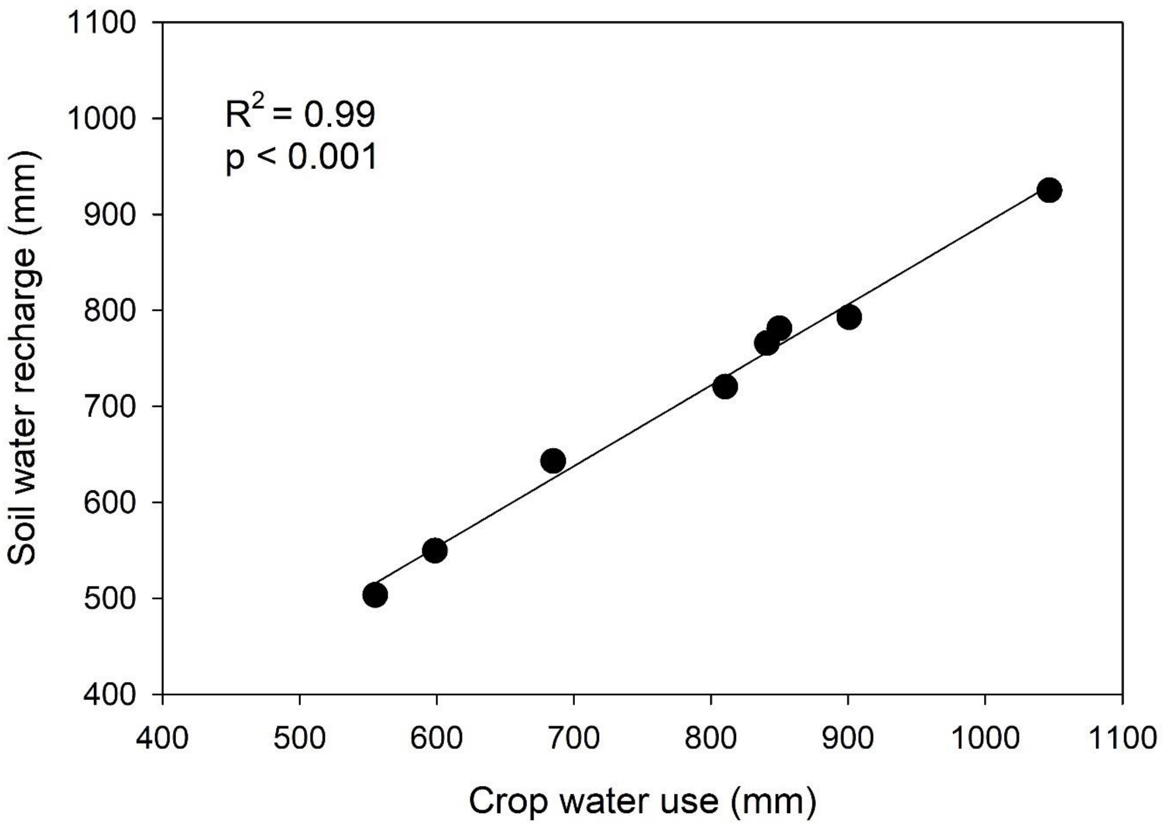

Figure 2.7: The relationship between crop water use and soil water recharge caused by irrigation and rainfall

3.3 Canopy temperature

The stress hours derived from the canopy temperature data were accumulated from 74 DAS until the stress accumulation stopped around 155 DAS (i.e. Tc remained below 28°C). Maximum daily canopy temperature was frequently higher in COMP (data not shown). Under similar weather conditions, canopy temperature is a function of plant-available water. As such, these results concur with soil water observations (Figure 2.6) which showed reduced water use in COMP treatment. Higher canopy temperature in COMP resulted in a faster rate of stress accumulation compared with the CONT. At the end of the season, the average cumulative stress time was 30% higher in COMP compared with the CONT (Figure 2.8).

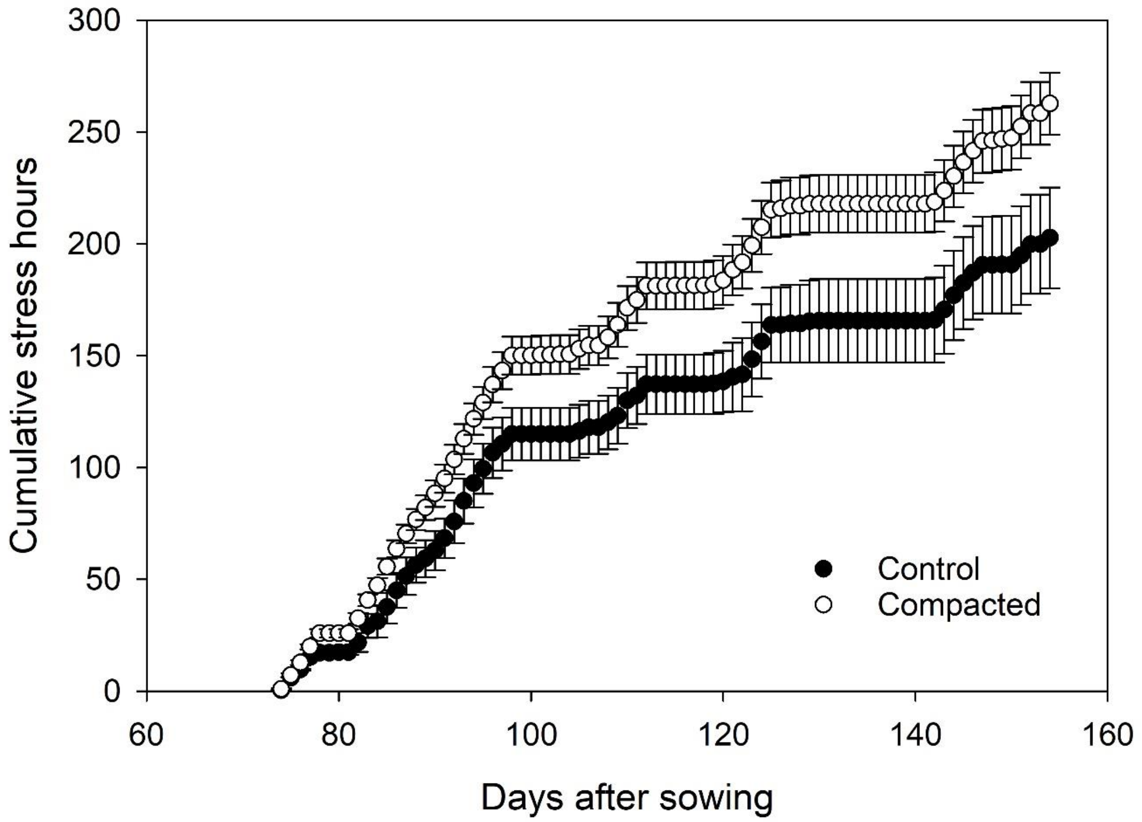

Figure 2.8: Average cumulative stress hours for each treatment starting from 74 days after sowing, error bars are standard error of the mean

3.4 Yield and crop development

The average plant density in CONT (9.6 ± 0.3) and COMP (10 ± 0.3) were not significantly different. Lint turnout ranged 42-44% in different plots (data not shown). Average lint yield in CONT (2778 kg ha^{-1}) was significantly higher than COMP (2191 ± 33) – a difference of 27% (Table 2.3). Compaction resulted in significant decrease of 19%, 56% and 21% in vegetative dry matter, reproductive dry matter, and leaf area, respectively, compared with the CONT (Table 2.3). The field measurements showed negative effects on plant growth parameters occurred within ten days of compaction. Compaction resulted in shorter plants with a smaller fruit load (squares and bolls) compared with the CONT (Figure 2.8). The significantly lower number of squares in the COMP was a function of a smaller number of fruiting sites and/or higher fruit shedding in this treatment (Figure 2.9). Micronaire and fibre length were similar between treatments; however, fibre strength was significantly higher in COMP compared with CONT (Table 2.3).

Table 2.3: Biomass, yield and fibre quality (mean and standard error of the mean); different letters show the significant differences (p <0.05)

Treatment	Vegetative dry matter	Reproductive dry matter	Total dry matter	Leaf area	Yield	Micronaire	Fibre length	Fibre strength
	Mg ha^{-1}	Mg ha^{-1}	Mg ha^{-1}	m^2 m^{-2}	kg ha^{-1}		mm	g tex^{-1}
CONT	7.5±0.3A	8.6±0.5A	16.1±0.8A	4.1±0.3A	2778±123A	4.7±0.1A	31.2±0.3A	30.2±0.4A
COMP	6.3±0.7B	5.5±0.2B	11.9±0.8B	3.4±0.5B	2191±33B	4.4±0.1A	31.4±0.4A	32.1±0.4B

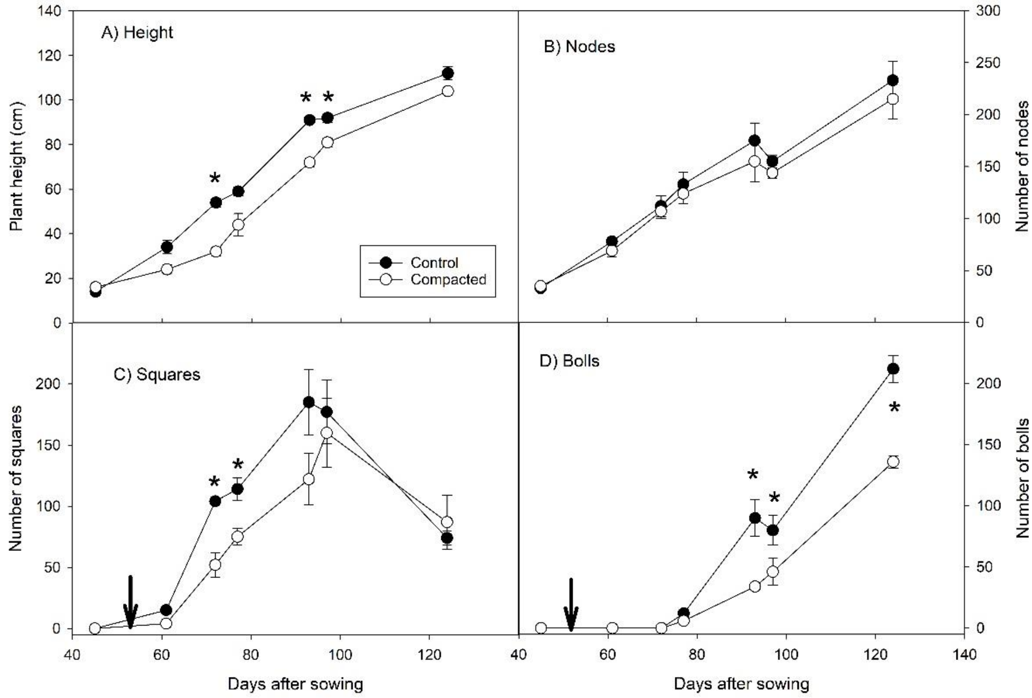

Figure 2.9: Plant growth characteristics measured on seven occasions over the course of season; error bars are standard error of the mean; significant differences (p<0.05) are shown by star (*) symbol; black arrow is showing the date when compaction was applied to respective plots

3.5 Relationship between crop water use, stress time and yield

The linear relationship between CWU and lint yield was only significant for water use at 0.3 – 0.5m depth (Table 2.4). The relationship between CWU for the full profile (0 – 1 m) and lint yield was not significant. Similarly, the relationship between CWU and stress time (measured using canopy temperature) was significant for 0.3m – 0.5m and for 0.5m – 0.7m (Table 2.4). The relationship between CWU for the full profile (0 – 1 m) and stress time was not significant.

Table 2.4: Linear regression between 1) crop water use and yield and, 2) crop water use and cumulative stress measured using canopy temperature; * p<0.05; ** p<0.01

Depth (m)	Crop water use vs. yield	Crop water use vs. total stress

	R^2	R^2
0.00 – 0.15	0.07	0.24
0.15 – 0.30	0.00	0.18
0.30 – 0.50	0.61*	0.84*
0.50 – 0.70	0.11	0.85**
0.70 – 0.10	0.00	0.25

4. Discussion

This paper reports a novel approach to demonstrate the effect of soil compaction on farm productivity in irrigated cotton systems. To our knowledge this is the first study related to soil compaction in any crop to show the direct relationship between yield, plant stress time and crop water use at specific soil depths. Simultaneous monitoring of below ground (soil, water) and above ground (plants) parameters enabled better understanding of the mechanisms through which soil compaction affects farm productivity. Soil compaction on both sides of planted rows from a tractor weighing 19.2 Mg resulted in lint yield loss of 27%. Yield losses of up to 29% associated with soil compaction have also been reported in cotton systems elsewhere (Kulkarni et al., 2010). Significant yield losses due to compaction have also been reported in grain crops in Australia (Hussein et al., 2021; Li et al., 2007).

The reduction in yield and crop water use were mainly a function of reduced crop water use at 0.3m – 0.5m depth which was reflected in the significant linear relationship (R^2 = 0.61) between yield and crop water use at this depth: this relationship was not significant for other depths (Table 2.4). The reduced water use at 0.3 – 0.5m depth in COMP plots induced water stress which is shown in the significant relationship between total stress time and crop water use (R^2 = 0.83) at this depth (Table 2.5). There was an equally strong relationship between crop water use at 0.5 – 0.7m depth and stress time which is an important finding and highlights that even the small differences in access to soil water at this depth can have a disproportionally large effect on plant stress. A recent study in a rainfed sorghum showed 65% decrease in rainfall use efficiency due to compaction using a simulation model (Hussein et al., 2021).

It is important to note that reduced water extraction from 0.3 – 0.5m depth and, to a lesser degree, at 0.5 – 0.7m depth despite water presence indicates physical constraints to root penetration in sub-soil which was also confirmed in increased soil strength at this depth (Hamza and Anderson, 2005; Raper, 2005). Although not measured, the physical constraints to root development caused by compaction can result in 'L-shaped' roots in cotton where roots start to grow laterally in the softer soil above the compacted layer (McGarry, 1990; Taylor and Burnett, 1964). Compaction reduces soil porosity through degradation of soil structure which decreases the concentration of oxygen near root elongation zone. In irrigated systems, filling of soil pores with water further depletes soil oxygen levels. The low soil oxygen environment in the rootzone reduces root growth pressure thus slowing root penetration into the deeper soil (Souty et al., 1988). Plants tend to compensate the lack of root access to deeper soil by increasing water and nutrient uptake from the shallower soil layer (Nosalewicz and Lipiec, 2014). Thus, compaction can limit the volume of soil for plant root proliferation and as a result, the plant's ability to explore and access additional available water and nutrients. Yield losses occur when plants are not able to fulfill their requirements for water and nutrients from the limited volume of soil that roots have access to (Arvidsson, 1999; Hussein et al., 2021; Phillips and Kirkham, 1962; Soane and van Ouwerkerk, 2013). There is an ongoing interest in remote monitoring of soil water using contact and non-contact sensors including UAV, and satellite based systems to inform irrigation scheduling decisions (Al-Naji et al., 2021). These sensing systems need to start integrating the effect of compaction on soil water availability and its effects on economic yield loss.

The strong linear relationship between crop water use and soil water recharge (Figure 2.7) suggests compaction affects both the processes in a similar fashion. In water-limited systems this relationship would be interpreted as soil water recharge driving crop water use, however, this was not true in our case as VWC data (Figure 2.5) showed abundant water present in soil profile at >0.3 m depths. The continuous measurements of soil water clearly showed compaction reducing the soil water recharge following irrigation and rainfall events. Although not measured, this would likely have increased run off, based on research in grains system, where soil compaction decreased water infiltration by 12% thus increasing surface runoff by 47% (Li et al., 2007). The increase in runoff can result in higher carbon and nutrient losses in hydrological pathways further impacting the on-farm sustainability (Macdonald et al., 2020; Nachimuthu et al., 2018). Soil water recharge was reduced by compaction, likely through two pathways: 1) changes in soil structure creating physical constraints that reduced water infiltration to deeper soil layers, and 2) reduced water extraction in COMP plots because of physical constraints to root penetration below 0.3m depth resulted in smaller soil water deficits as shown in VWC data (Figure 2.5) thus decreasing the volume of pores available for soil water recharge.

These results demonstrated that compaction reduces farm productivity through multiple processes. Continuous measurements of canopy temperature quantified the effect of reduced water availability on plant stress as yield ultimately is a function of stress as reflected in the significant linear relationship between yield and total stress hours (Figure S2.3). The relationship between plant stress derived from canopy temperature and yield is consistent with an earlier study conducted on the same farm in a nearby field (Conaty et al., 2015). Measurements of plant development during the season and destructive biomass sampling showed that crop stress slowed plant development which had a cumulative effect on final yield. It is suggested that measurements of root development at different depths and laterally could add value to the suite of measurements conducted in this study.

4.1 Implications for agronomic management

The reduction in crop water use because of compaction was most pronounced at 0.3 – 0.5m depth with smaller changes in soil water content below this depth regardless of the treatment because of background compaction from historic traffic. Irrigations in Australian cotton systems are predominantly scheduled by monitoring soil water in the root zone with an irrigation triggered when the soil water reaches a pre-determined target water deficit. As discussed above, compaction changes the root zone by restricting root growth. The soil water data (Figure 2.5) shows that reduced water use would result in crop taking longer to reach the target soil water deficit used to trigger an irrigation. Crop will likely suffer water stress in this situation unless irrigations are applied more frequently to compensate for the effect of compaction. Although it is important to monitor soil water at the depth from which the roots are drawing the water, and the extent to which soil water is being replenished following irrigation/rainfall, it does not adequately inform irrigation scheduling decisions. The availability of soil water is affected by the severity of compaction which can vary between years and locations. We suggest in addition to measuring soil water, crop stress should also be measured using easier-to-use canopy temperature or other similar approaches that show the response of soil water availability (or lack thereof). When crop has limited access to soil water (e.g. due to compaction), it shuts down its stomata in an attempt to conserve water resulting in elevated canopy temperature (Jones, 1999), as confirmed by our study where stress time was higher in the COMP treatment. Thus, monitoring plants directly (eg canopy temperature) can inform the growers how soil compaction might be affecting soil water availability and may help optimize the timing of irrigation. In compacted soils minimizing crop water stress will require increasing the frequency of irrigations. In one example, in a field cultivated under wet conditions (and hence compacted) the farmer had to triple the number of irrigations to match the yield in non-compacted fields (12 versus 4) giving the farmer enormous workload (McGarry, 1995b). In Australia, cotton is predominantly grown on soils with high water holding capacity (eg Vertisols) and not being able to use water stored at depths below 0.3m due to compaction is an underutilization of the increasingly scarce water resource. Thus, avoiding compaction remains the best strategy to optimize water productivity.

4.2 Implications for soil management

The observed change in soil strength after traffic (Figure 2.4) and its effect on crop water use (Figure 2.6) shows the effect of compaction was most severe below 0.3m depth. The annual tillage operations to 0.3m will not alleviate the compaction effect in subsoil. Although the soils of north western NSW are cracking clays with swelling and shrinking characteristics, their potential to self-repair deeper soil layers is not clear (Sarmah et al., 1996). The self-repairing takes several wetting and drying cycles to make significant improvement from the effect of compaction and depends on factors such as clay content, clay type and proportion of exchangeable cations (McGarry, 1995a; McHugh et al., 2009; Radford et al., 2007). In order to minimise the time to repair the compacted soil, alternate strategies such as deep-rooted crops or crop rotation need to be incorporated into the cropping system to improve the soil structure and complement the self-repairing capacity of these soils (Pillai and McGarry, 1999). Ultimately, the potential of any method to repair the compacted soil will depend on the severity and depth of compaction.

The mantra of “prevention is better than cure” also applies to the soil compaction issue. It has been suggested that efforts should focus on the source of the problem (area trafficked by heavy machinery) rather than trying to solve the problem (compaction) after the fact (Bluett et al., 2019). Across the world, farmers have adopted different approaches to minimize the effects of farm traffic on soil compaction, however, the idea of limiting the weight of machinery has largely been ignored as that would result in slowing down farm operations (Kirby, 2007). Soil compaction is considered a secondary issue for the manufacturers of heavy farm machinery (Van den Akker et al., 2003). The proportion of area that is compacted when using heavy machinery can be decreased by adopting controlled traffic farming (CTF) which restricts the farm traffic to permanent traffic lanes. Controlled traffic farming has been shown to increase yield and water use efficiency, and decrease losses through surface runoff (Hussein et al., 2021; Li et al., 2007). Although CTF is considered an effective and economically feasible approach to reduce the effects of soil compaction on productivity (Antille et al., 2016; Bartimote et al., 2017; Bennett et al., 2017; Hussein et al., 2021; McKenzie, 1998; Tullberg et al., 2007), its adoption in Australian cotton industry has been slow. The lack of interest in CTF adoption despite scientific evidence of its benefits has been attributed to a range of factors including incompatibility of equipment imported from Europe and North America, associated costs of conversion and its effect on warranties – e.g. converting a dual tyre cotton picker to a single tyre picker (Chamen, 2015; Tullberg et al., 2007). The loss of productivity caused by soil compaction is long-term and therefore is less obvious to farmers than, for example, the effect of water stress on yield. It is important to demonstrate the effect of soil compaction on agronomic factors that are more visible to farmers during the cotton season. For example, farmers are more likely to take action if they see a direct effect of compaction on water use efficiency and yield. This action may include attempts to avoid or minimize soil compaction and change in agronomic practices to minimize the effects of compaction within a cotton season.

4.3 Economic impact to the industry

This case study demonstrates that farm machinery induced soil compaction impacts yield and consequently results in economic losses. This study showed a significant reduction of 2.6 bales ha^{-1} (1 bale = 227 kg) in lint yield due to compaction from in-season traffic which equates to loss of A$1293 ha^{-1} assuming the rate of A$500 per bale.

These results are based on traffic wheels compacting furrows on both sides of all plant beds on a farm, however, on a typical cotton farm in Australia only a proportion of beds is compacted on either side by wheel tracks while most beds are compacted at least on one side depending on the type of farm machinery. Both sides of the plant beds are also compacted when permanent wheel tracks are not used. Harvesting operation using a dual tyre round module picker is considered the biggest source of compaction in Australian cotton production systems (Bennett et al., 2015; Braunack and Johnston, 2014). The dual tyre configuration designed to pick six rows in each run leads to wheel track on either side and single side of the plant beds in 67% and 33% of the farm, respectively. As a cotton picker is used at the end of season, the losses from picker related soil compaction would occur in the following winter and summer crops (e.g. wheat and cotton). Growers can remediate soil to a degree during fallow using soil amelioration practices such as deep ripping; however, this would require additional investment.

Other farm machinery would compact beds on one side only. A conservative estimate of yield loss of two bales per hectare in the rows compacted on both sides of the bed (i.e. 67%) by a round module picker would equate to a loss of A$670 per hectare in the following cotton season. The average area under cotton production in Australia in last ten years (2009-10 to 2018-19) was 413,000 ha with average gross value of A$1.9 billion (ABARES, 2019). Yield loss of two bales per ha across 67% of the area under cotton production is equivalent to $276 million loss across the industry (assuming a price of A$500 per bale). These estimates of loss at industry scale are indicative and need more investigation as the timing and method of compaction application in this study is different to a commercial cotton farm. We recommend detailed studies should be conducted on commercial farms to quantify the effect of compaction especially from harvesting operation using round bale picker with dual tyre configurations. The economic gains from using modern pickers should be weighed against the productivity loss due to soil compaction caused by such equipment. While the lightweight swarm bots are being trialled for various agricultural operations such as targeted weed control and future technological improvement could lead to a light weight cotton harvesting bots, the cotton growers need to tailor the soil management to minimise the compaction until such technology is practical.

5. Conclusions

In this paper we presented a novel approach of investigating the complex problem of soil compaction which can cause potential economic loss to growers using irrigated cotton as case study. Soil compaction on both sides of the plant row increased plant stress time by 30% resulting in a significant yield loss of 27%. The plant stress in compacted soil was likely caused by physical constraints for roots to grow below 0.3m which was reflected in reduced water extraction by roots at this depth. In addition to direct yield loss, compaction also decreased crop water use and soil water recharge following irrigation and rainfall events. This study demonstrated the value of using canopy temperature as an indicator of crop water stress, in addition to soil water, to inform irrigation decisions especially in situations where soil water availability is reduced due to soil compaction. Although the timing and magnitude of soil compaction might be different on a commercial cotton farm compared with this study, the processes through which compaction affects farm productivity will be similar. The methods presented in this paper can be used to conduct similar studies on commercial farms of cotton and other crops to investigate the effect of compaction on yield and soil water dynamics in individual rows including the rows compacted on one side only. Ideally, all efforts should be made to avoid compaction, however, where this is not achievable, the implications for agronomic management should be considered to minimize yield losses. Demonstrating economic consequences of soil compaction to growers using the integrated approach used in this study may trigger practice change to minimize soil compaction on farms.

Acknowledgements

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References

ABARES, 2019. Agricultural commodity statistics 2019, In: Sciences, A.B.o.A.a.R.E.a. (Ed.), Canberra.

ACPM, 2020. Australian Cotton Production Manual. Cotton Research and Development Corporation, CottonInfo, Australia.

Al-Naji, A., Fakhri, A.B., Gharghan, S.K., Chahl, J., 2021. Soil color analysis based on a RGB camera and an artificial neural network towards smart irrigation: A pilot study. Heliyon 7, e06078.

Antille, D.L., Bennett, J.M., Jensen, T.A., 2016. Soil compaction and controlled traffic considerations in Australian cotton-farming systems. Crop and Pasture Science 67, 1-28.

Antille, D.L., Chamen, W.C.T., Tullberg, J.N., Lal, R., 2015. The potential of controlled traffic farming to mitigate greenhouse gas emissions and enhance carbon sequestration in arable land: a critical review. Transactions of the ASABE 58, 707-731.

Arvidsson, J., 1999. Nutrient uptake and growth of barley as affected by soil compaction. Plant and soil 208, 9-19.

ASAE, 1986. ASAE S313. 2. Soil cone penetrometer. ASAE, St. Joseph MI, USA.

Bartimote, T., Quigley, R., Bennett, J.M., Hall, J., Brodrick, R., Tan, D.K.Y., 2017. A comparative study of conventional and controlled traffic in irrigated cotton: II. Economic and physiological analysis. Soil and Tillage Research 168, 133-142.

Bennett, J.M., Roberton, S.D., Jensen, T.A., Antille, D.L., Hall, J., 2017. A comparative study of conventional and controlled traffic in irrigated cotton: I. Heavy machinery impact on the soil resource. Soil and Tillage Research 168, 143-154.

Bennett, J.M., Roberton, S.D., Marchuk, S., Woodhouse, N.P., Antille, D.L., Jensen, T.A., Keller, T., 2019. The soil structural cost of traffic from heavy machinery in Vertisols. Soil and Tillage Research 185, 85-93.

Bennett, J.M., Woodhouse, N.P., Keller, T., Jensen, T.A., Antille, D.L., 2015. Advances in cotton harvesting technology: a review and implications for the John Deere Round Baler Cotton Picker. Journal of Cotton Science 19, 225-249.

Bluett, C., Tullberg, J.N., McPhee, J.E., Antille, D.L., 2019. Soil and Tillage Research: Why still focus on soil compaction? Soil and Tillage Research 194, 104282.

Braunack, M.V., Johnston, D.B., 2014. Changes in soil cone resistance due to cotton picker traffic during harvest on Australian cotton soils. Soil and Tillage Research 140, 29-39.

Braunack, M.V., McGarry, D., Venture, S.Y.D.J., 2006. Traffic control and tillage strategies for harvesting and planting of sugarcane (Saccharum officinarum) in Australia. Soil and Tillage Research 89, 86-102.

Burke, J.J., Mahan, J.R., Hatfield, J.L., 1988. Crop-specific thermal kinetic windows in relation to wheat and cotton biomass production. Agronomy Journal 80, 553-556.

CCA, 2020. Qualitative report on the 2019-20 cotton season: a survey of consultants. Crop Consultants Australia.

Chamen, T., 2015. Controlled traffic farming–from worldwide research to adoption in Europe and its future prospects. Acta Technologica Agriculturae 18, 64-73.

Conaty, W.C., Burke, J.J., Mahan, J.R., Neilsen, J.E., Sutton, B.G., 2012. Determining the optimum plant temperature of cotton physiology and yield to improve plant-based irrigation scheduling. Crop Science 52, 1828-1836.

Conaty, W.C., Mahan, J.R., Neilsen, J.E., Tan, D.K.Y., Yeates, S.J., Sutton, B.G., 2015. The relationship between cotton canopy temperature and yield, fibre quality and water-use efficiency. Field Crops Research 183, 329-341.

CSD, 2020. Irrigated Cotton Guide, Acres of Opportunty. Cotton Seed Distributors, Australia.

Hamza, M.A., Anderson, W.K., 2005. Soil compaction in cropping systems: A review of the nature, causes and possible solutions. Soil and Tillage Research 82, 121-145.

Hulugalle, N.R., Weaver, T.B. & Finlay, L.A. 2017. Soil structure in permanent beds under irrigated cotton-based cropping systems in a Vertisol. Soil and Tillage Research 165, 107–112

Hussein, M.A., Antille, D.L., Kodur, S., Chen, G., Tullberg, J.N., 2021. Controlled traffic farming effects on productivity of grain sorghum, rainfall and fertiliser nitrogen use efficiency. Journal of Agriculture and Food Research 3, 100-111.

Idso, S.B., Jackson, R.D., Reginato, R.J., 1977. Remote sensing for agricultural water management and crop yield prediction. Agricultural Water Management 1, 299-310.

Isbell, R., 2016. The Australian soil classification, 2 ed. CSIRO publishing, Australia.

Jackson, R.D., Idso, S.B., Reginato, R.J., Pinter Jr, P.J., 1981. Canopy temperature as a crop water stress indicator. Water resources research 17, 1133-1138.

Jones, H.G., 1999. Use of infrared thermometry for estimation of stomatal conductance as a possible aid to irrigation scheduling. Agricultural and forest meteorology 95, 139-149.

Keller, T., Arvidsson, J., 2004. Technical solutions to reduce the risk of subsoil compaction: effects of dual wheels, tandem wheels and tyre inflation pressure on stress propagation in soil. Soil and Tillage Research 79, 191-205.

Kirby, M., 2007. Whither soil compaction research? Soil and Tillage Research 93, 472-475.

Kulkarni, S.S., Bajwa, S.G., Huitink, G., 2010. Investigation of the effects of soil compaction in cotton. Transactions of the ASABE 53, 667-674.

Kutzbach, H.D., 2000. Trends in power and machinery. Journal of Agricultural Engineering Research 76, 237-247.

Li, Y.X., Tullberg, J.N., Freebairn, D.M., 2007. Wheel traffic and tillage effects on runoff and crop yield. Soil and Tillage Research 97, 282-292.

Macdonald, B.C.T., Nachimuthu, G., Chang, Y.F., Nadelko, A.J., Tuomi, S., Watkins, M., 2020. Nitrogen composition in furrow irrigated run-off water. Agricultural Water Management 242, 106399.

Mahan, J.R., Burke, J.J., Wanjura, D.F., Upchurch, D.R., 2005. Determination of temperature and time thresholds for BIOTIC irrigation of peanut on the Southern High Plains of Texas. Irrigation Science 23, 145-152.

McGarry, D., 1990. Soil compaction and cotton growth on a vertisol. Soil Research 28, 869-877.

McGarry, D., 1995a. The optimisation of soil structure for cotton production. In ‘Challenging the future, pp. 14-17.

McGarry, D., 1995b. The optimisation of soil structure for cotton production. In ‘Challenging the future', World Cotton Research Conference, Brisbane, Australia, pp. 14-17.

McHugh, A.D., Tullberg, J.N., Freebairn, D.M., 2009. Controlled traffic farming restores soil structure. Soil and Tillage Research 104, 164-172.

McKenzie, D.C., 1998. SOILpak for cotton growers. NSW Agriculture.

Nachimuthu, G., Hulugalle, N.R., Watkins, M.D., Finlay, L.A., McCorkell, B., 2018. Irrigation induced surface carbon flow in a Vertisol under furrow irrigated cotton cropping systems. Soil and Tillage Research 183, 8-18.

Nosalewicz, A., Lipiec, J., 2014. The effect of compacted soil layers on vertical root distribution and water uptake by wheat. Plant and Soil 375, 229-240

Phillips, R.E., Kirkham, D., 1962. Soil Compaction in the Field and Corn Growth 1. Agronomy journal 54, 29-34.

Pillai, U.P., McGarry, D., 1999. Structure repair of a compacted Vertisol with wet-dry cycles and crops. Soil Science Society of America Journal 63, 201-210.

Radford, B.J., Yule, D.F., McGarry, D., Playford, C., 2007. Amelioration of soil compaction can take 5 years on a Vertisol under no till in the semi-arid subtropics. Soil and Tillage Research 97, 249-255.

Raper, R.L., 2005. Agricultural traffic impacts on soil. Journal of Terramechanics 42, 259-280.

Roberton, S.D., Bennett, J.M., 2017. Efficacy of delaying cotton defoliation to mitigate compaction risk at wet harvest. Crop and Pasture Science 68, 466-473.

Roth, G., Harris, G., Gillies, M., Montgomery, J., Wigginton, D., 2013. Water-use efficiency and productivity trends in Australian irrigated cotton: a review. Crop and Pasture Science 64, 1033-1048.

Sarmah, A.K., Pillai-McGarry, U., McGarry, D., 1996. Repair of the structure of a compacted Vertisol via wet/dry cycles. Soil and Tillage Research 38, 17-33.

Soane, B.D., van Ouwerkerk, C., 2013. Soil compaction in crop production. Developments in Agricultural Engineering II. Elsevier.

Soil Survey Staff, 2010. Keys to soil taxonomy. Natural Resources Conservation, Service of the United States Department of Agriculture, Washington, DC

Souty, N., Stepniewski, W., Rode, C., 1988. The influence of external oxygen concentration on axial root growth force of maize radicles. Agronomie, EDP Sciences, 8 (4), 295-300.

Taylor, H.M., Burnett, E., 1964. Influence of soil strength on the root growth habit of plants. Soil Science 98, 174-180.

Tullberg, J.N., Yule, D.F., McGarry, D., 2007. Controlled traffic farming—from research to adoption in Australia. Soil and Tillage Research 97, 272-281.

Van den Akker, J.J.H., Arvidsson, J., Horn, R., 2003. Introduction to the special issue on experiences with the impact and prevention of subsoil compaction in the European Union. Soil and Tillage Research 73, 1-8.

Supplementary material

Table S2.1: Multiple linear regression for predicting soil strength (CI) after traffic; model accounted for 97% variance in both row and furrow

Position	Parameter	Estimate	p
Row	Constant	0.343	<0.001
	Depth	0.007	<0.01
	CI before traffic	0.392	<0.001
Furrow	Constant	0.21	<0.05
	Depth	0.018	<0.01
	CI before traffic	0.625	<0.001

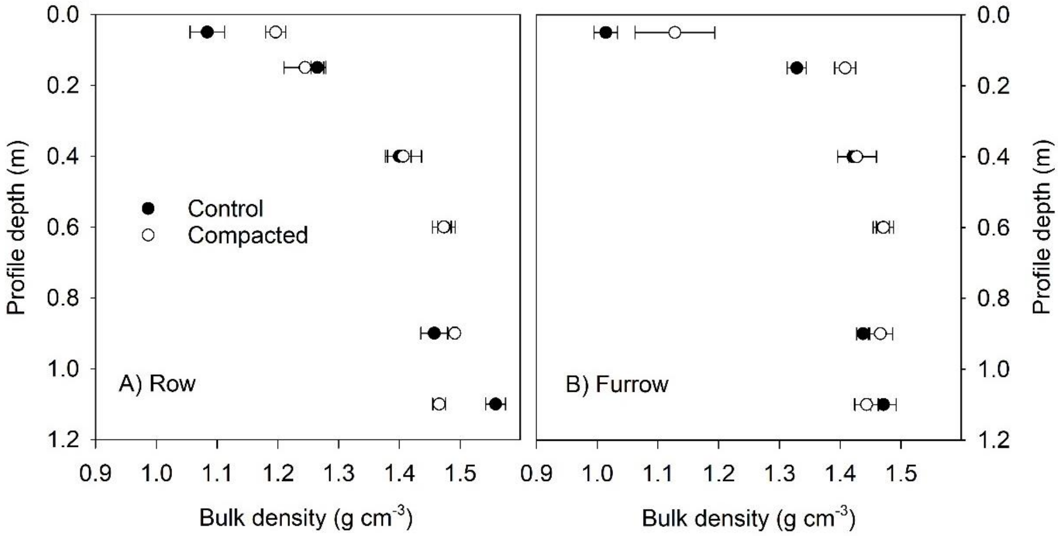

Figure S2.2: Bulk density measured at the end of cotton season in rows (A) and furrows (B); depths are shown as mid-point of the section of core used to measure bulk density; error bars are standard error of the mean

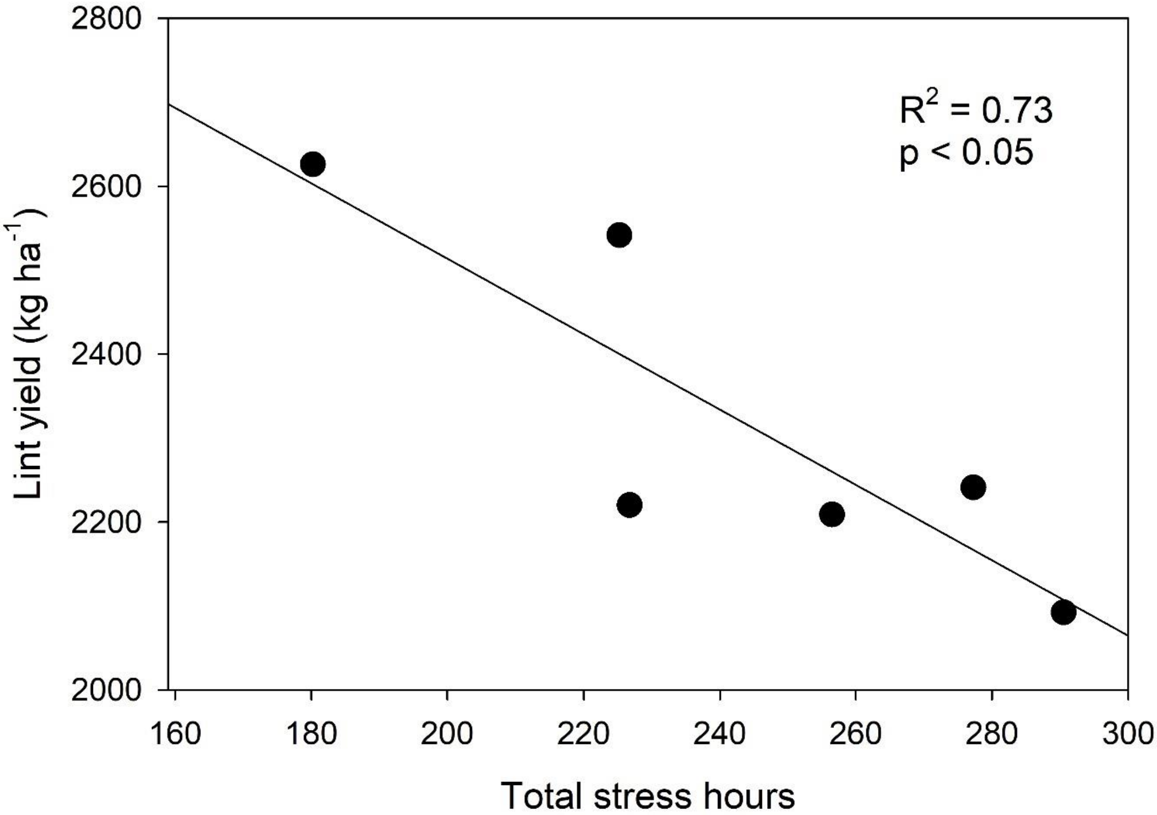

Figure S2.3: Simple linear regression between cotton lint yield and total season stress hours derived from canopy temperature (n=6)

Chapter 3: Does soil compaction have a legacy effect on wheat yield, cotton lint yield and soil properties?

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Key findings

- Soil compaction did not impact the yields of following wheat or cotton crops in a furrow-irrigated system
- Soil compaction did not impact soil water use by the subsequent cotton crop
- A single wheat rotation crop was sufficient to alleviate the soil compaction caused by a 19.2 tonne tractor on moist Vertosols with a clay content of 62%

1 Introduction

Soil compaction is a common soil constraint impacting cotton productivity in Australia (CRDC, 2020). Previous research on the amelioration of soil compaction — done in a controlled environment using intact soil cores taken from compacted fields — found that it can take several wetting and drying cycles to alleviate compaction in Australian swelling and shrinking cracking clay soils (Pillai-McGarry et al., 1994). We conducted a field investigation to assess the legacy effect of soil compaction, specifically, to investigate the number of years it takes to alleviate the soil compaction under field conditions. The results of this study will improve grower's understanding and amelioration of soil compaction. In this report, we continue the monitoring of a simulated compaction experiment reported previously by Jamali et al. (2021), which examined the impact of soil compaction on cotton production using canopy sensors and soil moisture probes.

2 Methods

The experimental site is located on an alluvial floodplain in the lower Namoi valley—Field D1 at the Australian Cotton Research Institute (ACRI) (30°11'42.98"S 149°36'52.86"E). A detailed description of the field and the treatments were presented by Jamali et al. (2021). This report details the results of the original treatments on a wheat crop planted in the winter of 2020 and a cotton crop planted in the summer of 2021-22. An additional treatment (semi-compacted as described below) was also included in the 2021-22 season. The treatments included

1. Control (non-compacted)
2. Compacted (Furrows compacted on either side of the bed)
3. Semi-compacted (Furrows compacted on one side of the bed)

Crop management was similar to the trial explained in Chapter 2. Soil water use was measured in each plot (one position per plot) using a neutron probe moisture meter and soil penetrometer resistance was measured at the top of the bed in each plot, as described by Jamali et al. (2021).

Plant biomass samples were taken from 1 m^2 per plot from late March to early April by taking whole shoot and bolls. Samples were dried at 60° C until constant weight and the final dry biomass recorded. Disease incidence was recorded in the 2021-22 season by counting the number of plants with visual infection symptoms per square metre and reported as a percentage of all plants sampled.

Cotton was handpicked from 1 m^2 per plot for yield estimation. A sub-sample of cotton was ginned to calculate the lint and seed turnout.

All the statistical analysis was carried out using Genstat 18.2 (*VSN International Ltd*) using analysis of variance of a randomised block design with four replications. Probabilities <5% were considered significant.

3 Results and discussion

The wheat yield results showed no significant difference between control and compacted plots (Figure 3.1). The lack of difference in wheat yield could be the result of sufficient rainfall recharging the soil profile during the season to overcome the traditional limitations of soil water extraction caused by plant roots due to compaction.

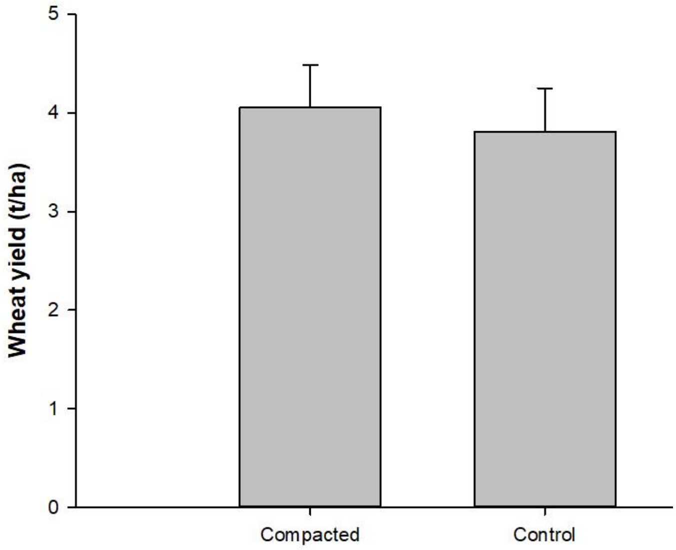

Figure 3.1. Wheat yield as influenced by soil compaction (bars are standard error of the mean)

There was also no legacy effect of soil compaction on cotton lint yield at harvest or on any agronomic parameters measured at the maximum biomass stage (Table 3.1). There was also no difference between semi-compacted and control or compacted plots. However, there was an inverse relationship between disease incidence with compaction. The fully compacted plot recorded no disease incidence and semi-compacted plots recorded lower disease incidence than the control plots (Table 3.1). The reason for lower disease incidence is not clear as root biomass was not assessed.

Table 3.1. Legacy effect of soil compaction on cotton lint yield at harvest and growth parameters at maximum biomass stage (bales/ha) during the 2021-22 season

Treatment	Lint yield (kg/ha)	Disease incidence%	Plant height (cm)	Number of nodes/plants	Vegetative dry matter (t/ha)	Reproductive dry matter (t/ha)	Total dry matter (t/ha)
Control	13.34	15.3	101	23.4	6.1	10.6	16.7
Compacted	15.52	0.0	101	22.9	5.6	10.1	15.7
Semi-compacted	13.41	3.1	98	22.1	4.9	9.1	14.0
LSD (*P<0.05*)	NS	NS	NS	NS	NS	NS	NS

The soil water content (Table 3.2) and soil resistance (Table 3.3) results showed no impact of the compacted treatments across various depths. Soil resistance can be influenced by soil moisture, so the penetrometer readings were conducted when the soil water content was similar for all plots (Table 3.2). There was a difference in soil resistance and soil water content during the 2019-20 season between compacted and control plots (Jamali et al., 2021). Previous research indicated that, it can take up to five or six wetting and drying cycles to self-repair the soil compaction in cotton growing soils of Australia (Pillai-McGarry et al., 1994). Our results over two cotton seasons suggest that soil compaction caused by heavy machinery of ~19.2 tonnes in this cracking soil with 62% clay content may be repaired after a single wheat rotation crop in similar seasonal conditions from 2020 to 2022.

Table 3.2. Pre-irrigation soil water storage (mm) difference between treatments at various depths during the 2019-20 and 2021-22 seasons

Treatment	0-120 cm	0-10 cm	10-30 cm	30-50 cm	50-75 cm	75-105 cm	105-120 cm
				2021-22			
Compacted	426	27.4	58.8	67.2	88.9	117.6	65.9
Control	423	24.5	58.7	67.0	89.2	117.7	66.3
P value	0.365	0.070	0.311	0.484	0.381	0.044	0.670
				2019-20			
Compacted	417	14.7	65.5	77.1	96.1	105.2	58.12
Control	416	16.4	58.7	73.5	94.0	113.7	59.33
P value	0.930	0.472	0.034	0.131	0.424	0.286	0.383
				Soil water content during soil resistance measurements			
Compacted	434	31.2	58.6	67.7	85.8	122.3	68.4
Control	431	29.7	58.1	66.2	87.1	121.0	68.5
P value	0.970	0.301	0.537	0.839	0.680	0.197	0.788

Table 3.3. Soil resistance (KPa) of compacted and control treatments measured (middle of beds) during the 2021-22 season

Treatment	0-45 cm	10 cm	21 cm	30 cm	40 cm	45 cm
			Beds			
Compacted	2382	1982	2485	2536	3343	3580
Control	2597	2257	2591	2885	3693	3818
Semi-compacted	2641	1994	2712	3044	3818	4160
P value	0.390	0.472	0.608	0.144	0.308	0.205

4 Conclusions

The results suggest there was no further legacy effect of soil compaction on cotton lint yield and wheat yield in subsequent seasons beyond the season when compaction occurred. The self-repair potential of Vertosols with a clay content of 62% likely assisted the natural and wheat rotation-mediated alleviation of soil compaction. Future investigation needs to repeat this research on a greater range of soils typically used for irrigated cotton production, focusing on the time required to repair the compacted soil using natural and rotation crop tactics.

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References

CRDC, 2020. 2020 Grower Survey. Cotton Research and Development Corporation, p. 63.

Jamali, H., Nachimuthu, G., Palmer, B., Hodgson, D., Hundt, A., Nunn, C., Braunack, M., 2021. Soil compaction in a new light: Know the cost of doing nothing – A cotton case study. 213, 105158.

Pillai-McGarry, U., Sarmah, A.J., McGarry, D., 1994. Structure Repair with Wet/Dry Cycles in a Cotton Soil World Cotton Research Conference, Brisbane.

Chapter 4: Facts and fallacies of winter cover crop rotation and wheat rotation crop stubble management in an irrigated cotton system

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Key findings

- A winter cover crop of oats may not boost the lint yield of irrigated cotton planted every summer
- Growing oats as cover crop resulted in higher soil water storage in wetter-than-average years, however, the subsequent cotton did not benefit from this the soil moisture due to other soil constraints
- Incorporating the wheat stubble or leaving it as standing stubble had no impact on cotton productivity. Leaving it as standing stubble will minimise the tillage and energy use.
- Wheat standing stubble system resulted in higher wheat yield (wheat planted after cotton) than wheat stubble incorporated during drought.
- Standing stubble will minimise atleast two tillage operations and overall traffic within the cotton farms and improve the productivity and sustainability of irrigated cropping systems

1 Introduction

Cover crops are often postulated to improve soil health. They are reported to enhance soil physical and chemical properties, crop productivity, soil carbon and nutrient cycling. However, studies questioning the benefits of cover crops also exist in the scientific literature. In Australia, cotton-based irrigated cropping systems result in better gross margins for growers than exclusively grain-based irrigated cropping systems. The benefits of crop rotation on nutrient cycling, soil carbon (Rochester, 2011) and soil physical properties (Hulugalle and Scott, 2008) within the Australian cotton cropping system are well established. The benefits of vetch as a cover crop rotation whether mulched as surface mulch (Hulugalle and Scott, 2008; Hulugalle et al., 2010) or incorporated (Rochester, 2011) in a two-year rotation cycle was reported earlier. As cotton is a high-value crop, designing a cropping system that includes cotton every summer with winter break crops may improve the gross margin and productivity of cotton cropping systems in Australia. A field experiment was conducted to investigate the effectiveness of winter cover crops (Oats) in improving the soil health, cotton productivity and gross margin of cotton cropping systems under minimum tillage. Continuous cotton with and without a cover crop was compared among themselves and against cotton wheat systems with two different methods of stubble management.

2 Methods

The experiment was conducted at the Australian Cotton Research Institute (ACRI). (149^{0}47′E, 30^{0}13′S) near Narrabri in New South Wales (NSW), Australia. The soil is a deep uniform self-mulching grey clay (Isbell RF, 2021) and is classified as a fine, thermic, smectitic, Typic Haplustert (Soil Survey Staff, 2010). The mean annual rainfall for the region between 1993 and 2020 was 618 mm (Longpaddock, 2020). The area has a semi-arid climate and experiences four distinct seasons with a mild winter and a hot summer. The soil's mean particle size distribution at 0–1.2 m depth was (per 100 g soil): 64 g clay, 11 g silt, and 25 g sand. Exchangeable sodium percentage (ESP) was 4% at 0-0.6m and 12% at 0.6–1.2 m depths.

The experiment initially included four crop rotation systems with cotton as the main crop. All the treatments were maintained as a permanent bed system. In 2020, a fifth system was introduced by subdividing the cotton-wheat [standing stubble] system into two by retaining the historical system and introducing chickpea rotation (T5 as described below). The five systems currently under investigation included

T1: Cotton-Oats (summer cotton–winter oats–summer cotton)

T2: Cotton monoculture (summer cotton–winter fallow–summer cotton)

T3: Cotton-Wheat [stubble incorporated]- Cotton (summer cotton–winter wheat– summer and winter fallow–summer cotton)

T4: Cotton-Wheat [standing stubble]- Cotton (summer cotton–winter wheat– summer and winter fallow–summer cotton)

T5-Cotton- Chickpea [standing stubble]- Cotton- Wheat [standing stubble]- Cotton- Chickpea [standing stubble]- Cotton

In T3, the wheat stubble was incorporated into the beds after harvest with a disc hiller. Treatment T1 was formerly cotton–vetch–cotton until 2013. Treatment T5 was subdivided from T4 in 2020 when chickpea was introduced. This system includes chickpeas every four years for disease management.

The chronology of the experimental treatments from 2014 to 2017 is summarised in Table 2 of Nachimuthu et al. (2017). The chronology of the experimental treatments from 2017 to 2022 is summarised in Table 4.1 below.

Table 4.1. A comparative summary of treatment characteristics for crop-sequence treatments on permanent beds (Field D1, ACRI Narrabri) *

Treatment	T1: Cotton – oats	T2: Cotton monoculture	T3a: Cotton-Wheat [stubble incorporated]	T3b: Cotton-Wheat [stubble incorporated]	T4a: Cotton-Wheat [standing stubble]	T4b: Cotton-Wheat [standing stubble]	T5: Cotton-Chickpea-[standing stubble]-Cotton-Wheat-[standing stubble]
Historical rotation (until 2011)	**Cotton-Vetch-Cotton**	**Cotton monoculture**	**Cotton-Wheat**	**Cotton-Wheat**	**Cotton-Wheat-Vetch**	**Cotton-Wheat-Vetch**	**Cotton-Wheat- Vetch**
Historical rotation (until 2017)	**Cotton-oats-Cotton**	**Cotton monoculture**	**Cotton-Wheat**	**Cotton-Wheat**	**Cotton-Wheat-Vetch**	**Cotton-Wheat-Vetch**	**Cotton-Wheat- Vetch**
Tillage	**Minimum (restricted to beds top 10 cm)**	**Minimum (restricted to beds top 10 cm)**	**Minimum (restricted to beds top 10 cm)**	**Minimum (restricted to beds top 10 cm)**	**Minimum (restricted to beds top 10 cm)**	**Minimum (restricted to beds top 10 cm)**	**Minimum (restricted to beds top 10 cm)**
Stubble management	Standing stubble	Not applicable	Incorporated	Incorporated	Standing stubble	Standing stubble	Standing stubble
Crops planted in Winter 2017	Oats	(Fallow)	Wheat	(Fallow)	Wheat	(Fallow)	(Fallow)
Harvest	-	-	Nov 2017	-	Nov 2017	-	-
Crops planted in October 2017	Cotton	Cotton		Cotton		Cotton	Cotton

Total fertiliser for cotton	260 kg N/ha	260 kg N/ha		260 kg N/ha		260 kg N/ha	260 kg N/ha
Cotton Harvest	April 2018	April 2018		April 2018		April 2018	April 2018
Crops planted in Winter 2018	Oats	(Fallow)	(Fallow)	Wheat	(Fallow)	Wheat	Wheat
Harvest	-	-		Nov 2018		Nov 2018	Nov 2018
Crops planted in Nov 2018	Cotton	Cotton	Cotton	(Wheat fallow)	Cotton	(Wheat fallow)	(Wheat fallow)
Total fertiliser	220 kg N/ha	220 kg N/ha	220 kg N/ha	-	220 kg N/ha	-	-
Cotton Harvest	May 2019	May 2019	May 2019	-	May 2019	-	-
Crops planted in Winter 2019	Oats	(Fallow)	Wheat	(Fallow)	Wheat	(Fallow)	(Fallow)
Fertiliser to winter crops	20 kg N/ha	-	70 kg N/ha	-	70 kg N/ha	-	-
Harvest	-	-	Oct 2019	-	Oct 2019	-	-
Crops planted in Oct 2019	Cotton	Cotton	(Wheat fallow)	Cotton	(Wheat fallow)	Cotton	Cotton
Total fertiliser	240 kg N/ha	240 kg N/ha	-	240 kg N/ha	-	240 kg N/ha	240 kg N/ha
Cotton harvest	May 2020	May 2020		May 2020		May 2020	May 2020
Crops planted in Winter 2020	Oats	(Fallow)	(Fallow)	Wheat	(Fallow)	Wheat	Chickpeas
Fertiliser	20 kg N/ha	-	-	70 kg N/ha	-	70 kg N/ha	-
Harvest	-	-		Nov 2020		Nov 2020	Nov 2020
Crops planted in Nov 2020	Cotton	Cotton	Cotton	(Wheat fallow)	Cotton	(Wheat fallow)	(Chickpea fallow)
Total fertiliser	180 kg N/ha	180 kg N/ha	180 kg N/ha	-	180 kg N/ha	-	-
Cotton Harvest	May 2021	May 2021	May 2021	-	May 2021	-	-
Crops planted in Winter 2021	Oats	(Fallow)	Wheat	(Fallow)	Wheat	(Fallow)	(Fallow)
Fertiliser to winter crops	60 kg N/ha	-	60 kg N/ha	-	60 kg N/ha	-	-
Harvest	-	-	Dec 2021	-	Dec 2021	-	-
Crops planted in Oct 2021	Cotton	Cotton	(Wheat fallow)	Cotton	(Wheat fallow)	Cotton	Cotton
Total fertiliser	280 kg N/ha	280 kg N/ha	-	280 kg N/ha	-	280 kg N/ha	280 kg N/ha
Cotton harvest	May 2022	May 2022		May 2022		May 2022	May 2022

*This trial is a randomised complete block design with three replicates.

Cotton variety Sicot 748 B3F® was planted every summer in the respective treatments at a seed rate of 15 kg/ha. All the crops in the rotation system were irrigated by furrow irrigation systems with siphons @ 1ML/ha (~100 mm) when the rainfall was insufficient to meet the evapotranspiration demand. Cotton was picked from late April to late June with a 4-row picker after defoliation in April. After cotton picking, the cotton was slashed and incorporated into the beds with a disc-hiller. The paddock was prepared for cropping using minimum tillage (permanent beds) with tillage operations (disc-hilling) restricted to the bed after cotton picking. Wheat, chickpea and oats crops were irrigated, although the requirement for irrigation was minimal during winter and spring. During drought years, the winter and cover crops were only irrigated after planting for establishment in order to save water for the summer cotton crop. The oats were sprayed out in September before maturity and cotton was sown directly into the oat stubble in October/November each year.

Cotton growth parameters were periodically recorded. Monitoring included the number of nodes, plant height, green bolls and opened bolls. However, there were occasions where high rainfall limited access to the field suspending monitoring. Plant biomass samples were taken from 2 m^2 quadrats in each plot between late March to early April. Whole shoots and bolls were collected and dried at 60ºC until constant weight with the dry biomass recorded. Disease incidence (% of infected plants/m^2) was visually assessed in the cuts made during the 2021–22 season.

Crop yield was estimated by harvesting the economic produce (cotton, chickpea or wheat) in the middle 4 to 8 rows of each plot using a mechanical harvester. A sub-sample of cotton was ginned to calculate the lint and seed turnout. In 2021 and 2022, a hand harvest of 3 m^2 per plot was performed due to electronic faults with the picker scale. Economic analysis and gross margins of the cropping systems investigated are described in Chapter 5.

Soil strength was measured as cone index (CI) using a cone penetrometer (RIMIK, ~12.5 mm diameter cone, 30° included angle) at 10 positions from head ditch to tail drain in each plot. At each position, soil strength was measured in the centre of a plant row (row), in the middle of the furrow (furrow) and the side of the bed. Measurements were made at 1.5 cm intervals to a depth of 45 cm. The treatment mean was calculated for each position and depth before and after compaction.

Soil samples (0-1.2 m at increments of 0.0-0.10, 0.10-0.30, 0.30-0.60, 0.60-1.2 m depth) were taken from all four replications during September/October of each planting season and analysed for SOC using the Walkley and Black method (Method 6A1) (Rayment and Lyons, 2011) during 2018 and 2020.

Soil temperature (5 cm depth) was monitored at one position per plot within plant line during the two seasons using Tinytag plus2 (Gemini data loggers (UK) Ltd, Chichester, West Sussex PO198UJ, UK).

Soil water content at various depths from 10 to 120 cm was measured during 2018-19 to 2021-22 seasons with a neutron moisture meter (CPN 503-DR Hydroprobe®, CPN International, Concord, CA) which had previously been calibrated for this paddock (Hulugalle et al., 2013). Topsoil (0-10 cm) soil water content was measured gravimetrically. Soil water storage was calculated before every irrigation and seasonal average soil water storage before the irrigation were presented.

All statistical analyses were carried out by Genstat 18.2 (*VSN International Ltd*) using analysis of variance of a randomised complete block design.

3 Results and discussion

Cotton lint yield results are summarised in Table 4.2. The cotton-wheat rotation [wheat stubble incorporated] or [standing stubble] resulted in better lint yields than cotton monoculture or cotton-oats cover crop rotation. There was no significant difference between wheat [stubble incorporated] or wheat [standing stubble] systems. Leaving wheat stubbles on the soil surface without tillage will reduce the traffic and energy use within a cotton-wheat cropping system and therefore improve the overall sustainability of the cotton production system.

Table 4.2. Effect of crop rotation and P application on cotton yield (bales/ha) in field D1, ACRI from 2017-18 to 2021-22 seasons

Treatment	2017-18	2018-19	2019-20	2020-21[#]	2021-22
T1: Cotton-Oats	9.21	9.01	11.01	11.98	10.19
T2: Cotton monoculture	9.73	11.03	11.68	11.28	10.05
T3: Cotton-wheat [stubble incorporated]	11.70	12.34	13.03	11.98	13.34
T4: Cotton-wheat [standing stubble]	11.88	11.71	13.24	12.39	13.81
T5: Cotton-chickpea- cotton-wheat	-	-	-	-	13.77
LSD (P<0.05)	1.25***	1.031***	0.848***	#	2.560*

[#]-data was not analysed statistically as some reps were missed due to electronic issues with the picker scale

The inclusion of an oats cover crop had no benefits over cotton monoculture in terms of cotton lint yield productivity (Table 4.2). The lack of yield benefit may be due to immobilisation of mineral nitrogen by the oats stubble leading to early-season N deficiency. The cotton crop gown after oats exhibited visibly paler green leaves compared to the monoculture treatment (T2). Seasonal average soil temperature during the 2020-21 season was lower (P<0.05) in the cotton-wheat (22.39ºC) than the cotton monoculture (22.65ºC) and the cotton-oats (22.84ºC). There was no interaction between months and treatments in soil temperatures (Figure 4.3A). A similar trend was observed in the 2021-22 season with cotton-wheat (24.31 ºC) ≈ cotton-chickpea (24.45 ºC) < cotton-oats (25.40 ºC) ≈ cotton monoculture (25.17 ºC). These results indicate that soil temperature in the cotton-oats system was not lower than other treatments earlier in the season (Figure 4.2). The observed results could be a factor of good canopy cover in cotton-wheat and cotton-chickpea rotation compared to the other two treatments in later months from February to March in both years.

In addition, the cotton-oats cover crop system experienced more traffic compared to cotton monoculture, with in-crop operations necessarily carried out within a narrow time window between the oat crop harvest and cotton planting. As a result, some field operations were conducted at inappropriate soil moisture contents that can lead to soil compaction. The soil resistance within the cotton-oats system was higher when compared with the cotton-wheat systems but similar to cotton monoculture (Figure 4.1). This indicates the cotton monoculture and cotton-oats systems were compacted due to less fallow time compared to the cotton-wheat system with long fallow and a greater opportunity to self-repair through the swelling and shrinking of the clay in the soil.

Disease (verticillium wilt) assessment in the 2021-22 season showed high variability between plots. The results (Figure 4.3) indicated a trend of incidence: cotton monoculture > cotton-oats > cotton-wheat [standing stubble] ≥ cotton-chickpea> cotton-wheat [stubble incorporated]. The oats cover crop system was second worst in terms of disease incidence and therefore not an effective break crop, compared to wheat in a two-year rotation cycle.

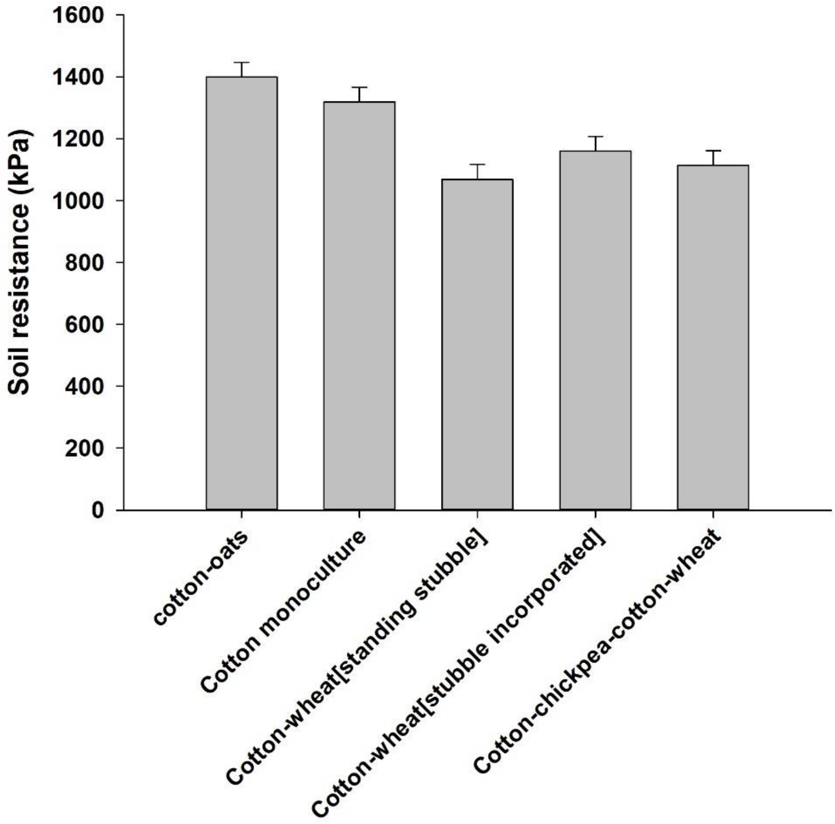
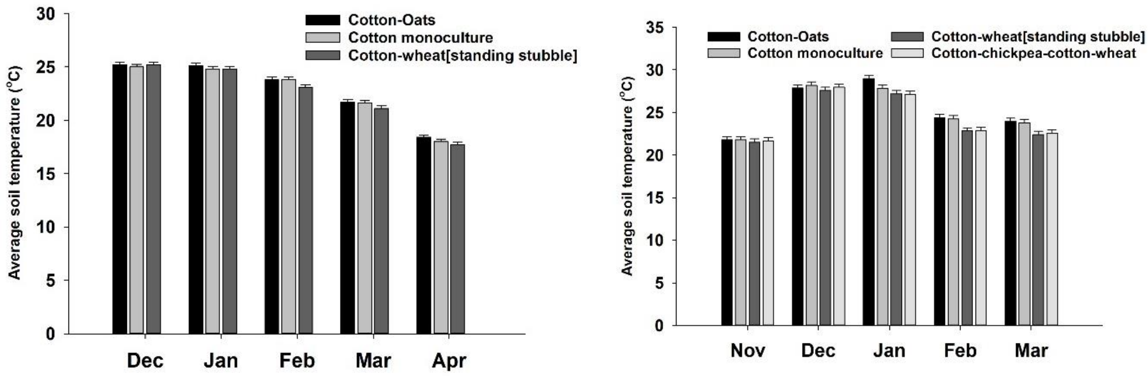


Figure 4.1. Effect of crop rotation on soil resistance measured during 2021-22 season (0-45 cm average). Error bars indicate standard error of differences of means.



A) 2020-21 season

B) 2021-22 season

Figure 4.2. Average monthly soil temperature at 5 cm depth in ACRI field D1. Error bars indicate standard error of differences of means.

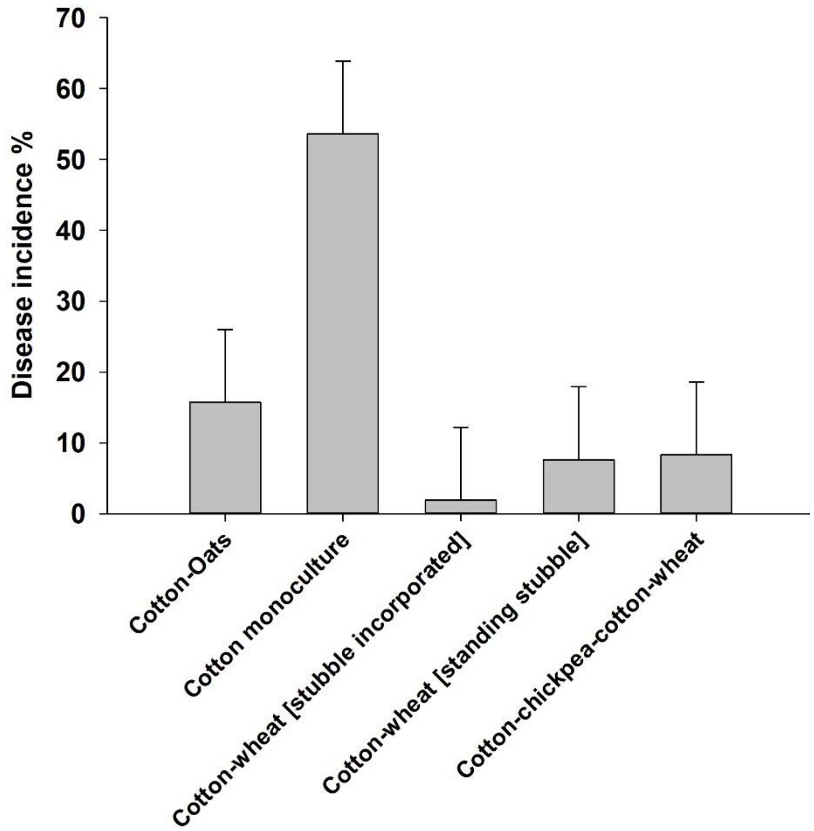


Figure 4.3. Effect of cotton cropping systems on visual scores of verticillium incidence (2021-22 season) in 2 m^2 biomass cuts. Error bars indicate standard error of the means.

Table 4.2. Effect of cotton cropping systems on cotton plant drymatter (t/ha) at maximum biomass stage

Cropping System	2017-18	2018-19	2019-20	2020-21	2021-22
T1: Cotton-Oats	9.21	10.94	14.71	12.97	12.08
T2: Cotton monoculture	9.73	11.53	15.09	14.51	9.51
T3: Cotton-wheat [stubble incorporated]	11.70	14.39	17.40	15.20	14.60
T4: Cotton-wheat [standing stubble]	11.88	11.84	16.14	13.62	14.58
T5: Cotton-chickpea- cotton-wheat	-	-	-	-	13.02
LSD (P<0.05)	1.25	NS	2.037*	NS	NS

Wheat yields tended to be higher in the standing stubble systems than the stubble incorporated treatments (Figure 4.4) from 2017 to 2019 when the in-crop rainfall was low (2019 was the driest season). However, stubble management did not influence wheat yield in the other years when there was sufficient in-crop rainfall (Figure 4.5). This suggests that the wheat standing stubble system improved resilience during drought and can improve the water use efficiency of the cotton-based cropping system. The soil resistance (compaction) was also lower with the wheat standing stubble system (Figure 4.1) compared with all other cropping systems. Similarly, there was no difference in wheat yield between compacted and control plots during wet years in another trial within the same field (Chapter 3). The sufficient rainfall during the season was able to overcome the soil compaction-induced water limitations. The long-term gross margin/ML of water was always higher for cotton-wheat systems than cotton monoculture (Chapter 5).

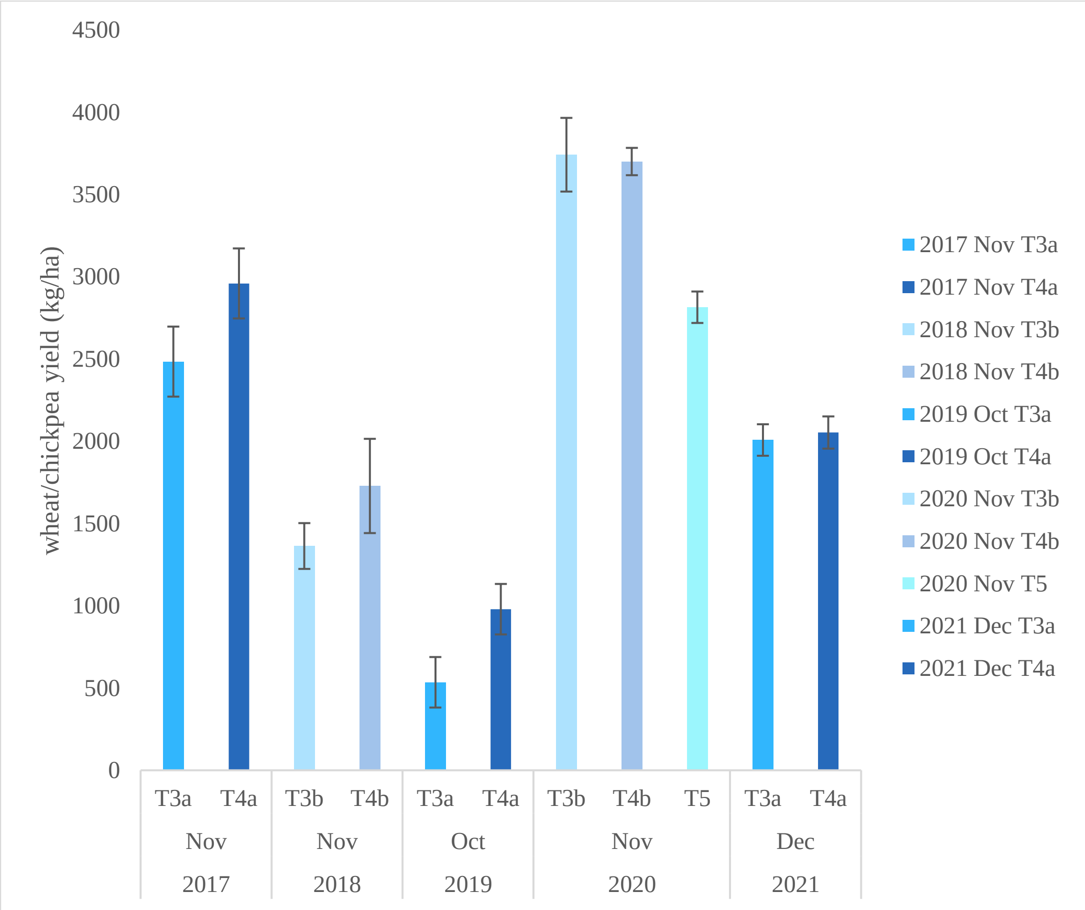


Figure 4.4. Wheat/Chickpea yield in field D1 from 2017 to 2021 (T3a- Cotton-wheat [stubble incorporated] phase 1, T3b- Cotton-wheat [stubble incorporated] phase 2, T4a- Cotton-wheat [standing stubble] phase 1, T4b-Cotton-wheat [standing stubble] phase 2, T5- Cotton-chickpea-cotton-wheat

Table 4.3. Soil water storage (mm) before irrigation (0-120 cm) as influenced by cropping systems (seasonal average)

Cropping System	2018-19		2019-20		2020-21		2021-22	
T1: Cotton-Oats	384	a	425	b	429	b	434	a
T2: Cotton monoculture	358	a	409	ab	413	ab	427	a
T3: Cotton-wheat [stubble incorporated]	359	a	392	a	405	a	439	a
T4: Cotton-wheat [standing stubble]	370	a	395	a	412	ab	440	a
T5: Cotton-chickpea- cotton-wheat							439	a

The average profile soil water content indicated that there were no treatment effects on soil water storage in the 2018-19 and 2021-22 seasons (Table 4.3). In 2018-19, the field was impacted by hail storms and there was high variability with the cotton plant regrowth. The 2021-22 season had higher-than-average summer rainfall and this might have contributed towards the lack of difference in soil water storage. However, in the 2019-20 and 2020-21 seasons, the soil water storage under the cotton-oats cover crop system was greater than in the cotton-wheat stubble incorporated systems (Table 4.3 and Table 4.4). This suggests that the cover crop improved water infiltration and soil porosity resulting in higher soil water storage. However, the following cotton crops were unable to benefit from the increased soil water storage, either due to irrigation supplying adequate water or due to some other constraints brought about by the cover crop (Table 4.2).

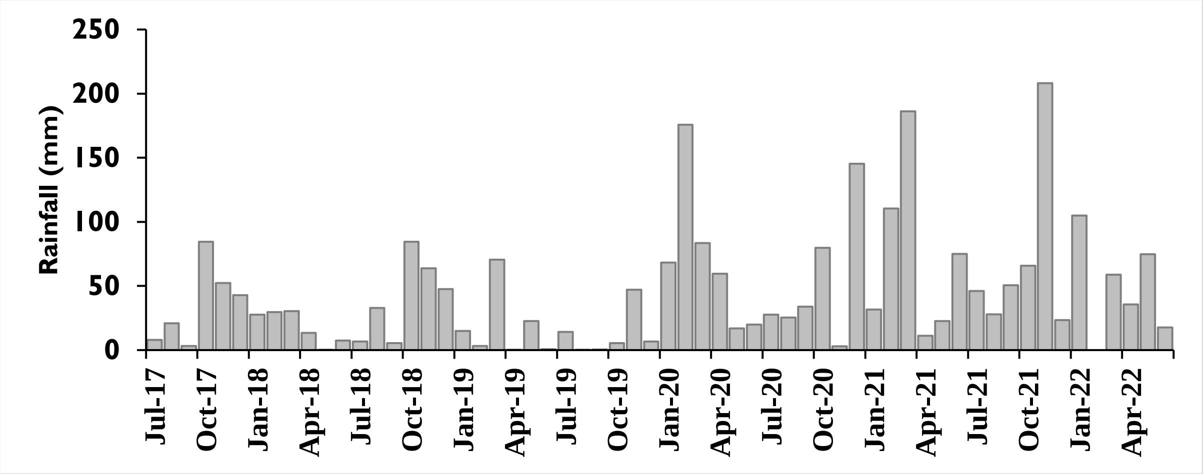


Figure 4.5. Monthly rainfall total from July 2017 to June 2022

The soil organic carbon concentrations in field D1 indicated a decline in 0-30 cm depth from 2018 to 2020. The SOC at lower depths (>30 cm) were similar before planting over two years (Figure 4.6). The decline is due to the drought conditions and this was reflected to low winter crop yield (Figure 4.4). The detailed soil organic carbon trends and stocks as influenced by cropping systems will be investigated and presented in DAN2305.

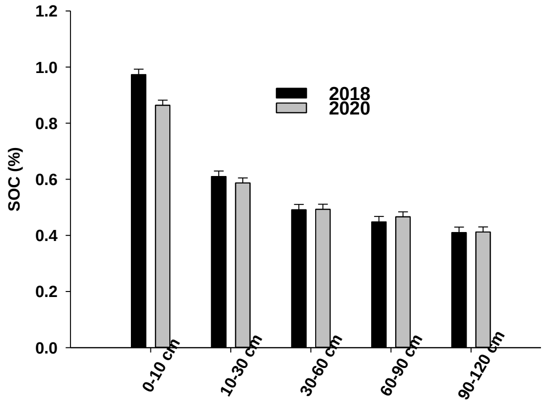


Figure 4.6. Soil organic carbon concentrations at ACRI field D1 (2018 and 2020).

Table 4.4. Soil water storage (mm) before irrigation at different depths as influenced by cropping systems (seasonal average)

Cropping system	0-10 cm		10-30 cm		30-50 cm		50-75 cm		75-105 cm		105-120 cm	
							2019-20					
T1: Cotton-Oats	19	a	58	b	74	b	96	a	116	b	56	A
T2: Cotton monoculture	19	a	57	b	72	ab	92	a	110	ab	58	Ab
T3: Cotton-wheat [stubble incorporated]	19	a	55	ab	65	a	89	a	107	a	59	Ab
T4: Cotton-wheat [standing stubble]	19	a	49	a	68	ab	91	a	109	a	61	B
							2020-21					
T1: Cotton-Oats	25	a	60	b	72	b	94	a	116	b	62	B
T2: Cotton monoculture	25	a	58	b	70	ab	91	a	110	a	58	A
T3: Cotton-wheat [stubble incorporated]	26	a	56	b	68	ab	89	a	109	a	57	A
T4: Cotton-wheat [standing stubble]	27	a	48	a	67	a	93	a	117	b	60	B
							2021-22					
T1: Cotton-Oats	26	a	62	a	72	a	94	a	117	a	63	A
T2: Cotton monoculture	25	a	62	a	71	a	93	a	115	a	62	A
T3: Cotton-wheat [stubble incorporated]	25	a	63	a	71	a	95	a	120	a	64	A
T4: Cotton-wheat [standing stubble]	25	a	63	a	73	a	96	a	119	a	63	A
T5: Cotton-chickpea- cotton-wheat	25	a	62	a	73	a	96	a	119	a	64	A

4 Conclusions

Long-term continuous cropping research showed the benefits of leaving wheat as standing stubble after harvest compared to stubble incorporation by tillage. The benefits include less tillage and fuel use and better wheat yields during dry winter years.

A winter oat cover crop may not be a suitable break crop for a system planted with cotton every summer. The gross margin/ML of water is always higher for the cotton-wheat system; however, the gross margin/ha is higher for cotton monoculture over the long term.

Future research needs to focus on additional rotation crops that can alleviate soil compaction and improve the soil organic carbon and productivity of the cropping systems.

Acknowledgements

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References

Hulugalle, N.R., Scott, F., 2008. A review of the changes in soil quality and profitability accomplished by sowing rotation crops after cotton in Australian Vertosols from 1970 to 2006. 46, 173-190.

Hulugalle, N.R., Weaver, T.B., Finlay, L.A., 2010. Soil water storage and drainage under cotton-based cropping systems in a furrow-irrigated Vertisol. 97, 1703-1710.

Hulugalle, N.R., Weaver, T.B., Finlay, L.A., 2013. Soil water storage, drainage, and leaching in four irrigated cotton-based cropping systems sown in a Vertosol with subsoil sodicity. 50, 652-663.

Isbell RF, N.C.o.S.a.T., 2021. The Australian Soil Classification, 3rd edn., 3rd ed. CSIRO Publishing, Melbourne.

Longpaddock, 2020. SILO - Australian climate data from 1889 to yesterday Queensland Government

Nachimuthu, G., Hulugalle, N.R., Watkins, M.D., Scott, F., Rollins, M., 2017. Resilient cotton-farming systems in irrigated Vertosols: soil quality, carbon and nutrient losses, cotton growth and yield in long-term studies. NSW Department of Primary Industries and Cotton Research and Development Corporation, Narrabri, Australia, p. 100.

Rayment, G.E., Lyons, D.J., 2011. Soil Chemical Methods - Australasia. CSIRO publishing, Australia.

Rochester, I.J., 2011. Sequestering carbon in minimum-tilled clay soils used for irrigated cotton and grain production. 112, 1-7.

Soil Survey Staff, 2010. Keys to Soil Taxonomy, 11th ed. Natural Resources Conservation Service of the United States Department of Agriculture: Washington, DC.

Chapter 5: Field D1 trial economic results and analysis

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Key messages

- For the 2 year period winter 2019 and summer 2020/21, continuous cotton (T2) returned the highest gross margin of $4,960/ha. The total gross margin per ha for the rest of the treatments ranged between $2,971/ha for T3a and $4,640/ha for T1.
- Gross margins for treatments varied across all treatments due to variations in yield, variable costs, and crop sequences. However, continuous cotton (T2) consistently returned the highest average gross margin per hectare, between 8% and 38% higher than the gross margin for other treatments.
- The gross margin performances of cotton-wheat rotations were higher than the rest of treatments.
- When water is the limiting factor, T4 (cotton-wheat-vetch) returned the highest gross margin per ML.

1 Introduction

This report presents the gross margin analysis for the results of the ACRI Field D1cotton trial conducted in Narrabri from winter 2019 to summer 2020/21 cropping seasons. The gross margin for the treatments that were compared within the D1 trial were:

T1 = Cotton-oats-cotton-oats (C-O-C-O), after 2013 oats was substituted for vetch.

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)

Also Treatment 5 was introduced to test chickpea in the rotation, it was split from T4b, with chickpea to be grown instead of wheat.

The type of budget used in this analysis is gross margin. A gross margin is the gross income from an enterprise less the variable costs incurred in achieving it. Variable costs are those costs directly attributable to an enterprise and which vary in proportion to the size of an enterprise. For example, if the area of cotton sown doubles, then the variable costs associated with growing it, such as seed, chemicals, and fertilisers, will also roughly double.

The gross margins reported here are not the same as gross profit, because they do not include overhead costs such as depreciation, interest payments, rates, or permanent labour which have to be met regardless of enterprise size. While simple gross margin analyses are useful at the enterprise scale, invariably a more thorough analysis at the whole farm scale is required to assess financial impacts of different cropping rotations over a longer period.

For the purpose of this analysis, commodity prices and input costs are kept constant across years to avoid confounding the treatment results with the impact of price variability. Gross margin (GM) results were calculated using the following long-term average prices;

- cotton lint price of $450 per bale,
- cotton seed price of $170 per tonne
- chickpea price of $500 per tonne

- wheat price of $295 per tonne for 14% protein (ex-farm) and
- estimated costs for the actual operations conducted on each treatment, including fallow costs. Prices are kept the same across the years to avoid confounding the treatment results with commodity price variability. Results are presented on both gross margin per hectare (GM/ha) and gross margin per megalitre (GM/ML) basis.

Gross margin for one hectare of cotton assumed gross margin for the associated refuge crop. In the 2019 and 2020-21 seasons, Bollgard® 3 varieties were planted with unsprayed conventional cotton grown as the refuge. For every hectare of Bollgard® 3 cotton grown, there was 0.025 hectare of unsprayed cotton for refuge. Therefore, in the gross margin comparison of one hectare of cotton is 97.5% Bollgard® 3 and 2.5% unsprayed conventional cotton. The yields shown are the full yield/ha for the Bollgard® 3 cotton, but the income, costs and gross margins reported are all 97.5% Bollgard® 3 and 2.5% refuge crop when cotton is grown.

2 Results

Winter 2019 season

In winter 2019, T3a and T4a were sown to wheat. The wheat yields for T3a and T4a were very low, the oats sown in T1 was sprayed out and green manured. The rest of the treatments were fallowed with little or no operations (Table 5.1).

Table 5.1: Winter 2019 season results

	T1	T2	T3a	T3b	T4a	T4b	T5
2019	C-O-C-O	C-F-C-F	C-W-F-F	F-F-C-W	C-W-F-V	F-V-C-W	F-V-C-W
Crop	*oats*	*fallow*	*wheat*	*fallow*	*wheat*	*fallow*	*fallow*
Yield (t/ha)			0.53		0.98		
Protein %			0.16		0.16		
Screenings %			21.00		21.00		
Water use (ML/ha)	1.00		1.00		1.00		
Income ($/ha)			129		239		
Variable cost ($/ha)	279	11	387		328		
Gross margin ($/ha)	- 279	- 11	- 258		-89		
Gross Margin (ML)	-279		-258		- 89		

Summer 2019-20 season

The summer 2019-20 season saw all treatments grow cotton crop except T3a and T2a which were fallowed after growing wheat in the winter 2019. Since all cotton treatments were applied with the same amount of water (6 ML/ha), any differences GM/ML were derived directly from the differences in yield, variable costs and crop sequences (Table 5.2). The wheat rotation treatments returned higher cotton yields than the continuous cotton (T2) or cotton-oats treatment (T1).

Table 5.2: Summer 2019-20 season results

	T1	T2	T3a	T3b	T4a	T4b	T5
	C-O-C-O	C-F-C-F	C-W-F-F	F-F-C-W	C-W-F-V	F-V-C-W	F-V-C-W
Crop	*cotton*	*cotton*	*fallow*	*cotton*	*fallow*	*cotton*	*cotton*
Lint yield (Bales/ha)	11.01	10.93		13.03		13.03	13.03
Seed yield (t/ha)	2.41	1.30		3.06		3.06	3.06
Water use (ML/ha)	6	6		6		6	6
Income ($/ha)	5,230	5,062	-	6,224		6,224	6,224
Variable costs ($/ha)	3,224	3,221	-	3,410	0	3,408	3,408
Gross Margin ($/ha)	2,007	1,841	-	2,814	-	2,816	2,816
Gross Margin ($/ML)	334	307		469		469	469

T3b, T4b and T5 treatments returned about 2 bales/ha higher yield than T1 and T2. This resulted in a higher gross margin for these treatments and hence the highest gross margin per ML.

Winter 2019 and summer 2019-20 seasons

The results for winter 2019 and summer 2019-20 seasons show all treatments with fallow/cotton treatment returned gross margin per ML ranging from $305/ML to $469/ML (Table 5.3). Gross margin per ML for T4b and T5 were equal since T4b was split to form T5 to assess the inclusion of chickpea in the rotation in the following winter.

Table 5.3: Winter 2019 and summer 2019/20 seasons results

	T1	T2	T3a	T3b	T4a	T4b	T5
2019 & 2019/20	C-V-C-V	C-F-C-F	C-W-F-F	F-F-C-W	C-W-F-V	F-V-C-W	F-V-C-Cp
Crop	*oats/cotton*	*fallow/cotton*	*wheat/fallow*	*fallow/cotton*	*wheat/fallow*	*fallow/cotton*	*fallow/cotton*

Water use (ML/ha)	7.0	6.0	1.0	6.0	1.0	6.0	6.0
Income ($/ha)	5,230	5,062	129	6,224	239	6,224	6,224
Variable Costs ($/ha)	3,503	3,232	387	3,410	328	3,408	3,408
Gross margin ($/ha)	1,727	1,830	-258	2,814	-89	2,816	2,816
Gross margin $/ML	247	305	-258	469	-89	469	469

The T3a and T3b phases of the wheat/fallow treatments returned negative gross margin per ha due to not having a cotton crop (Figure 5.1).

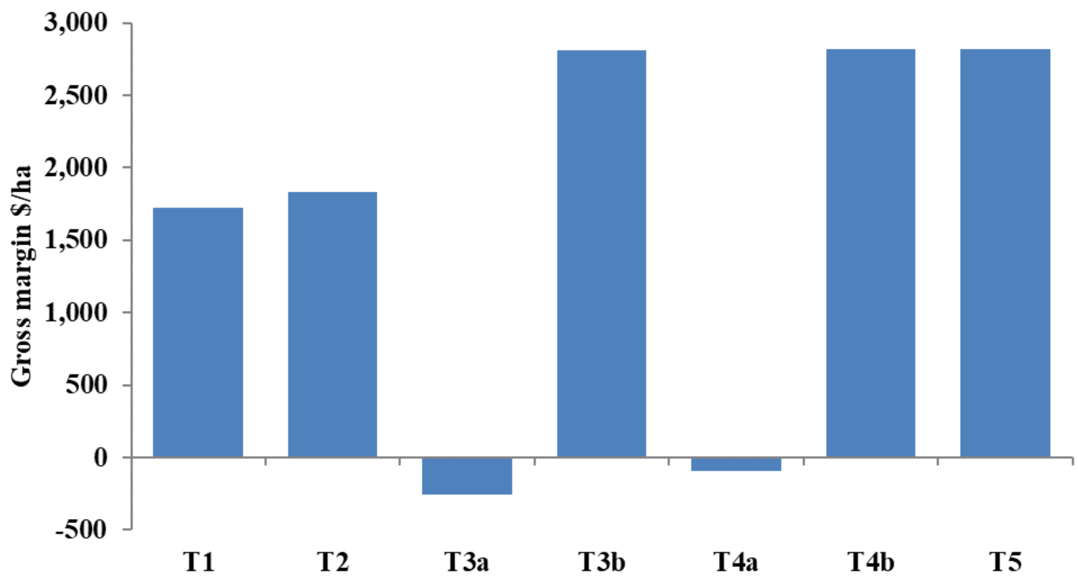

Figure 5.1: Winter 2019 and summer 2019/20

Winter 2020 season

In winter 2020 cropping season, the "b" phases of Treatments 3 and 4 were sown to wheat but Treatments T1 and T5 were sown to oats and chickpea respectively Table 5.4. The oats crop was green manured by spraying and slashing and therefore not harvested. The treatments sown to crops were irrigated and fallow treatments were treated with herbicide and/or cultivation.

The retained stubble treatment (T4b) returned the highest wheat yield. But T5 returned the highest gross margin ($721/ML) due to the high value assumed for chickpeas.

Table 5.4: Winter 2020 season results

	T1	T2	T3a	T3b	T4a	T4b	T5
2020	C-V-C-V	C-F-C-F	C-W-F-F	F-F-C-W	C-W-F-V	F-V-C-W	F-V-C-Cp
Crop	*oats*	*fallow*	*fallow*	*wheat*	*fallow*	*wheat*	*chickpea*
Yield (t/ha)				3.62		3.78	2.0
Protein %				14.0%		14.8%	23.1%
Water use (ML /ha)	1.0			1.0		1.0	1.0
Income ($/ha)				865		903	975
Variable costs ($/ha)	414	48	15	224	15	227	254
Gross margin ($/ha)	-414	-48	-15	641	-15	676	721
Gross Margin ($/ML)	-414			641		676	721

Summer 2020-21 season

In the summer 2020-21 season four treatments were sown to cotton crops and three treatments were left fallow following the winter 2021 season sown to wheat and chickpea (Table 5.5). All treatments sown to cotton crop returned gross margin per ML between $530 and $566 per MLT4a returned the highest gross margin per ha and per ML ($3,395 /ha and $566/ML).

Table 5.5: Summer 2020-21 season results

	T1	T2	T3a	T3b	T4a	T4b	T5
2020/21	C-V-C-V	C-F-C-F	C-W-F-F	F-F-C-W	C-W-F-V	F-V-C-W	F-V-C-Cp
Crop	*oats/ cotton*	*fallow/ cotton*	*fallow/ cotton*	*wheat/ fallow*	*fallow/ cotton*	*wheat/ fallow*	*chickpea/ fallow*
Lint Yield (Bales/ha)	11.98	11.28	11.98		12.39		
Seed yield (t/ha)	3.20	3.12	3.03		2.80		
Water use (ML/ha)	6.00	6.00	6.00		5.90		
Income ($/ha)	5,787	5,326	5,758	-	5,900	-	-

Variable cost ($/ha)	2,461	2,147	2,514	46	2,505	30	30
Gross margin ($/ha)	3,326	3,179	3,244	-46	3,395	- 30	- 30
Gross margin ($/ML)	554	530	541		566		

Winter 2020 and summer 2020-21 seasons

The results for winter 2020 and summer 2020-21 seasons are reported in (Table 5.6). Gross margin per ML varied from $416 per ML with T1and $721 per ML with T5. Gross margins for treatments with wheat were higher than continuous cotton rotation and treatment with green-manured oats which consistently returned the lowest gross margins.

Table 5.6: Winter 2020 and summer 2020-21 seasons results

	T1	**T2**	**T3a**	**T3b**	**T4a**	**T4b**	**T5**
	C-O-C-O	C-F-C-F	C-W-F-F	F-F-C-W	C-W-F-V	F-V-C-W	F-V-C-Cp
Crop	*oats/ cotton*	*fallow/ cotton*	*Fallow /cotton*	*wheat/ fallow*	*fallow/ cotton*	*wheat/ fallow*	*chickpea/ fallow*
Water use (ML/ha)	7.0	6.0	6.0	1.0	6.0	1.0	1.0
Income ($/ha)	5,787	5,326	5,758	865	5,900	903	975
Variable cost ($/ha)	2,874	2,195	2,529	271	2,520	257	254
Gross margin ($/ha)	2,913	3,131	3,229	595	3,380	646	721
Gross margin $/ML	416	522	538	595	563	646	721

Figure 5.2 shows the GM/ha and GM/ML for individual treatments with Treatments T3 and T4 averaged. Treatment T3a returned the highest GM/ha and the GM/ha for Treatments T3a, T4b and T5 were the lowest.

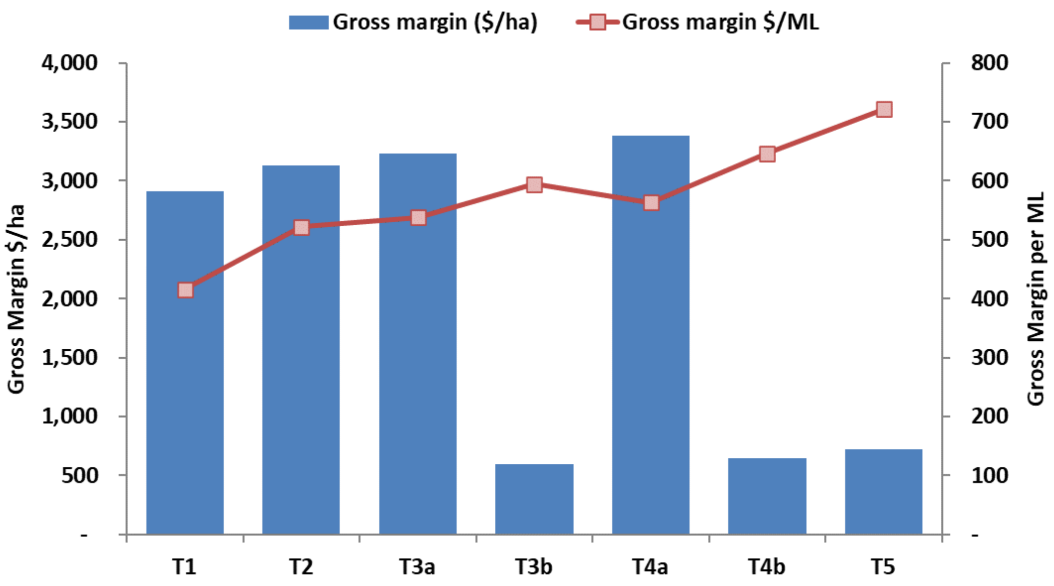

Figure 5.2: Winter 2020 and summer 2020-21 reasons

Two-year total results

Total gross margin per hectare for the full winter 2019 and summer 2020-2021 seasons varied between $2,971with T3a and $4,960 with T2 (Table 5.7).

Table 5.7: Winter 2019 to summer 2020/21 season results (2 years)

	T1	T2	T3a	T3b	T4a	T4b	T5
Crop	C-V-C-V	C-F-C-F	C-W-F-F	F-F-C-W	C-W-F-V	F-V-C-W	F-V-C-Cp
Water use (ML/ha)	14	12	7	7	7	7	7
Income ($/ha)	11,017	10,388	5,888	7,089	6,139	7,128	7,199
Variable cost ($/ha)	6,377	5,428	2,917	3,680	2,849	3,665	3,662
Gross margin ($/ha)	4,640	4,960	2,971	3,409	3,290	3,462	3,537
Gross margin $/ML	331	413	424	487	470	495	505

However, gross margin per ML varied from $331 with T1 and $505 for T5 (Figure 5.3).

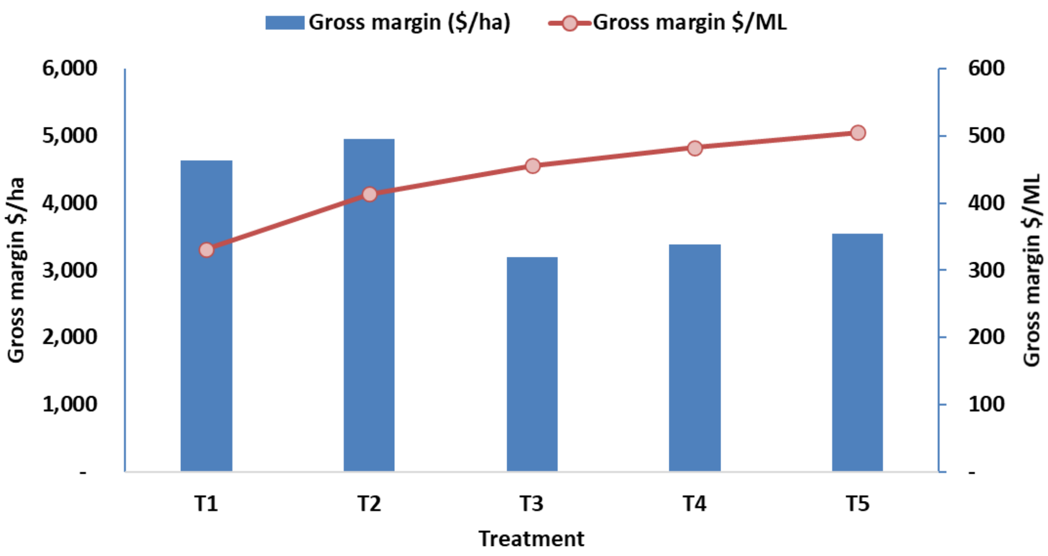

Figure 5.3: Winter 2020 and summer 2020-2021 results

Cotton-vetch-cotton-chickpea treatment (T5) returned the highest gross margin per ML for the two full year results. The difference in GM/ML was largely due to the total amount of water used.

Cumulative results (2003 to 2021)

Cotton-vetch-cotton-chickpea treatment (T5) returned the highest gross margin per ML for the two full year results. Continuous cotton (T2) returned the highest cumulative gross margin of $37,093 in the entire period of 18 years (Table 5.8), followed by continuous cotton vetch treatment (T1), with a total gross margin of $33, 291.

Table 5.8: Total gross margins from 2003 to 2021

	T1	T2	T3	T4	T5
Cotton years (no)	18	18	9	9	9
Water use (ML/ha)	135	130	83	73	83
Income	78,622	77,971	49,713	52,339	48,625
Variable costs	44,651	40,878	25,335	25,177	25,772
Total gross margin ($)	33,971	37,093	24,378	27,162	22,854
Gross margin/ha/year	1,887	2,061	1,354	1,509	1,270
Gross margin $/ML	252	289	292	371	274
GM/ML Difference to T2	-13%		1%	28%	-5%

Gross margin per ha per year varied from $1,270 for T5 and $2,061 for T2. In comparison to T2, other treatments returned less gross margin per hectare per year in the range of 8% with T1 to 38% with T5 (Figure 5.4). The per centage differences in across treatments show that when land is limiting, T2 returns the highest gross margin per hectare. But when water is limiting T4 returned the highest gross margin per ML.

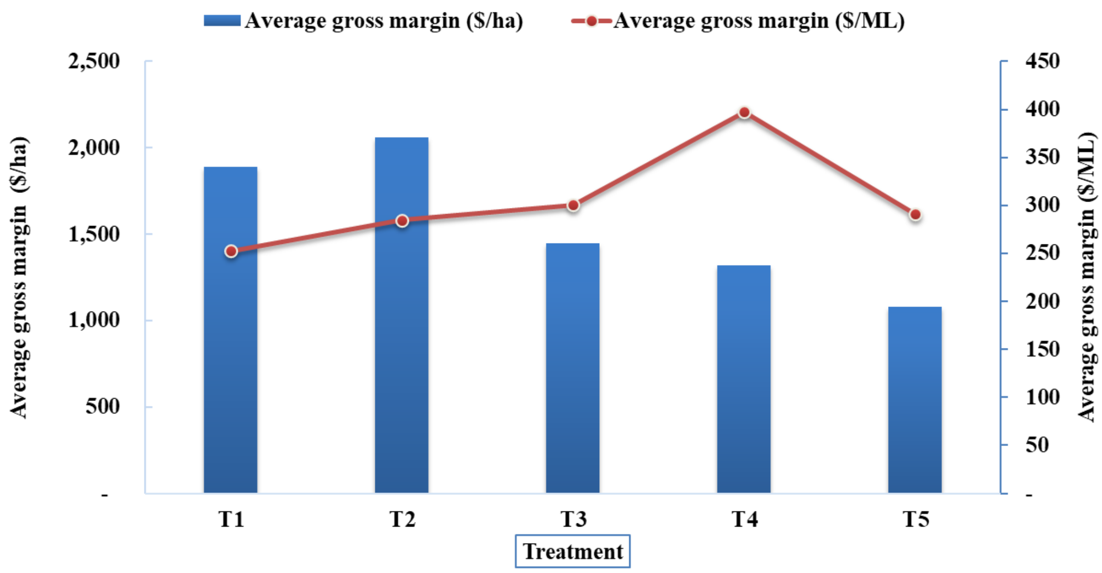

Figure 5.4: Average gross margin $/ha/year

However, T3 and T4 performed better than T2 in terms of gross margin Per ML since T2 used relatively higher amount of irrigated water. Hence, T4 returned an estimated 28% higher gross margin per ML as compared with T2.

Figure 5.5 shows the cumulative gross margins for each treatment since 2003. T5 is showing as separate since it was the same as the ‘b’ phase of T4 until winter 2020 where T4 was split to form T5 which as then sown with chickpea.

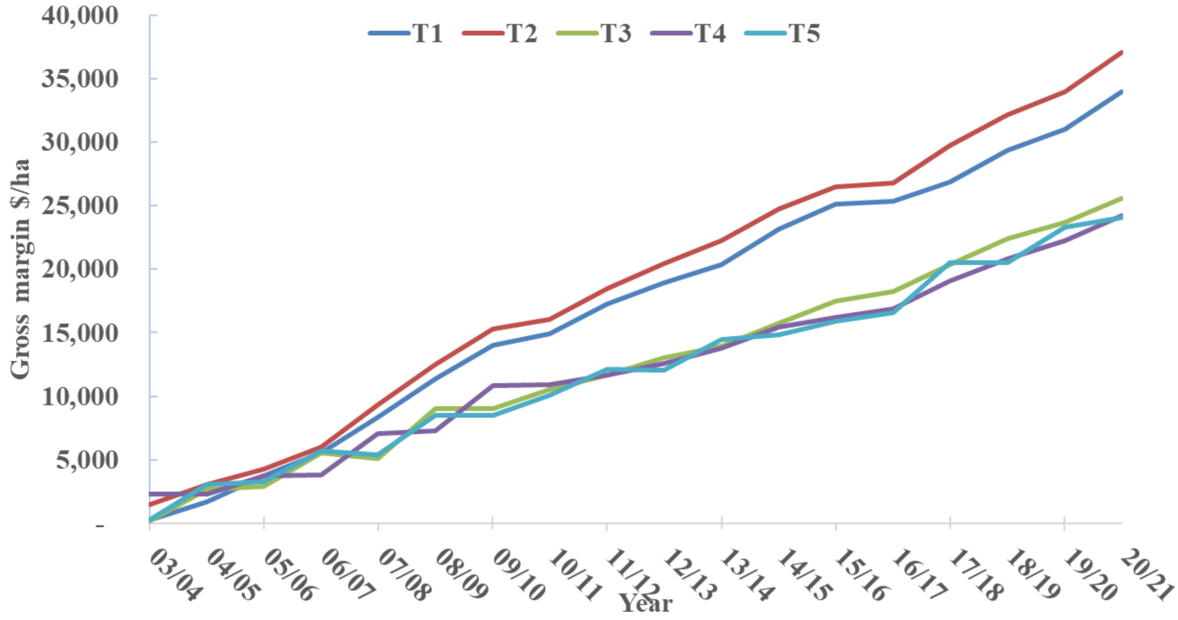

Figure 5.5: Cumulative gross margin 2004 to 2021

In terms of average return on variable costs (Figure 5.6), the T3 (cotton-wheat) returned a higher annual gross margin per dollar of variable costs than T4. The two continuous cotton rotations were the highest cost but also gave the highest gross margin returns. The dominant rotations, that performed the best (in terms of $/ha) for the costs invested in them, were T3 and T2. T5 has been left out for now since it was recently split from T4b to include chickpeas and hasn't completed a full rotation cycle, with cotton to be grown after chickpea still to be done.

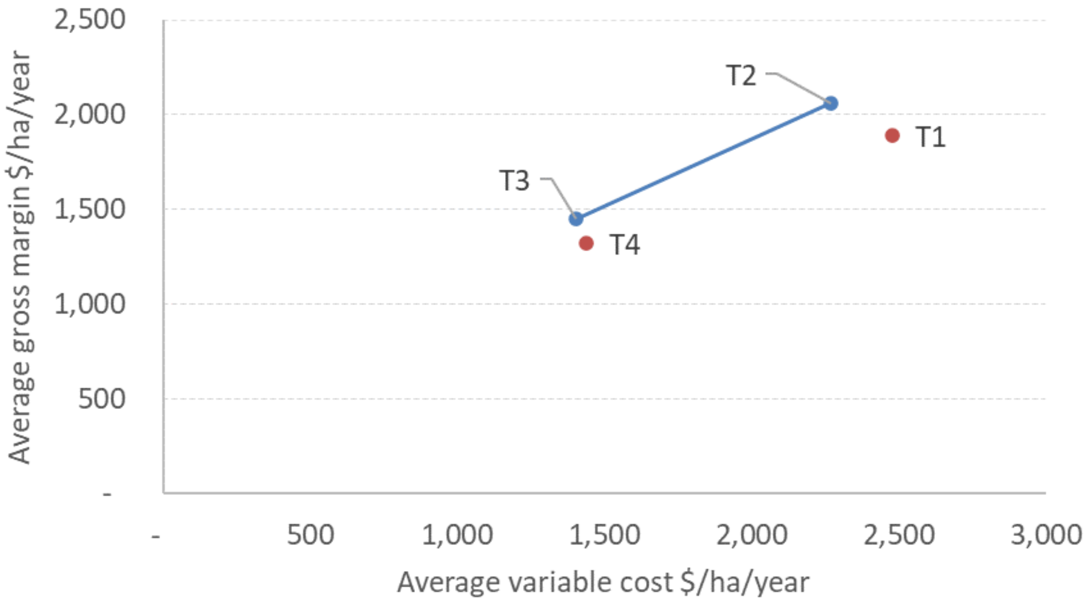

Figure 5.6: Return on variable costs

3 Conclusion

Gross margin per hectare and ML varied across all treatments due to variation in yield, water use and crop sequence. However, continuous cotton (T2) consistently performed better than other treatments by about 8% with T2. The performances of cotton-wheat rotations were higher other treatments. When water is the limiting factor, T4 returned the highest gross margin per ML.

Chapter 6: Legacy effect of method and timing of phosphorus application on cotton lint yield and biomass

Key findings

- There was a cotton lint yield response to P fertiliser when applied before an oats cover crop
- There was no legacy effect of applied P on cotton lint yield beyond the season of application

1 Introduction

Phosphorus (P) is a key nutrient in irrigated cotton production, with large amounts needed in available form to achieve the yield potential of cotton when all other plant needs are met and no constraints to production exist (Constable and Bange, 2015; Schwab et al., 2000). Recent research where P fertiliser was mixed throughout the plant bed showed an increase in lint yield in soils with Colwell P above the critical level typically recommended for a lint yield response (Dorahy et al., 2004; Nachimuthu et al., 2018). Cotton responses to P application vary, with different critical P levels reported in the literature (Bronson et al., 2001; Crozier et al., 2004). However, there is limited research on lint yield responses beyond the season of application. This study examined the yield response over two sucessive seasons to P fertiliser added to an oats cover crop before the first cotton crop.

2 Methods

The experimental site is located on an alluvial floodplain in the lower Namoi valley—Field D1 at the Australian Cotton Research Institute (ACRI) (30°11’42.98”S 149°36’52.86”E). The field has an area of 4.53ha, is 170 meters long. The P experiment was superimposed onto a cover crop rotation treatment within a long-term tillage rotation experiment (Oats/Cotton/Oats) with three replications. The soil is a deep uniform self-mulching grey clay (Isbell RF, 2021) and is classified as a fine, thermic, smectitic, Typic Haplustert (Soil Survey Staff, 2010). The mean annual rainfall for the region between 1993 and 2020 was 618 mm (Longpaddock, 2020). The area has a semi-arid climate and experiences four distinct seasons with a mild winter and a hot summer. The mean particle size distribution at 0–1.2 m depth was (per 100 g soil): 64 g clay, 11 g silt, and 25 g sand. Exchangeable sodium percentage (ESP) at 0-0.6m and 0.6–1.2 m depths were 4 and 12 respectively.

In September 2015, 6 cores were collected to 120 cm from across the paddock. Each set of two cores (head ditch and tail drain ends) were composited by depth before analysis. The data in Table 6.1 is an average of three composite samples.

Field D1 is a long-term rotation and selected plots from this field that were used for the 2019-22 experiment formed part of a cotton-oats-cotton rotation. The field crop operations from 2018-19 to 2020-21 were described in Schwenke et al 2021. During 2021-22, we examined the legacy effect of the previous year’s P fertiliser timing and method of application treatments. The experiment consisted of eight treatments replicated three times in a strip-plot design:

- P banded before oats
- P banded before cotton
- Banding control oats (no P applied, but equipment used for banding passed through these plots)
- P banded control cotton (no P applied, but equipment used for banding passed through these plots)
- P incorporated (mixed) before oats
- P incorporated (mixed) before cotton

- Incorporated control oats (no P applied, but operations used to apply and mix P were conducted)
- Incorporated control cotton (no P applied, but operations used to apply and mix P were conducted)

Planting of cotton (Var Sicot 748 B3F) occurred in late October 2021. The crops were irrigated by furrow irrigation systems with siphons @ 1ML/ha (~100 mm) if the rainfall was insufficient to meet the evapotranspiration demand. After cotton picking, the cotton was slashed and incorporated into the beds with a disc-hiller. Land preparation was minimum tillage (permanent beds) with tillage operations (disc-hilling) restricted to the bed after cotton picking. The oats cover crops were irrigated, although the requirement for supplemental watering was minimal during winter and spring. The oats were sprayed out in September, prior to maturity and cotton was sown directly into the oat stubble in October/November each year.

Table 6.1 - Baseline soil characteristics of experimental plots within Field D1,

Analyte	**0-10 cm**	**10-30 cm**	**30-60 cm**	**60-120 cm**
Soil pH_{CaCl2}	7.36	7.43	7.45	7.53
Soil pH_{water}	7.75	8.09	8.30	8.32
Electrical conductivity	157	154	216	276
Soil OC (g/100 g)	0.85	0.84	0.38	0.32
Exchangeable Ca (cmol (+)/kg)	18.33	18.67	16.33	14.00
Exchangeable Mg (cmol (+)/kg)	10.30	11.33	12.33	13.00
Exchangeable Na (cmol (+)/kg)	0.86	1.37	2.73	3.93
Exchangeable K (cmol (+)/kg)	0.88	0.63	0.55	0.57
Sodicity (Exchangeable Sodium %)	2.8	4.3	8.5	12.4
Colwell P (mg/kg)	24.6	14.4	15.4	
BSES P (mg/kg)	185	172	181	
Solution P (mg/kg)	0.103	0.045	0.061	
Clay (%) (mean particle size 0-1m)	64			
Silt (%) (mean particle size 0-1m)	11			
Sand (%) (mean particle size 0-1m)	25			

*- results are from 2002 samples

Cotton growth parameters were monitored periodically to assess the vegetative growth rate (data not presented). Plant biomass samples were taken from 1 m^2 per plot from late March to early April by taking whole shoot and bolls samples which were dried at 60^o C until constant weight and the final dry biomass was recorded. Disease incidence was recorded in the 2021-22 season by counting the number of plants with visual infection symptoms per square metre and reported as a percentage of total plants sampled.

Cotton was handpicked from 1 m^2 per plot for yield estimation. A sub-sample of cotton was ginned to calculate the lint and seed turnout.

All the statistical analysis was carried out using Genstat 18.2 (*VSN International Ltd*). Analysis of variance using a three-way factorial randomised block design with method, timing and fertiliser as three factors.

3 Results and discussion

Cotton lint yield results from 2020-21 and 2021-22 are summarised in Table 6.2 and Table 6.3. Application of P fertiliser before oats cover crop resulted in better lint yield than applying P before cotton in the 2020-21 season (Table 6.2). However, this applied P did not have any further impact on cotton yield in the subsequent season (2021-22) (Table 6.3). A previous trial within the same field also demonstrated there was no legacy effect of applied P on cotton lint yield (Schwenke et al., 2021). Although mixing the P fertiliser throughout the beds resulted in higher cotton total dry matter (Figure 6.1), there was no effect of the method of P application on cotton lint yield.

Table 6.2. Effect of timing of phosphorus (P) application on cotton lint yield during the 2020-21 season (bales/ha)

Treatments	- P	+ P
Before Cotton	9.27	9.11
Before Oats	8.68	10.13
LSD ($P<0.10$) for Method* Timing		0.99

Table 6.3. Legacy effect of previous season phosphorus application on cotton lint yield (bales/ha) during the 2021-22 season

Treatments	-P before cotton	+P before cotton	-P before Oats	+P before Oats
P Banded	13.06	9.38	11.50	10.15
P Mixed	10.89	10.38	12.34	9.66
All factors and their interactions are not significant				

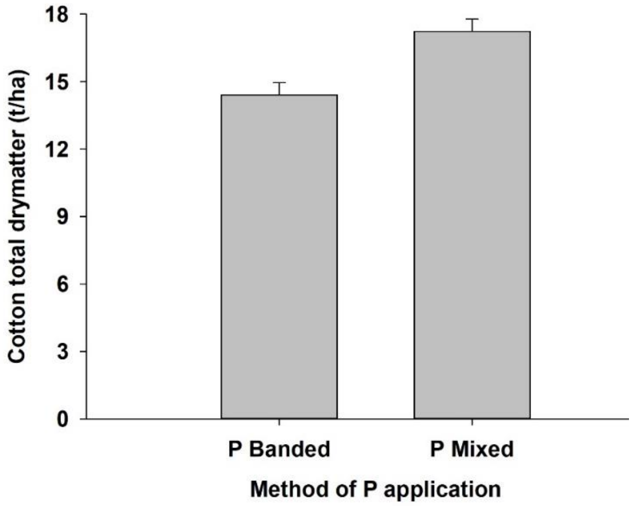

Figure 6.1. Legacy effect method of P application on cotton plant dry matter (t/ha)

As there was no legacy effect of applied P on agronomic parameters other than dry matter, we presented the average values across all the plots. The average plant height, the number of nodes and disease incidence were 81 cm, 22.5 nodes and 37% respectively.

The soil Colwell P levels were 25 mg/kg in the topsoil (0-10 cm) and 14 mg/kg in the subsoil (10-30 cm). The BSES P (Table 6.1) is a slowly available source of P in the soil that replenishes the Colwell P when the plant uptake is not matched by fertiliser input. However, in this soil, there has been long-term mining of P by the continuous cropping, i.e. P export in cotton seed and grain has not been replaced by fertiliser inputs. As a result, newly applied P may be adsorbed or fixed to slowly available P pool thus preventing any legacy effect of applied P. Future research needs to quantify the amount of applied P moving into BSES P pool to improve the understanding of P dynamics in the cotton growing soils and the response of applied P to cotton.

4 Conclusions

There was a lint yield response to P applied before the oats cover crop. However, there was no legacy effect of applied P on cotton lint yield in the subsequent season. In order to better understand the response of cotton plants to applied P fertiliser, future research needs to quantify the movement of applied P to the slowly available BSES P pool in the soil.

Acknowledgements

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References

Bronson, K.F., Onken, A.B., Booker, J.D., Lascano, R.J., Provin, T.L., Torbert, H.A., 2001. Irrigated cotton lint yields as affected by phosphorus fertilizer and landscape position. 32, 1959-1967.

Constable, G.A., Bange, M.P., 2015. The yield potential of cotton (Gossypium hirsutum L.). 182, 98-106.

Crozier, C., Walls, B., Hardy, D., Steven, J., 2004. Agronomy and soils: Response of cotton to P and K soil fertility gradients in North Carolina. 8.

Dorahy, C.G., Rochester, I.J., Blair, G.J., 2004. Response of field-grown cotton (Gossypium hirsutum L.) to phosphorus fertilisation on alkaline soils in eastern Australia. 42, 913-920.

Isbell RF, N.C.o.S.a.T., 2021. The Australian Soil Classification, 3rd edn., 3rd ed. CSIRO Publishing, Melbourne.

Longpaddock, 2020. SILO - Australian climate data from 1889 to yesterday Queensland Government

Nachimuthu, G., Schwenke, G., Baird, J., Mercer, C., Bell, M., Guppy, C., 2018. Improving Phosphorus Management in Cotton, The 2018 Australian Cotton Confernece.

Schwab, G., Mullins, G., Burmester, C., 2000. Growth and nutrient uptake by cotton roots under field conditions. 31, 149-164.

Schwenke, G., Nachimuthu, G., Baird, J., Mercer, C., Macdonald, B.C.T., Bell, M., Bischof, C., Bai, M., Suter, H., 2021. More Profit from Nitrogen: Enhancing nutrient use efficiency in cotton. Cotton Research and Development Corporation and Federal Deaprtment of Agriculture, Water and Environment, p. 373.

Soil Survey Staff, 2010. Keys to Soil Taxonomy, 11th ed. Natural Resources Conservation Service of the United States Department of Agriculture: Washington, DC.

Chapter 7: Is there a legacy effect of maize rotation on cotton yield under maximum and minimum tillage?

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Key findings

- Maize rotation did not enhance cotton total drymatter or cotton lint yield over four years from 2018–19 to 2021–22
- There was a legacy effect of maize rotation on disease incidence. Verticillium wilt disease was lower after maize, even after four seasons since last planted
- Minimum-till cotton-wheat system yielded higher than cotton monoculture (averaged over minimum and maximum tillage)
- Crop resilience and recovery was better in the minimum tillage system
- The legacy effect of maize in the rotation on microbial catabolic properties varied in the different tillage and cropping system treatments.

1 Introduction

Wheat is the most popular rotation crop in Australian cotton production systems (Hulugalle and Scott, 2008), but cotton growers are increasingly looking to diversify their cropping enterprise with other crop options. Recent research reported the yield benefits of maize rotation in a two-crop sequence. There were only marginal yield benefits in a cotton-wheat-maize rotation (Hulugalle et al., 2020), although water infiltration was increased and reduced runoff (Nachimuthu et al., 2018). In addition, maize rotation is reported to improve the soil organic carbon (Osanai et al., 2020) but made it less resilient to structural degradation (Hulugalle et al., 2020). The gross margin from cotton is four times higher than the gross margin from maize (Nachimuthu et al., 2017). Therefore, maize needs a legacy benefit to justify the forgoing of profits by growing it compared to continuous cotton. This field experiment was conducted to investigate the legacy benefits of maize rotation on cotton productivity and gross margins under conventional and minimum tillage systems.

2 Methods

The experiment was conducted at the Australian Cotton Research Institute (ACRI) near Narrabri. (149^{0}47′E, 30^{0}13′S) in New South Wales (NSW), Australia. The soil is a deep uniform self-mulching grey clay (Isbell RF, 2021) and is classified as a fine, thermic, smectitic, Typic Haplustert (Soil Survey Staff, 2010). The mean annual rainfall for the region between 1993 and 2020 was 618 mm (Longpaddock, 2020) and the area has a semi-arid climate and experiences four distinct seasons with a mild winter and a hot summer. The soil in the experimental field is alkaline (average pH in 0.01 M $CaCl_2$ is 7.4 in the 0–0.3m depth) and non-saline (average electrical conductivity ($EC_{1:5}$) is 0.11 dS/m in the 0–0.3 m depth). The exchangeable cation concentrations are 17, 8.8, 1.13 and 0.56 cmol (+)/kg of calcium, magnesium, potassium and sodium respectively, and the exchangeable sodium percentage (ESP) is 2.2 at 0–0.3m. Particle size distribution in the 0–0.3m depth is 53 g 100^{-1} g clay (<2 µm), 21 g 100^{-1} g silt (2–20 µm) and 26 g/100 g sand (20 µm–2 mm).

This experiment was initiated in 1985 with three cropping systems; viz. cotton monoculture sown after either maximum or minimum tillage, and a minimum-tilled cotton-wheat rotation (Constable et al., 1992). Maximum tillage consists of slashing of cotton plants after harvest, followed by disc-ploughing and incorporation of cotton stalks to 0.2 m, chisel ploughing to 0.3m followed by 1-m bed construction and minimum tillage, slashing of cotton plants after harvest, followed by root cutting, incorporation of cotton stalks into beds, and bed renovation with a disc-hiller. Conventional cotton was sown until 1999, “Round-up Ready” cotton from 2000 to 2006, and “Bollgard-Roundup Ready Flex®” varieties thereafter. In 2014–15, “Bollgard-Liberty Link®” (Variety-Sicot 70 BL) was planted @ 18 kg/ha. The field has a slope of 0.1% from the head end to the tail end. The experiment was re-designed in 2011 to include maize. All the historical plots were considered as main plots and were split by either sowing a maize (*Zea mays* L.) crop during the summer following the previous year’s cotton or retaining the historical cropping system as a control. In the cotton-wheat system, maize was sown immediately after wheat.

The six treatments from 2011 included:

(1) maximum tillage cotton monoculture (MXT-CC),

(2) maximum tillage maize cotton (MXT-MC),

(3) minimum tillage cotton monoculture (MNT-CC),

(4) minimum tillage maize cotton (MNT-MC),

(5) minimum tillage cotton-wheat (MNT-CW) and

(6) minimum tillage cotton-wheat-maize (MNT-CWM).

The experimental design was a split-plot design where the historical tillage/rotation system combinations were designated as main plot treatments and +/- maize as sub-plots, replicated four times. The last maize crop was planted in the 2017–18 season and from the 2018–19 season, the three historical cropping systems were continued. However, the legacy effect of maize rotation is still being monitored and the data is presented for all six treatments.

The chronology of the experimental treatments from 2014 to 2017 was summarised in Table 1 of Nachimuthu et al. (2017). The chronology of the experimental treatments from 2017 to 2022 is summarised in Table 7.1 below.

Table 7.1 A comparative summary of treatment characteristics to evaluate the efficacy of sowing maize in rotation with cotton on cotton yield LTE at ACRI field C1*

Treatment	MXT-CC	MXT-MC	MNT-CC	MNT-MC	MNT-CW	MNT-CWM
Historical rotation (1985-2011)	**Cotton monoculture**	**Cotton monoculture**	**Cotton monoculture**	**Cotton monoculture**	**Cotton-Wheat (two year cycle)**	**Cotton-Wheat (two year cycle)**
Tillage	**Maximum (both beds and furrows)**	**Maximum (both beds and furrows)**	**Minimum (restricted to beds top 10 cm)**	**Minimum (restricted to beds top 10 cm)**	**Minimum (restricted to beds top 10 cm)**	**Minimum (restricted to beds top 10 cm)**
Crops planted in June 2017	Fallow	Fallow	Fallow	Fallow	Wheat	Wheat
Total N fertiliser applied	-	-	-	-	80 kg N/ha	80 kg N/ha
Winter crop harvest					Oct 2017	Oct 2017
Crops planted in Oct/Dec 2017	Cotton	Maize	Cotton	Maize	Wheat fallow	Maize

Total N fertiliser applied	260 kg N/ha	250 kg N/ha	260 kg N/ha	250 kg N/ha	-	250 kg N/ha
Harvest	April 2018	April 2018	April 2018	April 2018		April 2018
Tillage	August 2018	August 2018	August 2018	August 2018		August 2018
Crops planted in Nov 2018	Cotton	Cotton	Cotton	Cotton	Cotton	Cotton
Total N fertiliser applied	220 kg N/ha	220 kg N/ha	220 kg N/ha	220 kg N/ha	220 kg N/ha	220 kg N/ha
Harvest	May 2019	May 2019	May 2019	May 2019	May 2019	May 2019
Stalk puller, Tillage (25 cm) and laser levelling (top 5 cm)	June 2019	June 2019	June 2019	June 2019	June 2019	June 2019
Crop planted in July 2019	Wheat	Wheat	Wheat	Wheat	Wheat	Wheat
Total N fertiliser applied	90 kg N/ha	90 kg N/ha	90 kg N/ha	90 kg N/ha	90 kg N/ha	90 kg N/ha
Harvest	Sprayed as cover crop	Sprayed as cover crop	Sprayed as cover crop	Sprayed as cover crop	Nov 2019	Nov 2019
Crops planted in Oct 2019	Cotton	Cotton	Cotton	Cotton	Wheat fallow	Wheat fallow
Total fertiliser applied	240 kg N/ha	240 kg N/ha	240 kg N/ha	240 kg N/ha	-	-
Harvest	May 2020	May 2020	May 2020	May 2020	-	-
Tillage	Aug 2020	Aug 2020	Aug 2020	Aug 2020	Aug 2020	Aug 2020
Crops planted in Nov 2020	Cotton	Cotton	Cotton	Cotton	Cotton	Cotton
Total N fertiliser applied	180 kg N/ha	180 kg N/ha	180 kg N/ha	180 kg N/ha	180 kg N/ha	180 kg N/ha
Harvest and mulching	May/June 2021	May/June 2021	May/June 2021	May/June 2021	May/June 2021	May/June 2021
Tillage	August 2021	August 2021	August 2021	August 2021	July 2021	July 2021
Crops planted in July 2021	-	-	-	-	Wheat	Wheat
Total N fertiliser applied					60 kg N/ha	60 kg N/ha
Harvest					Dec 2021	Dec 2021
Crops planted in Oct 2021	Cotton	Cotton	Cotton	Cotton	-	-
Total N fertiliser applied	280 kg N/ha	280 kg N/ha	280 kg N/ha	280 kg N/ha	-	-
Harvest and mulching	May 2022	May 2022	May 2022	May 2022	-	-
Tillage	July 2022	July 2022	July 2022	July 2022	-	-

*This trial is a split-plot design with four replicates.

Cotton variety Sicot 746 B3F® was planted every summer in the respective treatments @ 15 kg/ha from 2016–17 to 2019–20 and in 2020–21 and 2021–22 seasons, Sicot 748B3F® was planted in all the plots.

All the crops in the rotation system were irrigated by furrow irrigation systems with siphons @ 1ML/ha (~100 mm) if the rainfall was insufficient to meet the evapotranspiration demand. Cotton was picked from late April to late June with a 4-row picker after defoliation in April/May. After cotton picking, the cotton was slashed and incorporated into the beds with a disc-hiller. Post-harvest operations or tillage were done as described earlier for minimum and maximum tillage. Herbicide was applied, if required, after assessing the weed population. Chipping of cotton volunteers occurred as required. Defoliation occurred from late March to early April every year when at least 60% of bolls had opened, and picking occurred during April/May/June with a mechanical four-row cotton picker. Between late March and early April, plant biomass samples were taken from 2 m^2 per plot by taking whole shoot samples and bolls samples. Samples were dried at 60^o C until constant weight and the final dry biomass recorded. Disease incidence was recorded in the 2021–22 season by counting the number of plants infected per square metre and reported as a percentage of total plants sampled. The final yield was estimated by harvesting the economic produce (cotton or wheat) in the middle 4 to 8 rows of each plot using a mechanical harvester and yield was reported on a tonnes per hectare basis. A sub-sample of cotton was ginned to calculate the lint and seed turnout. In 2021 and 2022, a hand harvest of 3 m^2 per plot was performed due to electronic faults with the picker scale.

Wheat (*cv.* Mustang or spitfire) was planted on raised beds during the 2017, 2019 and 2021 winters (June/July). Urea was applied to wheat as described in Table 7.1. The wheat was irrigated (100 mm per irrigation) when rainfall was insufficient to meet evaporative demand but was moderately stressed during the 2015 spring due to a shortfall in available water for irrigation. After the mechanical wheat harvest, maize was planted into standing wheat stubble. The control treatment was left fallow from harvest until October of the following year when cotton was planted.

Maize was planted @ 8 seeds m^{-2} or 20 kg ha^{-1} on raised beds during Dec 2017. Maize received fertiliser N at a rate of 250 kg N/ha as urea (surface applied prior to incrop irrigation in December 2017). Maize was irrigated at an average rate of 100 mm per irrigation with application frequency subject to rainfall and soil water content. It was harvested mechanically and then slashed to a height of 0.1 m. This was followed by a tractor-driven root cutter that cut the root system ~50 mm below the surface of the bed. Maize residues had partially decomposed by the time of cotton sowing, which occurred with no further tillage.

Visual soil assessment (Shepherd et al., 2008) was undertaken in every plot. The top 20 cm of soil were scored for soil texture, structure, colour, mottles, earthworms, rooting depth, surface ponding, crusting and surface cover, and soil erosion index using the method described in Shepherd, Stagnari et al. (2008). Each indicator was given a visual score of zero (poor), 1 (moderate) and 2 (good) based on the soil quality observed comparing the field guide manual. We also scored 0.5, and 1.5 if the indicators fell between two categories. Each score was then multiplied by a weighting factor according to the importance of that particular soil indicator. The soil quality index is an aggregated sum of the weighted indicators. Soil samples with a quality index of < 15 were classified as poor, 15–30 were classified as moderate and those with >30 were classified as good.

Soil samples (0-1.20 m at increments of 0.0-0.15, 0.15-0.30, 0.30-0.45, 0.45-0.60, 0.60-0.90, 0.90-1.20 m depth) were taken from all plots during September/October of each planting season and analysed for SOC using the Walkley and Black method (Rayment and Lyons, 2011). The results were presented for the 2018 and 2020 sampling in this report. A comparison of SOC measurement using the Walkley Black method and Mid-Infra-Red (MIR) technique (Hutengs et al., 2019) was undertaken for the topsoil (0-10 cm) samples in 2019. Samples were air-dried, ground and passed through a 0.2 mm sieve before scanning with MIR measurements. A subset of soil samples (0-10 cm) were transported with cool bricks to Adelaide before drying and were processed and analysed for microbial catabolic diversity (Gupta et al., 2019).

Soil pH (Soil: $CaCl_2$ =1:5) was measured monthly to look into changes in soil pH after flooding in late November early December 2021 in all the plots. Samples were taken in each plot (0-30 cm), composited, air dried and passed through 2 mm sieve before soil pH measurements.

Irrigation water and runoff water samples were collected during every irrigation and analysed for total organic carbon as described in Nachimuthu et al (2018). The total organic carbon loads were estimated using the irrigation water volume and runoff volume presented in Nachimuthu et al (2018). Irrigation-induced net carbon balance in terrestrial hydrological pathways was estimated.

All the statistical analysis was carried out using analysis of variance in Genstat 18.2 (*VSN International Ltd*), using a split-plot design with the historical cropping system as main plots and maize rotation as subplots.

3 Results and discussion

Cotton lint yield and total drymatter results are summarised in Table 7.2 and Table 7.3 respectively. Long-term historical cropping system influenced lint yield with the cotton-wheat system under minimum tillage yielding higher than cotton monoculture systems in 2018-19 and 2020-21 (Table 7.2). The long-term yield data from the cotton monoculture treatments showed that yields under minimum tillage were equal to or greater than those under maximum tillage (Figure 7.1). Minimum tillage requires less energy and therefore has a better environmental footprint.

Table 7.2. Effect of tillage and crop rotation on cotton lint yield (2017-18 to 2021-22 seasons)

<table>
<tr><th>Main plot</th><th>Maize (+/-)*</th><th>Treatment Code</th><th>2017-18 cotton yield</th><th>2018-19 cotton yield</th><th>2018-19 cotton yield</th><th>2019-20 cotton yield</th><th>2019-20 cotton yield</th><th>2020-21 cotton yield</th><th>2020-21 cotton yield</th><th>2021-22 cotton yield</th><th>2021-22 cotton yield</th></tr>
<tr><td rowspan="2">Minimum-tilled continuous cotton</td><td>-</td><td>MNT-CC</td><td>8.90</td><td>10.09</td><td rowspan="2">10.80</td><td>11.26</td><td rowspan="2">11.47</td><td>12.32</td><td rowspan="2">12.24</td><td>10.92</td><td rowspan="2">11.16</td></tr>
<tr><td>+</td><td>MNT-MC</td><td></td><td>11.51</td><td>11.68</td><td>12.17</td><td>11.39</td></tr>
<tr><td rowspan="2">Maximum-tilled continuous cotton</td><td>-</td><td>MXT-CC</td><td>9.80</td><td>11.65</td><td rowspan="2">11.55</td><td>10.75</td><td rowspan="2">10.68</td><td>12.16</td><td rowspan="2">12.33</td><td>9.97</td><td rowspan="2">9.87</td></tr>
<tr><td>+</td><td>MXT-MC</td><td></td><td>11.44</td><td>10.60</td><td>12.50</td><td>9.78</td></tr>
<tr><td rowspan="2">Minimum-tilled cotton-wheat</td><td>-</td><td>MNT-CW</td><td></td><td>12.83</td><td rowspan="2">12.69</td><td></td><td></td><td>14.01</td><td rowspan="2">13.93</td><td></td><td></td></tr>
<tr><td>+</td><td>MNT-CWM</td><td></td><td>12.55</td><td></td><td></td><td>13.84</td><td></td><td></td></tr>
<tr><td>LSD (P< 0.05)</td><td></td><td></td><td>0.892</td><td>1.208</td><td>1.164</td><td>NS</td><td>0.386</td><td>NS</td><td>1.510</td><td>NS</td><td>1.508</td></tr>
<tr><td rowspan="2">Overall sub treatment effect</td><td>Maize</td><td></td><td></td><td>11.83</td><td></td><td>11.14</td><td></td><td>12.83</td><td></td><td>10.58</td><td></td></tr>
<tr><td>Control</td><td></td><td></td><td>11.52</td><td></td><td>11.01</td><td></td><td>12.83</td><td></td><td>10.45</td><td></td></tr>
<tr><td>LSD</td><td></td><td></td><td></td><td>NS</td><td></td><td>NS</td><td></td><td>NS</td><td></td><td>NS</td><td></td></tr>
</table>

There was no legacy effect of maize rotation on cotton lint yield or cotton total drymatter from 2019-20 to 2021-22, whereas previous results had shown maize to benefit the first cotton crop following (Hulugalle et al., 2020). As land is not a limitation compared to water availability within a in Australian broadacre farm, continuing the maize rotation is likely to result in a positive impact on cotton yield over long term (Nachimuthu et al., 2017). The maize drymatter and yield within the three-crop (cotton-wheat-maize) systems were significantly lower than in the two-crop (maize-cotton) systems (Table 7.4). The lower maize yield following wheat was due to, (i) wheat stubble interfering with planting and resulting in a lower maize population, and (ii) immobilisation of soil and fertiliser N during the wheat stubble breakdown, resulting in less N for maize growth. Over four maize rotation cycles and three cotton cropping systems we can conclude that maize rotation is suitable as a two-crop rotation with cotton. However, the benefits from maize in a three-crop rotation over two years (cotton-wheat-maize) were negligible in terms of cotton productivity. The economic analysis also suggested the cotton-wheat rotation will result in a higher gross margin/ML of water (Nachimuthu et al., 2017). However, if water is not a limitation, the cotton monoculture system will result in a higher gross margin over the longer term.

Table 7.3. Effect of management practices on cotton plant dry matter in field C1, ACRI during 2017-18 to 2021-22 seasons.

<table>
<tr><th>Main plot</th><th>Maize (+/-)*</th><th>2017-18 cotton drymatter</th><th>2018-19 cotton drymatter</th><th>2018-19 cotton drymatter</th><th>2019-20 cotton drymatter</th><th>2019-20 cotton drymatter</th><th>2020-21 cotton drymatter</th><th>2020-21 cotton drymatter</th><th>2021-22 cotton drymatter</th><th>2021-22 cotton drymatter</th></tr>
<tr><td rowspan="2">Minimum-tilled continuous cotton</td><td>-</td><td rowspan="2">11.90</td><td>10.97</td><td rowspan="2">12.22</td><td>14.73</td><td rowspan="2">14.75</td><td>14.76</td><td rowspan="2">14.59</td><td>11.47</td><td rowspan="2">11.35</td></tr>
<tr><td>+</td><td>13.47</td><td>14.77</td><td>14.43</td><td>11.24</td></tr>
<tr><td rowspan="2">Maximum-tilled continuous cotton</td><td>-</td><td rowspan="2">10.51</td><td>11.44</td><td rowspan="2">12.05</td><td>13.64</td><td rowspan="2">12.99</td><td>13.32</td><td rowspan="2">13.13</td><td>10.96</td><td rowspan="2">12.09</td></tr>
<tr><td>+</td><td>12.65</td><td>12.34</td><td>12.94</td><td>13.22</td></tr>
<tr><td rowspan="2">Minimum-tilled cotton-wheat</td><td>-</td><td></td><td>13.15</td><td rowspan="2">12.69</td><td></td><td></td><td>17.04</td><td rowspan="2">16.84</td><td></td><td></td></tr>
<tr><td>+</td><td></td><td>12.23</td><td></td><td></td><td>16.65</td><td></td><td></td></tr>
<tr><td>LSD (P< 0.05)</td><td></td><td>NS</td><td>NS</td><td>NS</td><td>NS</td><td>1.693</td><td>NS</td><td>0.982</td><td>NS</td><td>NS</td></tr>
<tr><td rowspan="2">Overall sub treatment effect</td><td>Maize</td><td></td><td>12.78</td><td></td><td>13.56</td><td></td><td>14.67</td><td></td><td>12.23</td><td></td></tr>
<tr><td>Control</td><td></td><td>11.86</td><td></td><td>14.18</td><td></td><td>15.04</td><td></td><td>11.21</td><td></td></tr>
<tr><td>LSD</td><td></td><td></td><td>NS</td><td></td><td>NS</td><td></td><td>NS</td><td></td><td>NS</td><td></td></tr>
</table>

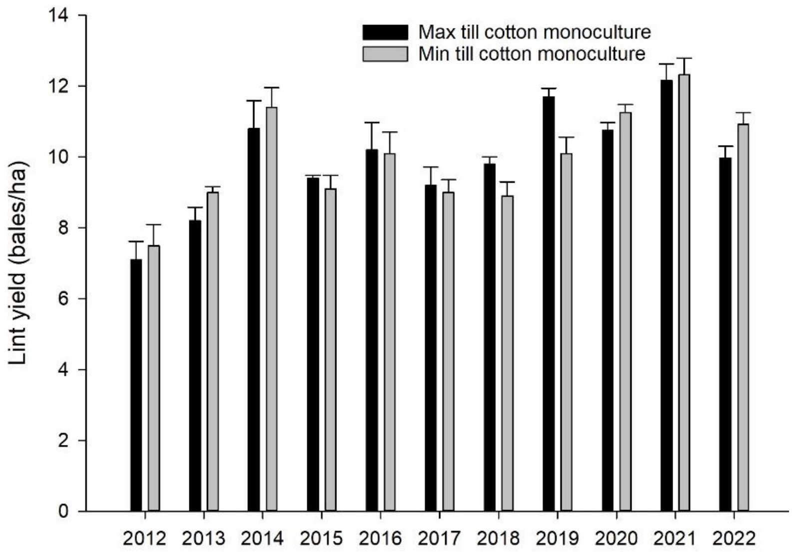

Figure 7.1. Effect of tillage on cotton lint yield from 2012 to 2022

Minimum tillage Maximum tillage

Plate 7.1. Cotton plant recovery after flooding (minimum tillage plots on left, maximum tillage on right).

The resilience of soil under minimum tillage practice was apparent with plant recovery after a major flood in 2021 as a visual indicator. The cotton plants were four weeks old when the flooding occurred in late November/early December 2021. The plants under minimum tillage recovered faster than those under minimum tillage. The main reason for the recovery was the difference in bed heights (Plate 7.1). The minimum tilled plots had higher beds than maximum tilled plots where the soil got washed away during the flood. Higher beds allowed the soil to aerate sooner after being inundated with length of time of inundation a key determinant of plant productivity (Hodgson, 1982). As a result, the minimum-tilled plots yielded 1.29 bales higher than maximum-tilled plots.

Table 7.4. Effect of management practices on maize yield and plant dry matter in field C1, ACRI during 2017-18 seasons

Treatment	Maize yield (t/ha)	Maize dry matter (t/ha)#
Maximum tillage maize cotton	6.62	4.85
Minimum tillage maize cotton	7.06	6.00
Minimum tillage-cotton wheat maize	5.40	4.49
LSD (P<0.05)	0.85**	NS

includes only stem and leaves

Disease incidence (verticillium wilt) was highly variable. The results (Figure 7.2) show a trend for lower disease incidence in the maize cotton system than in the cotton monoculture. There was no influence of tillage on disease and there was no interaction between tillage and maize rotation. This suggests that maize could be effective break crop to reduce the disease pressure, even after several seasons after the maize crop. The weed population measured in the 2019-20 season indicated maximum tillage systems recorded a higher weed population (22.5 weeds/m^2) than minimum tillage systems (2.3 weeds/m^2). This could be a result of cotton plants in the minimum tillage system providing a better smothering effect than the maximum tillage system as cotton biomass was higher under minimum tillage (Table 7.3). However, roundup-ready volunteers were higher under minimum tillage system and it could provide a challenge for sustainable soil management similar to resistant weeds under dryland no-till cropping systems.

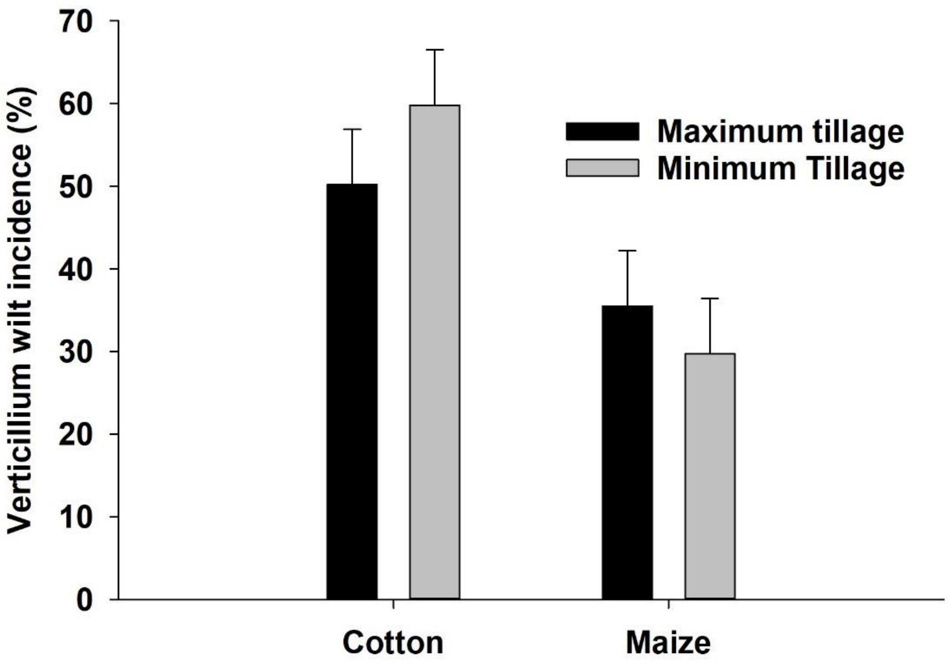

Figure 7.2. Legacy effect of maize rotation on verticillium incidence (2021-22 season)

The wheat yield over the four two-year rotation cycles from 2015 to 2021 shows an interesting difference between to the cotton-wheat-maize and cotton-wheat systems (Figure 7.3). Rotations including maize had a negative effect on wheat yield during 2015 (Nachimuthu et al., 2017) and 2017 (Figure 7.3). However, there was no legacy effect of maize on wheat grown in 2019 or 2021 (Figure 7.3). These results highlight that the 'system productivity' of a three-crop rotation will be lower due to lower wheat and maize yields (Table 7.4 and Figure 7.3).

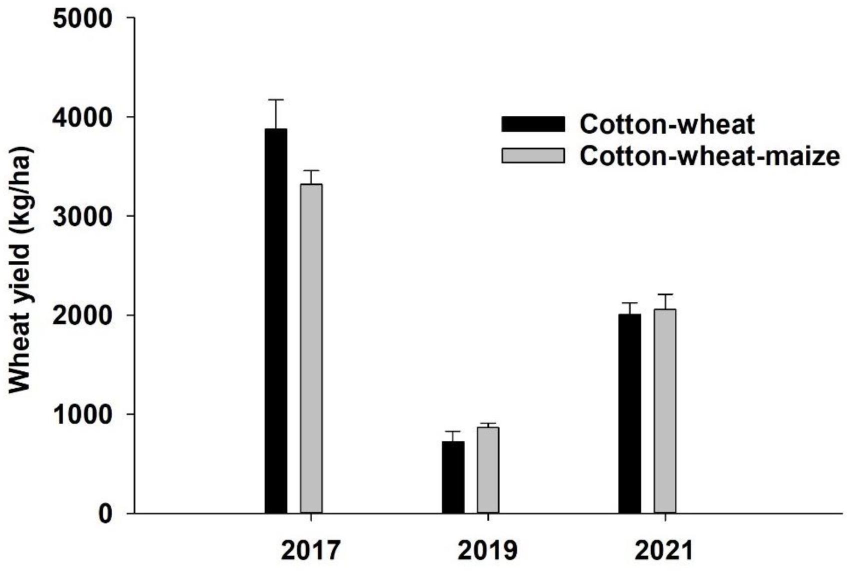

Figure 7.3. Wheat yield in field C1 from 2017 to 2021 as influenced by maize rotation

Soil organic carbon (SOC) declined in all sampled depths from 2018 to 2020 (Table 7.5). This is likely a result of the reduced input of plant matter during the severe drought. The inclusion of maize in the crop rotation improved the concentration of SOC in the topsoil (Figure 7.5), but this effect had dissipated by the 2020 sampling. Monitoring of SOC will be continued in DAN2305. The long-term SOC stocks calculated using the equivalent soil mass method will be presented in DAN2305.

A comparison of SOC measurement using the Walkley Black method and Mid-Infra-Red (MIR) technique for the topsoil (10 cm) samples showed no correlation between the two methods, making MIR unsuitable for SOC determination on this soil type. Improved, cheaper and more reliable methods are required for growers to undertake regular soil carbon measurements.

The microbial catabolic diversity in the 2019-20 season indicates the legacy effect of maize rotations. The effect of residual Maize seems to vary with different tillage treatments (Figure 7.4). For example, the effect of maize in the rotation on catabolic composition was greater with maximum tillage treatment compared with that in the minimum tillage treatments. In general, microbial activity and catabolic measures (i.e. community metabolic diversity, CMD and average metabolic response, AMR) were higher in the maximum tillage treatments compared to that in soils from minimum tillage treatments. For example, CMD was significantly ($P<0.017$) higher in the maximum tillage treatment (ave. 18.1±0.80) compared to minimum tillage cotton monoculture treatment (ave. 14.8±0.87). The general observation of higher microbial activity and catabolic potential measures (CMD and AMR) suggest greater microbial C turnover contributing to lower SOC, especially in view of the reduced plant C inputs. Additionally, the varying levels of legacy effect of maize in the different cropping systems indicate that microbial C turnover processes as influenced by disturbance (tillage) and crops grown can have significant effects on overall SOC status in cotton soils.

Table 7.5. Soil organic carbon concentrations within the long-term experiment at ACRI-field C1

Cropping systems						
2018	0-15 cm	15-30 cm	30-45 cm	45-60 cm	60-90 cm	90-120 cm
Maximum tillage cotton monoculture	0.94	0.78	0.67	0.64	0.57	0.57
Minimum tillage cotton monoculture	1.12	0.87	0.74	0.69	0.66	0.56
Minimum tillage cotton wheat	1.10	0.82	0.72	0.76	0.72	0.63
LSD (cropping system x depth) (P<0.05)			0.151			
2020						
Maximum tillage cotton monoculture	0.89	0.69	0.61	0.61	0.52	0.52
Minimum tillage cotton monoculture	0.92	0.72	0.66	0.64	0.61	0.44
Minimum tillage cotton wheat	0.97	0.77	0.67	0.64	0.61	0.55
LSD (cropping system x depth) (P<0.05)			0.059			

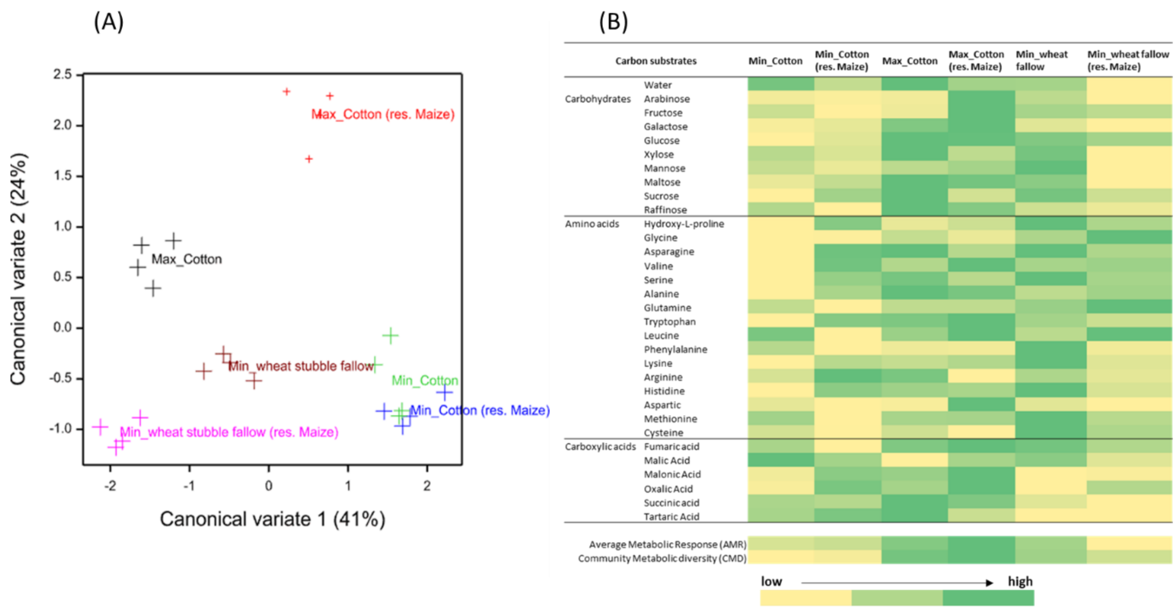

Figure 7.4. Effect of cotton cropping systems and maize rotation on microbial catabolic diversity, (A) Canonical analysis results for the community catabolic profiles from Microresp® assay, data points closer to each other suggest greater similarity and (B) heat map showing comparisons in carbon substrate utilization profiles (ability to utilize 31 different types of carbon substrates) expressed as CO_2 respiration differences between treatments.

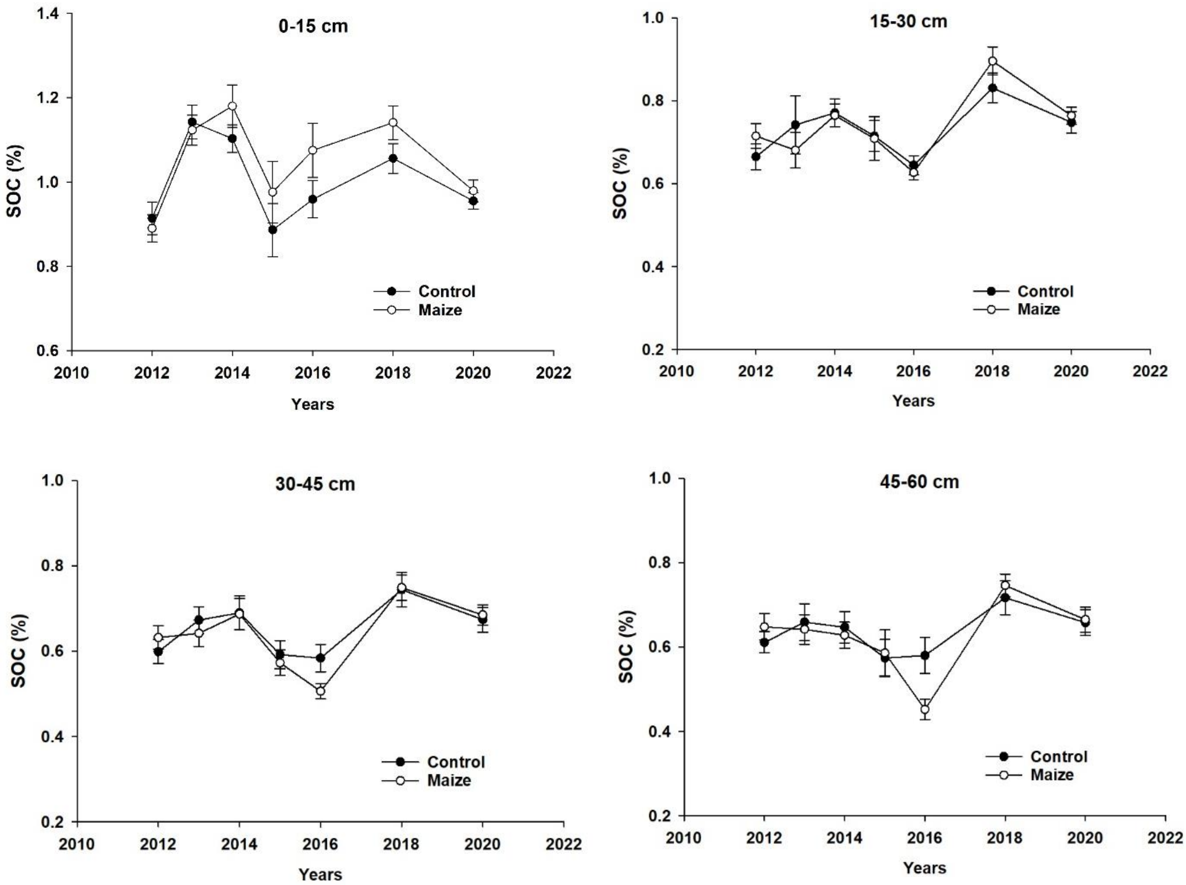

Figure 7.5. Soil organic carbon concentrations at various depths as influenced by maize rotation at ACRI field C1

The soil quality index (visual soil assessment (VSA)) was above 30 (good) for all plots: no treatment differences. All treatments adopted cotton stubble incorporation into the topsoil which improves the soil quality compared to past raking and burning practices. Crop rotation using cereals and legumes within cotton-based cropping systems is often postulated as a potential means to improve the soil properties that can enhance soil physical properties (Hulugalle and Scott, 2008) and fertility (Rochester, 2011; Rochester et al., 2001). While the soil quality index was rated as 'good' using the visual soil assessment method, there are still opportunities for improvement using the soil management practices. In particular, management options that will minimise compaction and improve soil fertility will enhance the opportunity for achieving nearer to the theoretical yield potential of 22 bales/ha if other production factors are not limiting.

One of the drawbacks of visual soil assessment is the biological indicator. Earthworms are the only biological indicator assessed in this method and they were not sighted in any of the treatments within this long-term trial and could be due to flood irrigation water logging the soil every 10-14 days. However, we noticed management-induced differences in cotton fabric degradation (Nachimuthu et al., 2022) and suggest that this may be a more appropriate biological quality indicator that is representative of soil organic matter degradation under cotton-growing conditions. The VSA (soil quality index or other individual scores for soil structure or porosity) was not correlated with crop performance (yield). So, further refinement is required to develop the relationship between soil quality index and cotton lint yield in Vertosols.

Soil pH decreased in all treatment plots following flooding in early December. These soils are slightly alkaline (Hulugalle et al., 2020). Previous reports are suggesting the soil pH of alkaline soils will move towards neutral due to entrapped carbon dioxide in the soil during the flood and slowly return to inherent soil pH after that (Ponnamperuma, 1972).

Table 7.6. Soil pH before and after flooding in field C1 during the 2021-22 season

Treatment	Sep-21 (before flooding)	Dec-21 (after flooding)
Maximum tillage cotton monoculture (MXT-CC)	7.30	7.19
Maximum tillage maize cotton (MXT-MC)	7.30	7.26
Minimum tillage cotton monoculture (MNT-CC)	7.31	7.28
Minimum tillage maize cotton (MNT-MC)	7.29	7.14
Minimum tillage cotton-wheat (MNT-CW)	7.32	7.21
Minimum tillage cotton-wheat-maize (MNT-CWM)	7.31	7.20
Average	7.31	7.21
LSD (P<0.05) for the month	0.058**	

The average TOC concentrations in irrigation water ranged from 1.98 to 36 mg/L and the runoff water ranged from 2.82 to 35 mg/L (Table 7.7). The carbon gains through irrigation water ranged from 14 to 288 kg C/ha and the carbon losses through irrigation water ranged from 7.3 to 104 kg C/ha. Overall, there were net gains (6.6 to 184 kg C/ha) to the cotton field through terrestrial hydrological pathways across four years so carbon movement in irrigation water did not contribute to the SOC decline in this field (Figure 7.5). The carbon loads in 2017-18 were much higher than in any other year. The difference in carbon loads, pH and electrical conductivity between years in the irrigation water is a combined result of the river, bore water qualities and recirculation of tail drain water from other fields. EC is higher in runoff water than in irrigation water and is expected as a result of the leaching of salt from the field during irrigation. Phosphorus movement within irrigation network was reported in More Profit from Nitrogen project.

The average seasonal soil water storage, measured a day before each irrigation, showed that the cotton monoculture system under minimum tillage stored less water than maximum tillage (Figure 7.6) suggesting the crop utilised the soil moisture more effectively to produce economic yield under minimum tillage (Table 7.2). There was also a maize effect in the 2019-20 season with more stored soil water under the maize-cotton system than cotton monoculture systems. However, the maize effect was absent in 2021-22 which suggests the legacy effect was short-lived for soil water storage.

Table 7.7. Irrigation and runoff water carbon loads from 2017-18 to 2020-21 seasons

Year	Sample	Water source	Number of irrigations	pH	EC (µs/cm)	TOC (mg/L)	Carbon loads (kg/ha)	Net carbon balance (kg/ha)
2017-18	Irrigation	River	8	6.92	348	36	288	
2017-18	Runoff		8	7.04	404	35	104	+184
2018-19	Irrigation	Bore	7	8.83	381	5.53	39	
2018-19	Runoff		7	8.65	432	8.40	22	+17
2019-20	Irrigation	Bore	7*	7.78	432	1.98	14	
2019-20	Runoff		7*	7.56	484	2.82	7.3	+6.6
2020-21	Irrigation	River	6	8.75	393	2.98	18	
2020-21	Runoff		6	8.27	466	4.42	10	+8.1

*There were only six irrigations. However, the planting irrigation was equivalent to two irrigations due to drought

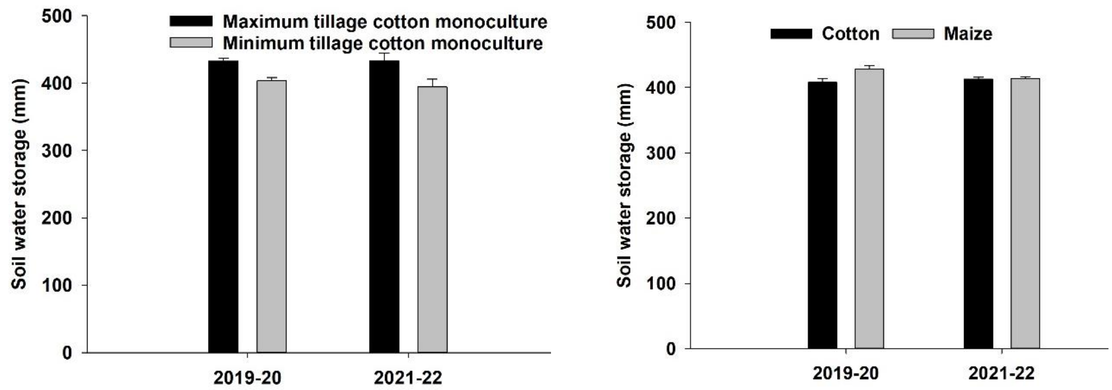

Figure 7.6. Effect of tillage and maize rotation on soil water storage before irrigations for cotton crop (seasonal average) during 2019-20 and 2021-22 seasons.

There was an overall historical cropping system impact on soil water storage during 2018-19 (Table 7.8). The cotton-wheat system had higher soil water storage than cotton monoculture under minimum tillage and the cotton-wheat system also recorded higher lint yield (Table 7.2). This suggests the cotton-wheat system will be more resilient to drought as it got higher soil water storage under similar soil management practices. However, in spite of recording higher soil water storage, the yields were lower under the maximum tillage cotton monoculture system, and there may be other constraints such as disease (Figure 7.2) or poor soil health limiting its water use efficiency.

Table 7.8. Soil water storage (0-120 cm) of cotton cropping systems during the 2018-19 and 2020-21 seasons (Pre-irrigation seasonal average)

	2018-19			2020-21	
Cropping system	control	corn	Main effect	control	corn
Maximum tillage cotton monoculture	362	389	375	448	447
Minimum tillage cotton monoculture	337	345	341	414	410
Minimum tillage cotton-wheat	373	375	374	428	423
LSD (P<0.05)	NS		10.88	NS	

4 Conclusions

The legacy of the effect of maize rotation on cotton lint yield was not present in the four years since its last planting in 2017–18. Maize is a good break crop for managing Verticillium disease. Minimum tillage systems were more resilient to flood impact. The water use efficiency of the minimum tilled cotton wheat system is higher than cotton monoculture system. Future research needs to focus on additional rotation crops that can alleviate soil compaction, increase soil organic carbon and benefit the productivity of the cotton crop.

Acknowledgements

This work was undertaken as part of DAN1801 funded by Cotton Research and Development Corporation and the NSW Department of Primary Industries. We thank Dr Nilantha Hulugalle for his contribution to the long-term trials. We thank all the technical, casual staff and farm staff from NSW DPI for their support with the trials and processing work. We thank Cotton Seed Distributors for the supply of seeds and CSIRO for assistance with ginning and fibre quality estimation.

References

Constable, G.A., Rochester, I.J., Daniells, I.G., 1992. Cotton yield and nitrogen requirement is modified by crop rotation and tillage method. Soil Tillage Res. 23, 41-59.

Gupta, V.V.S.R., Bramley, R.G.V., Greenfield, P., Yu, J., Herderich, M.J., 2019. Vineyard Soil Microbiome Composition Related to Rotundone Concentration in Australian Cool Climate ‘Peppery’ Shiraz Grapes. 10.

Hodgson, A., 1982. The effects of duration, timing and chemical amelioration of short-term waterlogging during furrow irrigation of cotton in a cracking grey clay. 33, 1019-1028.

Hulugalle, N.R., Nachimuthu, G., Kirkby, K., Lonergan, P., Heimoana, V., Watkins, M.D., Finlay, L.A., 2020. Sowing maize as a rotation crop in irrigated cotton cropping systems in a Vertosol: effects on soil properties, greenhouse gas emissions, black root rot incidence, cotton lint yield and fibre quality. 58, 137-150.

Hulugalle, N.R., Scott, F., 2008. A review of the changes in soil quality and profitability accomplished by sowing rotation crops after cotton in Australian Vertosols from 1970 to 2006. 46, 173-190.

Hutengs, C., Seidel, M., Oertel, F., Ludwig, B., Vohland, M., 2019. In situ and laboratory soil spectroscopy with portable visible-to-near-infrared and mid-infrared instruments for the assessment of organic carbon in soils. 355, 113900.

Isbell RF, N.C.o.S.a.T., 2021. The Australian Soil Classification, 3rd edn., 3rd ed. CSIRO Publishing, Melbourne.

Longpaddock, 2020. SILO - Australian climate data from 1889 to yesterday Queensland Government

Nachimuthu, G., Hulugalle, N.R., Watkins, M.D., Finlay, L.A., McCorkell, B., 2018. Irrigation induced surface carbon flow in a Vertisol under furrow irrigated cotton cropping systems. 183, 8-18.

Nachimuthu, G., Hulugalle, N.R., Watkins, M.D., Scott, F., Rollins, M., 2017. Resilient cotton-farming systems in irrigated Vertosols: soil quality, carbon and nutrient losses, cotton growth and yield in long-term studies. NSW Department of Primary Industries and Cotton Research and Development Corporation, Narrabri, Australia, p. 100.

Nachimuthu, G., Hundt, A., Palmer, B., Schwenke, G.D., Knox, O.G.G., 2022. Cotton strip assay detects soil microbial degradation differences among crop rotation and tillage experiments on Vertisols. 200, 106558.

Osanai, Y., Knox, O., Nachimuthu, G., Wilson, B., 2020. Increasing soil organic carbon with maize in cotton-based cropping systems: Mechanisms and potential. 299, 106985.

Ponnamperuma, F.N., 1972. The Chemistry of Submerged Soils, In: Brady, N.C. (Ed.), Advances in Agronomy. Academic Press, pp. 29-96.

Rayment, G.E., Lyons, D.J., 2011. Soil Chemical Methods - Australasia. CSIRO publishing, Australia.

Rochester, I.J., 2011. Sequestering carbon in minimum-tilled clay soils used for irrigated cotton and grain production. 112, 1-7.

Rochester, I.J., Peoples, M.B., Hulugalle, N.R., Gault, R.R., Constable, G.A., 2001. Using legumes to enhance nitrogen fertility and improve soil condition in cotton cropping systems. 70, 27-41.

Shepherd, G., Stagnari, F., Pisante, M., Benites, J., 2008. Visual Soil Assessments- Annual Crops. Food and Agriculture Organisation of the United Nations, Rome.

Soil Survey Staff, 2010. Keys to Soil Taxonomy, 11th ed. Natural Resources Conservation Service of the United States Department of Agriculture: Washington, DC.

Chapter 8: Field C1 trial Economic analysis and results– Project DAN1801

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Abstract

Across the two-year period, CWM.min till used the most irrigation water per hectare.

C.C reg till returned the highest gross margin per hectare, substantially higher than the counterpart C.C.min till treatment. CW.min till returned the lowest water use and the highest gross margin per ML of irrigation water.

1 Introduction

This report discusses economic results from the Field C1 rotation trial at ACRI, Narrabri from 2017 to 2018-19. Trials grown in C1 are a continuation of the tillage comparisons for two cotton farming systems, continuous cotton and cotton-wheat. In the 2011-12 season, these trials were extended to include maize.

In the extended trial, each of the three historical trials (yellow boxes in Figure 8.1), include two subplots that include the historical treatment (a) and a treatment that includes maize every second summer (b).

CC max till	**a. Cotton-fallow-Cotton-fallow (C.C.reg)** **b. Cotton-fallow-Maize-fallow (C.M.reg)**
CC min till	**a. Cotton-fallow-Cotton-fallow (C.C.min)** **b. Cotton-fallow-Maize-fallow (C.M.min)**
CW min till	**a. Cotton-Wheat-fallow-fallow (C.W.min)** **b. Cotton-Wheat-Maize-fallow (C.W.M.min)**

Figure 8.1: C1 trial and subplots

The type of budget used in this analysis is a gross margin. A gross margin is the gross income from an enterprise less the variable costs incurred in achieving it. Variable costs are those costs directly attributable to an enterprise and which vary in proportion to the size of an enterprise. For example, if the area of cotton sown doubles, then the variable costs associated with growing it, such as seed, chemicals, and fertilisers, will also roughly double.

The gross margins reported here are not the same as gross profit, because they do not include overhead costs such as depreciation, interest payments, rates, or permanent labour which have to be met regardless of enterprise size. While simple gross margin analyses are useful at the enterprise scale, invariably a more thorough analysis at the whole farm scale is required to assess financial impacts of different cropping rotations over a longer period.

This analysis will consider the recent seasonal gross margins for 2017 through to the 2018-19 cotton season.

Gross margin (GM) results were calculated using a long-term average cotton lint price of $450 per bale, cotton seed price of $170 per tonne, and a revised wheat price of $275 per tonne for APH2 grade, maize price of $200 per tonne (ex farm) and estimated costs for the actual operations conducted on each treatment, including fallow costs. Prices are kept the same across years to avoid confounding the treatment results with commodity price variability. Results are presented on both a gross margin per hectare (GM/ha) and per megalitre (GM/ML) basis.

Gross margin for one hectare of cotton also considers the associated refuge crop. In the 2017-18 and 2018-19 seasons at ACRI, Bollgard® 3 varieties were planted with unsprayed conventional cotton grown as the refuge. For every hectare of Bollgard® 3 cotton grown, there was 0.05 hectare of unsprayed cotton for refuge. Therefore, in the gross margin comparison, one hectare of cotton is 0.95 Bollgard® 3 and 0.05 unsprayed conventional cotton. The yields shown are the full yield/ha for the Bollgard® 3 cotton, but the income, costs and gross margins reported are all 95% Bollgard® 3 and 5% refuge crop when cotton is grown.

2 2017 Season Results

In the 2017 winter cropping season both of the cotton/wheat rotations had wheat, Cotton-Wheat-fallow-fallow (C.W.min) and Cotton-Wheat-Maize-fallow (C.W.M.min). The rest of the treatments were fallow. Wheat yield in the maize rotation (C.W.M.min) was higher at 3.71 t/ha, compared to 3.32 t/ha in the cotton/wheat rotation (C.W.min, Table 8.1). The wheat grade achieved in both treatments was APH2, with low screenings of 1.8%.

Table 8.1: 2017 Season Results

	C.C.reg	C.M.reg	C.C.min	C.M.min	C.W.min	C.W.M.min
Crop	*fallow*	*fallow*	*fallow*	*fallow*	*wheat*	*wheat*
Wheat t/ha					3.32	3.71
Income $/ha	N/A	N/A	N/A	N/A	913	1,020
Variable Costs $/ha	52	63	43	63	331	331
GM $/ha	(52)	(63)	(43)	(63)	582	690
GM $/ML	N/A	N/A	N/A	N/A	291	345

3 2017-18 Season Results

During the 2017-18 summer season, the cotton returned the highest yield under the regular tillage treatment compared to minimum tillage. Maize retuned the highest yield under the C.M.min treatment (7.06 t/ha), but the lowest under the C.W.M.min treatment (5.4 t/ha). Maize used a similar amount of water to cotton, but had a lower gross margin per hectare, so the GM $/ML was lower for maize.

Table 8.2: 2017-18 Season Results

	C.C.reg	C.M.reg	C.C.min	C.M.min	C.W.min	C.W.M.min
Crop	*cotton*	*maize*	*cotton*	*maize*	*fallow*	*maize*
Cotton Lint Yield	9.8		8.9			
Cotton Seed or grain yield	2.13	6.62	2.01	7.06		5.4
ML applied/ha	7.8	7.0	7.8	7.0		7.0
Income $/ha	4,533	1,324	4,129	1,556		1,080
Variable Costs $/ha	2,466	844	2,380	844	12	473
GM $/ha	2,067	480	1,749	712	(12)	607
GM $/ML	265	69	224	102		87

4 Full year results: 2017 and 2017-18 seasons

The results show that the continuous cotton treatments returned the highest GM/ha with the C.C.reg treatment returning the highest GM/ha (Table 8.3).

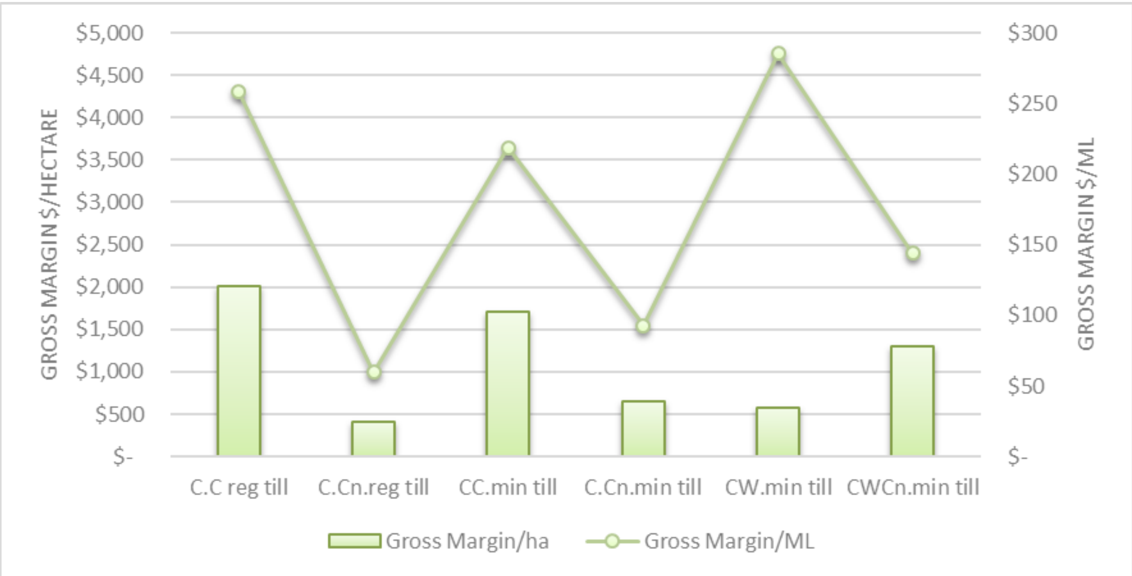

Figure 8.2: Gross margin/ha and per ML, 2017-18

The C.W.M.min treatment used the most water per hectare since it grew 2 crops during the year, wheat 2 ML/ha and maize, 7 ML/ha (Table 8.3).

Table 8.3: Full Year Results 2017 and 2017-18

Summary	C.C.reg	C.M.reg	C.C.min	C.M.min	C.W.min	C.W.M.min
Crop Sequence	*fallow/cotton*	*fallow/maize*	*fallow/cotton*	*fallow/maize*	*wheat/fallow*	*wheat/maize*
ML applied/ha	7.80	7.00	7.80	7.00	2.00	9.00
Income $/ha	4,533	1,324	4,129	1,556	913	2,100
Variable Costs $/ha	2,519	908	2,424	908	342	804
GM $/ha	2,015	416	1,706	648	570	1,296
GM $/ML	258	59	219	93	285	144

5 2018 Season Results

In the 2018 winter cropping season, all of the treatments were in fallow. Due to low rainfall during the season and subsequent lack of weed growth, only the C.C.reg and C.M.reg treatments incurred tillage costs of $32/ha each. The minimum till treatments did not require a herbicide.

6 Full year results: 2018 and 2018-19 seasons

In 2018-19, all treatments were under Bollgard 3® cotton, with an unsprayed conventional cotton refuge (5% of area). The cotton crops used the same amount of water (6.83 ML/ha) and therefore any differences in the performance on a GM/ML basis were derived directly from the performance on a GM/ha basis in this seasons comparison. The highest yield was returned by the C.W.min treatment. There was little difference between the two regular tillage treatments.

Table 8.4: 2018-19 Results

	C.C.reg	C.M.reg	C.C.min	C.M.min	C.W.min	C.W.M.min
Crop	*cotton*	*cotton*	*cotton*	*cotton*	*cotton*	*cotton*
Lint Yield (bales/ha)	11.65	11.44	10.09	11.51	12.83	10.91
ML applied/ha	6.83	6.83	6.83	6.83	6.83	6.83
Income $/ha	5,356	5,278	4,129	5,324	5,906	5,033
Variable Costs $/ha	2,644	2,595	2,380	2,568	2,664	2,533
GM $/ha	2,712	2,683	1,749	2,756	3,242	2,499
GM $/ML	397	393	256	404	475	366

The performance of the minimum till treatments varied widely (Figure 8.3), the effect of tillage or maize within the treatments was inconclusive in the 2018-19 season due to the variation in minimum tillage results within each sub-treatment and compared with the regular tillage treatments.

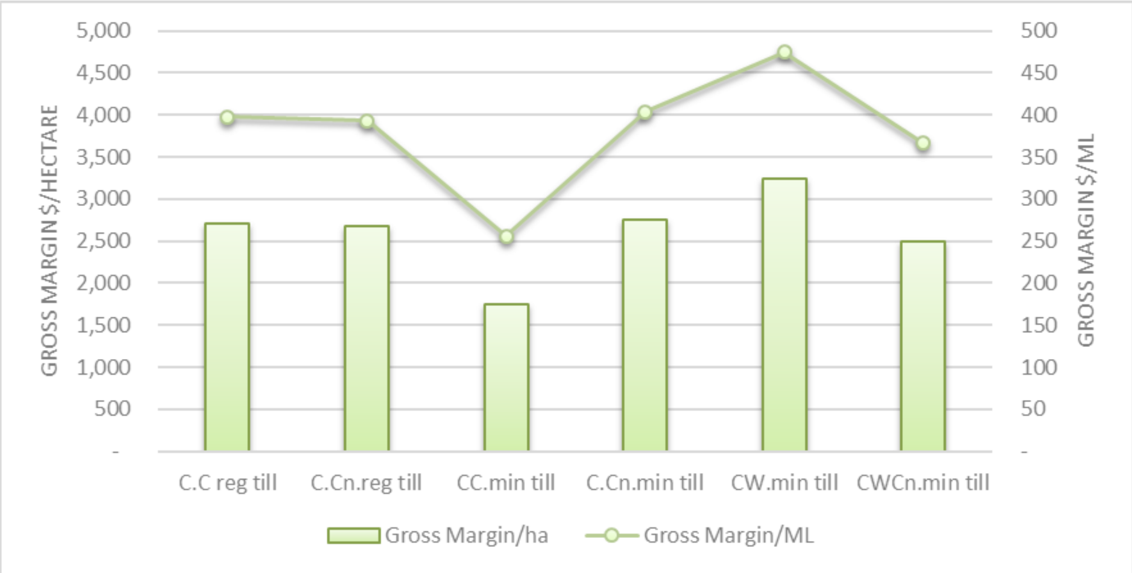

Figure 8.3: Gross margin/ha and per ML, 2018-19

7 Two-year results 2017 to 2018-19

Across the two-year period, CWM.min till used the most irrigation water per hectare.

C.C reg till returned the highest gross margin per hectare, substantially higher than the counterpart C.C.min till treatment. CW.min till returned the lowest water use and the highest gross margin per ML of irrigation water.

Table 8.5: Results 2017 to 2018-19

	C.C reg till	C.M.reg till	CC.min till	C.M.min till	CW.min till	CWM.min till
Water Use (ML)	14.63	13.83	14.63	13.83	8.83	15.83
Income $/ha	9,890	6,602	8,259	6,880	6,819	7,133
Variable Costs $/ha	5,163	3,503	4,804	3,476	3,006	3,337
GM $/ha	4,727	3,099	3,455	3,404	3,813	3,796
GM $/ML	323	224	236	246	432	240

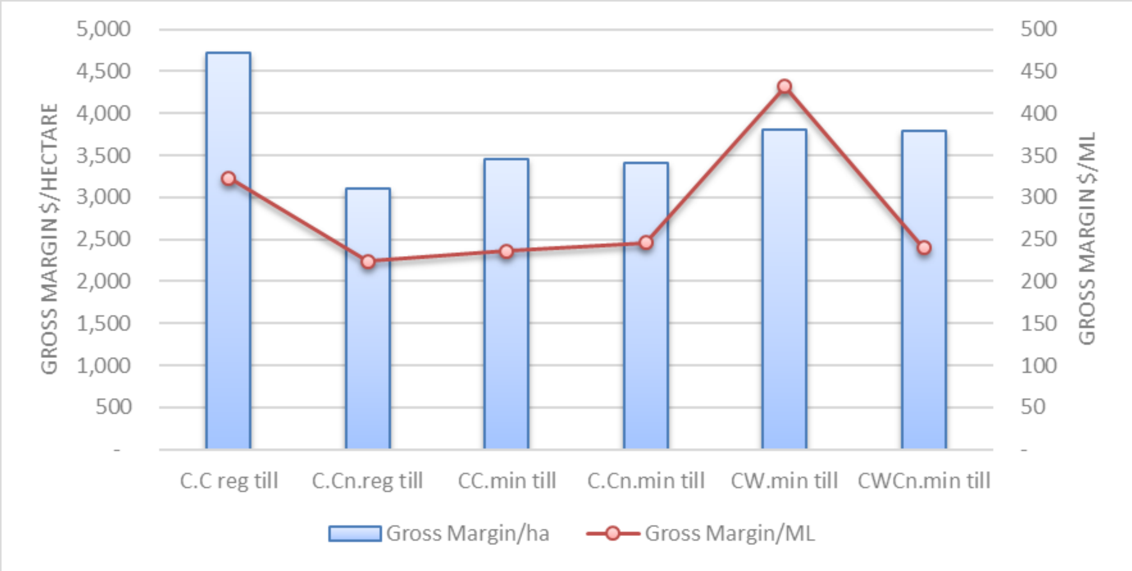

Figure 8.4: Gross margin/ha and per ML, 2017 to 2018-19

Chapter 9: Effect of foliar nutrient spray on cotton yield response after flooding

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Key findings

- Applying foliar nutrients to cotton after a flooding event had no effect on cotton growth or lint yield.

1 Introduction

In northern NSW and Qld, cotton is commonly grown in Vertosols (cracking clay soils) with typically higher nutritional fertility and water-holding capacity than other soils. However, these soils can become waterlogged during wetter-than-usual years, particularly after high intensity rainfall events. Under prolonged waterlogged conditions, various soil properties can change, such as soil pH and redox. When a soil is waterlogged, cotton roots are deprived of oxygen and the plant's growth will be affected. Under these circumstances, crop nutrition may be temporarily impacted as nutrient and micronutrient availability is related to soil properties (Palmer et al., 2023). Foliar application of nutrients is often promoted to assist cotton crops to recover quickly from the impact of floods and prolonged waterlogging conditions.

During the 2021–22 cotton-growing season, an experiment was conducted at the Australian Cotton Research Institute to investigate the efficacy of various foliar nutrient treatments on cotton biomass and yield in a field impacted by flooding.

2 Methods

Location

Field C1, Australian Cotton Research Institute, Narrabri (-30.20ºS, 149.60ºE)

Crop Management

Details of the cotton variety and crop operations dates are presented in Table 9.1 below.

Table 9.1. Crop management details for the foliar spray experiment conducted in the 2021-22 seasons

Crop operations	Field C1 (2021-22)
Date of planting	26 Oct 2021
Variety	Sicot 748 B3F®
Date of the first irrigation	28 Oct 2021
Date of flood peak	30 Nov 2021
Date of foliar spray treatment	20 Dec 2021
Date of first defoliation	22 Apr 2022
Date of harvest	26 May 2022

The field received 6 irrigations in total. The irrigation rate was ~ 100 mm/irrigation with application frequency being subject to rainfall and soil water content. Herbicide was applied as required. Handpicking was done to estimate the yield and this was followed by a mechanical harvester. The cotton plants were then slashed to a height of 0.1 m. This was followed by a tractor-driven root cutter that cut the root system ~50 mm below the surface of the bed.

Soil characteristics

Self-mulching cracking clay (Vertosol). The baseline soil properties of field C1 are presented in Nachimuthu et al. (2017).

Rainfall and Irrigation

The site received 467 mm of rainfall between the planting and first defoliation of cotton during the 2021–22 season. The rainfall events in November (208 mm monthly total with 106 mm in the last 10 days of November) resulted in riverine flooding which peaked at the Glencoe channel measurement station (nearby ACRI) on 30 November 2021, causing flooding of this field from the Namoi River overflow. The field was flooded for 3–4 days and the section of this field was flooded for 4 days with subsequent subsoil deep drainage slower than usual due to the saturated soil profile.

Fertiliser

N fertiliser was applied @ 180 kg N/ha as urea before planting, with another 100 kg N/ha applied in December as a top-up application to supplement the loss of soil and basal fertiliser N via leaching and denitrification. The foliar nutrient treatments were applied on 20 Dec 2021. This date was the earliest the field could be accessed due to follow up rainfall.

Weed and insect management

Weed management practices were conducted as per GM cotton agronomic practice requirements.

Biomass measurements and disease incidence

At the boll opening stage, all plants in one meter of plant row (within each treatment plot) were cut at the soil surface and bagged in the field. The wet weight of the entire 1 m cut was recorded and a subsample of three plants was used for assessing the weight, total nodes per plant, and plant height. These subsamples were separated for vegetative biomass (stems and leaves) and bolls and dried at 70ºC in a fan-forced dehydrator. The dried samples were weighed for dry biomass assessment.

Normalised differential vegetation index (NDVI) images and groundcover were recorded periodically over a month after application within each treatment plot using hand-held Greenseeker™ and photograph respectively. NDVI detects chlorophyll density and so can indicate whether the foliar treatments led to differences in plant biomass and plant nutrition. Ground cover percentage was calculated as GC%= % area covered by green matter in the area photographed. A uniform height was adopted above the plant to photograph each time.

Verticillium wilt is an invasive disease at ACRI. The disease incidence within each treatment plot was reported as a percentage of plants observed to be infected in the harvested one linear square meter.

Harvest, ginning and lint yield estimation

The final harvest occurred on 26 May 2022. Seed cotton was hand-picked and weighed immediately. A <500 g seed cotton subsample was ginned using a CSIRO custom build saw gin to determine the gin turnout (i.e., the percentage mass of seed and lint). The lint turnout (% lint) was used to estimate the lint yield from seed cotton and the results were reported as bales lint/ha.

Treatments

The experiment was a randomised block design with five treatments, each replicated four times. The foliar spray treatments included,

T1 - Control (distilled water)

T2 - N42 (urea ammonium nitrate: 42% nitrogen in product) 0.42% v/v in water (Yarra Pvt Ltd)

T3 – REDOX MAP (mono ammonium phosphate: 12% nitrogen, 26% phosphorus and 0-1% zinc in product) 1.3% v/v in water

T4 – Sigma Aldrich Zn (zinc sulfate heptahydrate) 0.38% w/v in water

T5 – 'CGS Shotgun' (Cotton Grower Services: nutrient analysis in Table 9.2 below)

All plots received 50 L/ha of spray volume of tank mix with concentrations described above.

Table 9.2- Nutrient analysis of foliar product CGS Shotgun*

Nutrient	Typical Analysis % (W/V)
Total Nitrogen (N)	4.8
Total Phosphorus (P)	10.4
Total Potassium (K)	2.5
Total Sulphur (S)	2.6
Total Manganese (Mn)	2.3
Total Zinc (Zn)	3.8
Total Copper (Cu)	0.27
Total Iron (Fe)	0.3
Total Boron (B)	0.28
Total Molybdenum (Mo)	0.16
Total Magnesium (Mg)	1.6
Total Cobalt (Co)	0.02

*- 5 L of this product was mixed with 50 L of water for field application

Statistical analysis

All the data analysis was carried out using Genstat (21st Edition, VSN International Ltd). The response factor (lint yield, dry biomass, fibre quality etc.) was analysed using Analysis of Variance. The treatment effects with a probability of <5% were considered as significant effects. In such cases, the least significant difference ($P < 0.05$) was used to compare treatment means.

3 Results and discussion

The results (Tables 9.3–9.5) showed no significant treatment effects of foliar-applied nutrients on lint yield, fibre quality or any other measured plant growth parameters (dry matter, plant height, NDVI, groundcover and disease incidence). This study investigated whether foliar application of selected nutrients applied after waterlogging, either alone, or in combination with other nutrients, was able to improve growth and yield. The NDVI results suggested that neither groundcover (%) nor plant health were improved by foliar-applied nutrients when compared to control plots (Table 9.3). Previous studies reported potential benefits to crop performance when nutrients were applied prior to waterlogging (Hodgson and MacLeod, 1988; NUTRIpak, 2018).

The average plant height, mainstem node number and disease incidence—all measured during the boll opening stage—also showed no impact of foliar nutrient treatments (Table 9.4). Likewise, vegetative dry matter, boll dry matter, total plant dry matter, lint yield (Table 9.4) and fibre quality (Table 9.5) were also not impacted by the foliar-applied nutrient treatments.

The crop received 180 kg N/ha as a basal pre-plant N application, most of which either leached or denitrified during the flooding event and was thus lost from the soil root zone. However, the top-up fertiliser application of 100 kg N/ha likely prevented crop N deficiency. The soil Colwell P levels were above 60 mg/kg for this field and P response at these levels was unlikely in Vertosols with high BSES P reserves, as in this case.

Micronutrient availability in soil is likely impacted by flooding. However, the lack of response for foliar nutrition suggests that the plants were unable to recover until after the flood water receded when the temporary unavailability of soil nutrients was reversed. Therefore, a foliar application of plant nutrients is unlikely to improve plant growth after flooding in this heavy cracking clay soil with high pH and native fertility. Errington et al. (2007) also reported a lack of cotton response to foliar P and K in the Vertosols. The long-term experiment within the same field suggested that the minimum tilled plots resulted in more intact beds (higher bed height) during the flood and better plant recovery compared to conventionally tilled plots. This together informs that better soil conditions will improve plant growth and yield in these soils with relatively high nutrient reserves compared to foliar-applied nutrients.

Table 9.3. Effect of various foliar nutrient sprays on NDVI and Groudcover% over time

Date	T1 (control)	T2 (N42)	T3 (MAP)	T4 (Zn)	T5 (shotgun)
			NDVI		
21/12/2021	0.18	0.19	0.19	0.20	0.19
14/01/2022	0.54	0.50	0.54	0.52	0.49
25/01/2022	0.76	0.72	0.72	0.73	0.73
31/01/2022	0.80	0.73	0.78	0.76	0.78
			Groundcover%		
21/12/2021	0.02	0.02	0.02	0.03	0.02
14/01/2022	0.21	0.19	0.18	0.19	0.20
25/01/2022	0.43	0.42	0.41	0.41	0.42
31/01/2022	0.53	0.54	0.50	0.50	0.51

Table 9.4. Effect of various foliar sprays on cotton biomass and lint yield

	Control	N42	MAP	Zn	Shotgun	P value
Parameters	T1	T2	T3	T4	T5	
Disease incidence %	39.8	45.4	31.2	39.6	32.0	NS
Plant height (cm)	89.7	87.5	83.5	83.7	85.5	NS
Average nodes/plant	22.2	21.5	21.0	21.3	21.5	NS
Vegetative dry matter (t/ha)	4.36	4.16	3.26	4.45	3.74	NS
Boll dry matter (t/ha)	7.68	7.25	6.31	7.91	7.06	NS
Total dry matter (t/ha)	12.03	11.41	9.57	12.36	10.8	NS
Lint yield (kg/ha)	2579	2373	2750	2315	2350	NS
Lint yield (bales/ha)	11.4	10.5	12.1	10.2	10.4	NS

Table 9.5. Effect of various foliar sprays on cotton lint fibre quality

	Control	N42	MAP	Zn	Shotgun	
Fibre quality parameters	T1	T2	T3	T4	T5	P value
Length	1.21	1.20	1.20	1.21	1.22	NS
Uniformity	84.1	84.4	84.5	84.7	84.8	NS
Short fibre index	5.40	6.02	6.05	5.72	5.88	NS
Strength	31.9	31.9	31.0	31.1	31.3	NS
Elongation	4.83	5.05	4.75	4.80	4.80	NS
Micronaire	4.49	4.40	4.17	4.38	4.24	NS
Maturity	0.88	0.87	0.87	0.88	0.87	NS

4 Conclusions

The application of foliar nutrient spray products after a significant flooding event on a Vertosol did not improve cotton lint yield, biomass or fibre quality, however previous studies indicated foliar nutrient sprays applied prior to flooding may improve crop performance. Improved soil structural properties through minimum tillage practices (higher bed height) is more likely to assist cotton recovery from floods than applying foliar nutrients.

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References

Errington, M., Campbell, L.C., Rochester, I., Tan, D.K.Y., 2007. Efficacy of foliar fertilization in cotton, World Cotton Research Conference.

Hodgson, A.S., MacLeod, D.A., 1988. Seasonal and Soil Fertility Effects on the Response of Waterlogged Cotton to Foliar-Applied Nitrogen Fertilizer. 80, 259-265.

Nachimuthu, G., Hulugalle, N.R., Watkins, M.D., Scott, F., Rollins, M., 2017. Resilient cotton-farming systems in irrigated Vertosols: soil quality, carbon and nutrient losses, cotton growth and yield in long-term studies. NSW Department of Primary Industries and Cotton Research and Development Corporation, Narrabri, Australia, p. 100.

NUTRIpak, 2018. NUTRIpak: A practical guide to cotton nutrition. CottonInfo and Cotton Research and Development Corporation.

Palmer, B., Guppy, C., Nachimuthu, G., Hulugalle, N., 2023. Changes in micronutrient concentrations under minimum tillage and cotton-based crop rotations in irrigated Vertisols In Press.

Chapter 10: Effect of hail damage simulation on cotton lint yield

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Key findings

- There was no influence of hail damage simulation on cotton lint yield across three experiments

1 Introduction

The hailstorm at the Australian Cotton Research Institute during the early summer 2018-19 season resulted in significant crop damage. However, the cotton crop was resilient and recovered after the damage resulting in a yield greater than 10 bales/ha on average. The cotton harvest in 2018-19 season resulted in higher than long-term average yield in a cotton monoculture system. The additional yield in that season was the cumulative effect of extended season and additional branching resulting in more bolls. The additional branching might have resulted in a better light interception and potentially contributed towards improvement in yield. However, the weather pattern may not allow extended season in all years and could result in yield penalty. To test the effect of this hail damage, two hail simulation trials were conducted in the 2019-20 season within the long-term trials by removing the tips of the cotton plants on the same date as the previous year of hail damage. Two experiments were carried out during 2019-20 and a single experiment was carried out during the 2020-21 season to investigate the effect of hailstorm damage on cotton lint yield. Our aim was to test if hail damage simulated crop are resulting in similar yield as that of control crops.

2 Methods

Location and crop management

The experiment was conducted at the Field C1 and D1, Australian Cotton Research Institute, Narrabri (-30.20, 149.60). The cotton variety details, planting, harvesting and first defoliation dates are presented in Table 10.1 below. Field C1 and D1 received 5 irrigations in 2019-20 and Field C1 received 6 irrigations in 2020-21 respectively.

Table 10.1. Crop management details for the three experiments conducted in the 2019-20 and 2020-21 seasons

Crop operations	Field C1 (2019-20)	Field D1 (2019-20)	Field C1 (2020-21)
Date of planting	31 Oct 2019	29 Oct 2019	03 Nov 2020
Date of the first irrigation	01 Nov 2019	31 Oct 2019	04 Nov 2020
Number of irrigations	7	6	6
Variety	Sicot 746 B3F®	Sicot 748 B3F®	Sicot 748 B3F®
Date of hail damage simulation	16 Dec 2019	16 Dec 2019	18 Dec 2019
Date of defoliation	24 Apr 2020	24 Apr 2020	16 Apr 2021
Date of harvest	18 May 2020	19 May 2020	28 May 2021

The irrigation rate was ~ 100 mm/irrigation with application frequency being subject to rainfall and soil water content. Herbicide was applied as required. Defoliation occurred on dates as per Table 10.1. Handpicking was done to estimate the yield and this was followed by a mechanical harvester to harvest the bulk crop. The cotton plants were then slashed to a height of 0.1 m. This was followed by a tractor-driven root cutter that cut the root system ~50 mm below the surface of the bed and pupae busting (top 10 cm).

Soil characteristics

Self-mulching cracking clay (Vertosol). The baseline characteristics of fields C1 and D1 are presented in Nachimuthu et al. (2017)

Rainfall and Irrigation

The site received 358 mm and 436 mm of rainfall between the planting and harvest of cotton during the 2019-20 and 2020-21 seasons respectively.

Fertiliser

N fertiliser was applied @ 240 kg N/ha as urea in 2019-20 for both the fields and 180 kg N/ha as urea in the 2020-21 season in field D1.

Weed and insect management

Weed management practices were conducted as per GM cotton agronomic practice requirements.

Harvest, ginning and lint yield estimation

The final harvest occurred as described in Table 10.1 for each experiment. Seed cotton was harvested handpicked and weighed immediately. A <500 g seed cotton subsample was ginned using a 20-saw gin with a pre-cleaner (Continental Eagle, Prattville, AL, USA) to determine the gin turnout (i.e., the percentages of seed and lint by mass). The lint turnout (% lint) was used to estimate the lint yield from seed cotton and the results were reported as bales lint/ha.

Treatments

The experiments in C1 used a randomised block design, with hail damage and control as the treatments. All treatments were replicated four times in both the 2019-20 and 2020-21seasons.

In Field D1, a factorial design was used with crop rotation as main plots and hail damage and control as subplots in the 2019-20 season. (Note: crop rotation results are presented in Chapter 4). Four replicates were used in this experiment as well.

The simulated hail damage treatments were applied by cutting the plant tips using either secateurs (2019–20) or a mechanical slasher (2020–21).

Statistical analysis

All data analysis was carried out using Genstat (21st Edition, VSN International Ltd). Lint yield was analysed using Analysis of variance to assess the effect of treatments in field C1 and the effect of crop rotation and treatment and their interactions in field D1.

3 Results and discussion

Lint yield

The 2019–20 experiments showed no significant difference in lint yield between the hail damage and control treatments (Table 10.2) in either field (C1 and D1). However, the lint yield in the cotton-wheat rotation was significantly higher than in the cotton monoculture (Data presented in the Chapter 4).

Table 10.2. Effect of hail simulation on cotton lint yield (bales/ha) in Field C1 and D1 (2019-20 season)

Field	Hail damage	Control	*P value*	LSD
C1	10.28	10.01	0.599	NS
D1	12.42	13.46	0.289	NS

The 2020-21 experiment also showed no difference in lint yield or average boll weight between simulated hail damage and control (Table 10.3). In this investigation we mainly focussed on if there was an yield penalty as a result of hail damage simulation and our results indicate there is no impact of hail damage simulation on cotton lint yield. These results have implications on decision support for growers who don't obtain appropriate crop insurance.

Table 10.3. Effect of hail simulation on cotton lint yield (bales/ha) and average boll weight (g/boll) in the 2020-21 season

Treatment	Lint yield (bales/ha)	Average boll weight (g/boll)
Hail damage	13.4	4.20
Control	12.6	4.31
P value	*0.743*	*0.868*
LSD	*NS*	*NS*

4 Conclusions

The results indicate no influence of hail damage simulation in lint yield across three experiments conducted across two separate years. The results suggest, if the growers don't have appropriate crop insurance, continuing the hail-damaged crop in December could result in average lint yield provided other factors are not limiting the cotton crop growth and maturity.

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References

Nachimuthu, G., Hulugalle, N.R., Watkins, M.D., Scott, F., Rollins, M., 2017. Resilient cotton-farming systems in irrigated Vertosols: soil quality, carbon and nutrient losses, cotton growth and yield in long-term studies. NSW Department of Primary Industries and Cotton Research and Development Corporation, Narrabri, Australia, p. 100.

Chapter 11: Changes in micronutrient concentrations under minimum tillage and cotton-based crop rotations in irrigated Vertosols

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Highlights

- Micronutrient stratification occurred with minimum tillage and cotton-cereal rotations
- Soil pH influenced DTPA-extractable Fe and Mn, SOC influenced DTPA-extractable Mn
- DTPA-extractable Zn was below the critical value and may limit plant growth
- Sampling increments of 0.02 m may help identify topsoil micronutrient constraints

Abstract

Australian irrigated cotton (*Gossypium hirsutum* L.) yields are among the highest in the world but may deplete soil nutrient reserves faster than in dryland systems. Little is known about changes in long-term micronutrient (Cu, Fe, Mn, Zn) concentrations in these systems. This study investigated changes in soil micronutrient concentrations over time in two long-term tillage and crop rotation experiments under furrow-irrigated cotton systems and a no-till dryland cropping enterprise. The tillage practices that were investigated were maximum (disc to 0.2 m, chisel ploughing to 0.3 m followed by the construction of beds in 1 m spacings) and minimum (mulching cotton residues, followed by root cutting, incorporation of cotton stalks and bed renovation with a disc-hiller) tillage. Soil samples were analysed for diethylenetriamine penta-acetic acid (DTPA) extractable micronutrients, x-ray fluorescence (XRF) total micronutrients, pH, and soil organic carbon (SOC). Both maximum and minimum tillage influenced topsoil distribution of DTPA-extractable Cu, Zn and Mn, with the greatest changes occurring in Mn concentration. Concentrations of Mn in the topsoil (0-0.15 m) during 2015 were higher than those in the subsoil (0.15-0.6 m) by 74% with maximum tillage and 159% with minimum tillage, suggesting greater stratification with the latter (28 mg kg^{-1} in topsoil vs 11 mg kg^{-1} in subsoil). Including wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) in cotton rotations increased DTPA-extractable Mn concentration. DTPA-extractable Mn was positively correlated with SOC in two experiments ($P < 0.01$) and DTPA Fe and pH were negatively correlated ($P < 0.01$). DTPA Zn concentrations under minimum-till cotton systems were stable over 18 years. DTPA Zn concentrations measured at 0.02 m increments suggested that soil below the fertiliser band depth (< 0.04 m) was potentially responsive to Zn application. Sampling in smaller depth increments in the topsoil (0.02 m increments in 0-0.1 m depth) more accurately identified micronutrient stratification and may improve management decisions when sowing. Our results indicated that managing soil pH and SOC in alkaline Vertisols under irrigated cotton systems was a more practical approach to address micronutrient availability than soil application of micronutrients. Future research should consider the implications of current agronomic practices in cotton production, such as the method and timing of nitrogen application as it influences changes in soil pH, which may impact micronutrient availability at critical crop growth stages.

Keywords

Trace elements; Nutrient stratification; Soil constraints; Plant-available nutrients; Soil-profile distribution; Soil carbon

1 Introduction

Soil management practices, such as conservation tillage, that minimise tillage and improve physical properties and soil carbon are alternatives to conventional soil management that uses aggressive tillage (ABS, 2018; Pretty and Bharucha, 2014). Additionally, crop rotations can improve the sustainability and productivity of cropping systems (Bowles et al., 2020; Shah et al., 2021). Crop rotation and tillage can also improve soil physical properties (Hulugalle et al., 2006; Somasundaram et al., 2018), infiltration, soil water storage, crop water use efficiency (Basche and DeLonge, 2019) and soil biological properties (Polain et al., 2020). Conservation tillage can, however, lead to nutrient stratification with higher concentrations occurring in the surface horizons (Dang et al., 2015; Wright et al., 2007). This is a significant constraint of conservation tillage. A key determinant of crop yield maximisation is the optimum spatial distribution and availability of nutrients throughout the soil volume such that roots can concurrently access essential nutrients and water reserves at depth (Su et al., 2018).

The widespread use of genetically modified (GM) technology (where cotton plants are embedded with genetic material to exhibit herbicide tolerance and produce *Bacillus thuringiensis* toxins) (Fleming et al., 2018) in cotton (*Gossypium hirsutum* L.), has implications for soil, nutrient and weed management. While herbicide-tolerant cotton increases the opportunity for minimising cultivation to achieve weed control, the mandatory post-harvest cultivation to manage *Helicoverpa spp.* resistance requires some soil disturbance at the end of each season. Additionally, cotton in Australia is surface mulched at the end of the season (Hulugalle et al., 2013) compared to residue removal via stalk pulling or stubble burning in other parts of the world (Jalota et al., 2008; Ramanjaneyulu et al., 2021). So, there is a significant difference between conservation tillage under dryland cropping systems across the world and minimum tillage under cotton cropping systems in Australia. Strategic tillage has been suggested as an alternative for potential herbicide-resistant weed management and to redistribute the stratified nutrients under dryland conditions (Wortmann and Dang, 2020). This is likely to occur to some extent in cotton systems at the end of every season with standard agronomic management of GM cotton. However, the depth of this soil disturbance varies across cotton industry fields ranging from 0.1 m to 0.3 m. This varying degree of tillage along with other cropping system components such as rotation crops could alter the soil nutrient profile and availability over depths. Rotation crops within cropping systems can alter the nutrient distribution of the soil profile depending on their rooting depth and crop demand (Armstrong et al., 2019; Houx et al., 2011) beyond the tillage depth in the profile.

In Australia, cotton production occurs predominantly in relatively fertile Vertisols (Soil Survey Staff 2014) with high clay content and high water-holding capacity (Vervoort et al., 2003). The intrinsic fertility of these Vertisols enabled historical crop production to occur with fewer fertiliser inputs, with most nutrient management practices emphasising nitrogen (N) (Macdonald et al., 2018) while neglecting other nutrients. Most Australian cotton is grown in soils with high pH (Filippi et al., 2019), which may limit the availability of some nutrients (Gentili et al., 2018). Soil N and its impact on crop growth have been studied extensively in Australia (Rochester, 2011, 2012; Rochester and Bange, 2016; Schwenke and McPherson, 2022; Weaver, 2022), with a more recent focus on phosphorus and potassium (Nachimuthu et al., 2022; Rochester, 2010). The research on micronutrients in Australian cotton has focussed on plant uptake as soil available micronutrients were not considered limiting (Constable et al., 1988). Earlier research that assessed micronutrient uptake in 35 cotton crops in Australia suggested sufficiency in Cu, Fe, Mn, and Zn (Constable et al., 1988) and more recently reported an improvement in nutrient use efficiency with modern cultivars for Zn, Cu and Fe and no change for Mn (Rochester and Constable, 2015). The research on soil micronutrient status across Australian cotton farms is, however, sparse.

Management errors such as over-fertilisation and over-irrigation may inhibit micronutrient availability. The availability of Fe, Cu and Zn may be reduced by acidification caused by high rates of N fertiliser application(Wright et al., 2007; Janke et al., 2022), which is of concern in Australia due to excessive N fertiliser use by many cotton growers (Macdonald et al., 2018). Vertisols are often prone to waterlogging due to their high clay concentration and low microporosity under wet conditions caused by over-irrigation or heavy rainfall (Hulme et al., 1991), which can impact the availability of nutrients such as Fe and Mn (Wollmer et al., 2019).

Each micronutrient plays a vital role in the cotton plant's metabolic processes, therefore specific micronutrients are required in varying quantities as determined by the plant's growth stage. For example, 73% of Zn uptake in irrigated cotton occurs during the crop's peak flowering stage (Rochester et al., 2012). Depending on soil conditions, rooting depth will dictate the nutrient extraction zone. Therefore, if the required micronutrient is not available to plants in an adequate amount in its nutrient extraction zone, crop development will be inhibited. In this way, nutrient stratification can lead to in-crop nutrient deficiencies. As the micronutrient cations in this study (Fe, Mn, Cu and Zn) are mostly immobile in soil (Fageria et al., 2010), stratification is an important consideration for plant availability and growth.

As micronutrients are required in very small quantities, assessing the long-term changes in total and available micronutrients over various depth increments under contrasting management practices such as varying tillage depth and crop rotation will unravel the current status of micronutrients and their stratification, if any, in Vertisols. This knowledge will improve decision-making for future nutrient management strategies suited for cotton cropping systems. This study investigated the following hypotheses; 1) there is a decline in total and plant available micronutrients across the soil profile over the long term in cotton growing Vertisols, 2) micronutrient stratification pattern differed over years with tillage and crop rotation, 3) plant available micronutrients are related to changes in soil pH and SOC, and 4) tillage influences topsoil micronutrient stratification.

These hypotheses were tested by analysing a combination of historical and recent soil samples from two long-term tillage and crop rotation experiments and a commercial dryland site. This study is the first of its kind to investigate long-term changes in micronutrient concentrations in Australian cotton systems and will result in an improved understanding of the micronutrient status as influenced by tillage and crop rotation practices.

2 Materials and methods

2.1 Site description

Two long-term experiments (Field C1 and D1) located at the Australian Cotton Research Institute (ACRI), Narrabri (149°47′E, 30°13′S), Australia and two commercial fields (Field 3 and 4) near Edgeroi (149°79’E, 30°11’S), Australia were investigated in this research. Mean annual rainfall for the region between 1993 and 2020 was 618mm (Longpaddock, 2020) and the area has a semi-arid climate, BSh (Kottek et al., 2006), and experiences four distinct seasons with a mild winter and a hot summer. January is the hottest month with a maximum daily mean temperature of 34.3°C and a minimum daily mean temperature of 20°C and July is the coolest month, with a maximum daily mean temperature of 17.8°C and a minimum daily mean temperature of 4°C (BOM, 2020).

2.2 Field treatments

2.2.1 Field C1

The soil was a deep, uniform grey clay and classified as a fine, thermic, smectitic, Typic Haplustert (Soil Survey Staff 2014). At the 0-1 m depth it had a particle size distribution of 64 g 100 g^{-1} clay (<2 μm), 11 g 100 g^{-1} silt (2–20 μm) and 25 g 100 g^{-1} sand (20 μm–2 mm), was alkaline (pH in 0.01 M $CaCl_2$ was 7.5) and non-saline (electrical conductivity ($EC^{1:5}$) was 0.29 dS m^{-1}). Exchangeable sodium percentage (ESP) was 3 at 0–0.6 m and 10 at 0.6–1.0 m. The experiment in field C1 had three treatments over four replications implemented from 1985 which were (1) maximum tillage and continuous cotton monoculture (summer cotton and winter fallow every year), (2) minimum tillage and continuous cotton monoculture (summer cotton and winter fallow every year) and (3) minimum tillage and cotton-wheat

(*Triticum aestivum* L.) rotation (summer cotton and winter wheat followed by summer and winter fallow).

Maximum tillage consisted of mulching of cotton plants after harvest, followed by disc-ploughing and incorporation of cotton stalks to 0.2 m, chisel ploughing to 0.3 m followed by the construction of beds at spacings of 1 m. Minimum tillage comprised mulching of cotton plants after harvest, followed by root cutting and incorporation of cotton stalks into beds to 0.1 m depth (to facilitate *Helicoverpa spp.* pupae destruction), and bed renovation with a disc-hiller. From 1995 to 1999, wheat stubble was incorporated with a disc-hiller before sowing cotton, but thereafter it was retained as standing stubble into which the following cotton crop was sown (Hulugalle et al., 2005). Conventional cotton was sown from 1985 to 1999, and genetically modified cotton varieties thereafter. The field had a slope of 0.1%. The experiment was re-designed in 2011 by splitting all plots and sowing either hybrid maize (*Zea mays* L.) varieties during the summer following the previous year's cotton (with respect to the cotton-wheat, this involved sowing maize immediately after wheat but before the next years cotton crop) or retaining the historical cropping system as a control. The experiment was laid out as a split-plot design where the historical tillage/rotation system combinations were designated as main plot treatments and +/- maize as sub-plots, replicated four times. The six treatments, thus, were: (1) maximum-tilled cotton monoculture (Max CC), (2) maximum-tilled cotton-maize (Max CM), (3) minimum-tilled cotton monoculture (Min CC), (4) minimum-tilled cotton-maize (Min CM), (5) minimum-tilled cotton-wheat (Min WCF) and (6) minimum-tilled cotton-wheat-maize (Min WCM) (Table 11.1). Cotton and rotation crops were irrigated at an average rate of 100 mm subject to water availability, rainfall, and soil water content. All crops were harvested mechanically with cotton picking occurring after chemical defoliation. Maize 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. Details of the field layout and crop management were reported by Hulugalle et al. (2020) and Nachimuthu et al. (2018).

Table 11.1 Treatment details and rotation history of fields C1 and D1 over the experimental period (1993 to 2015)

Field	C1	C1	C1	C1	C1	C1
Historic treatment (1985-2011)	Max CC	Max CC	Min CC	Min CC	Min WCF	Min WCF
Treatment (2011-2015)	Max CC	Max CM	Min CC	Min CM	Min WCF	Min WCM
Tillage depth	0.3 m	0.3 m	0.1 m	0.1 m	0.1 m	0.1 m
Summer crop even years	Cotton	Maize	Cotton	Maize	Cotton	Maize
Summer crop even years total fertiliser (kg N ha^{-1})	240-260	240-260	240-260	240-260	240-260	240-260
Winter crop even years	Fallow	Fallow	Fallow	Fallow	Fallow	Fallow
Winter crop even years total fertiliser (kg N ha^{-1})	-	-	-	-	-	-
Summer crop odd years	Cotton	Cotton	Cotton	Cotton	Cotton	Cotton
Summer crop odd years total fertiliser (kg N ha^{-1})	240-260	240-260	240-260	240-260	240-260	240-260

Winter crop odd years	Fallow	Fallow	Fallow	Fallow	Wheat	Wheat
Winter crop odd years total fertiliser (kg N ha^{-1})	-	-	-	-	80-100	80-100
Years soil cores were taken	1993, 2015	1993, 2015	1993, 2015	1993, 2015	1993, 2015	1993, 2015

Field	D1	D1	D1	D1
Treatments (2002 - 2015)	T1	T2	T3	T4
Tillage depth	0.1 m	0.1 m	0.1 m	0.1 m
Summer crop even years	Cotton	Cotton	Cotton	Cotton
Summer crop even years total fertiliser (kg N ha^{-1})	240-260	240-260	240-260	240-260
Winter crop even years	Cover crop*	Fallow	Wheat	Wheat
Winter crop even years total fertiliser (kg N ha^{-1})	- (#)	-	80-100	80-100
Summer crop odd years	Cotton	Cotton	Fallow	Fallow
Summer crop odd years total fertiliser (kg N ha^{-1})	240-260	240-260	-	-
Winter crop odd years	Cover crop*	Fallow	Fallow	Vetch
Winter crop odd years total fertiliser (kg N ha^{-1})	- (#)	-	-	-
Years soil cores were taken	2002, 2015	2002, 2015	2002, 2015	2002, 2015

* T1 cover crop was vetch 2002-2012, then oats 2013-2015

Oats received 20 kg N ha^{-1}

2.2.2 Field D1

The soil at the commencement of the study during 2002 was a deep, uniform grey clay and classified as a fine, thermic, smectitic, Typic Haplustert (Soil Survey Staff 2014). At the 0-1.2 m depth it had a particle size distribution of 64 g 100 g^{-1} clay (<2 µm), 11 g 100 g^{-1} silt (2–20 µm) and 25 g 100 g^{-1} sand (20 µm–2 mm), was neutral to alkaline and had an average pH in 0.01 M $CaCl_2$ of 7.0, and non-saline (electrical conductivity ($EC_{1:5}$) was 0.28 dS m^{-1}). Exchangeable sodium percentage (ESP) was 3 at 0–0.6 m and 9 at 0.6–1.2 m. The experimental treatments consisted of four cotton-based cropping systems sown with minimum tillage: (T1) vetch (*Vicia spp*.)-cotton rotation (summer cotton and winter vetch sown after cotton harvest each year), vetch was replaced with oats (*Avena sativa* L.) from 2013, (T2) continuous cotton (summer cotton and winter fallow every year), (T3) cotton-wheat rotation stubble incorporated (summer cotton and winter wheat, followed by a summer and winter fallow period where cotton was planted into wheat stubble which was incorporated into the beds by tillage post wheat harvest) and (T4) cotton - wheat stubble retained - vetch (summer cotton-winter wheat-summer fallow-summer and winter vetch-summer cotton) where wheat stubble was retained as an *in-situ* mulch into which the following vetch crop was sown. All treatments were sown after minimum tillage, viz. disc-hilling to repair 1m spaced beds before planting each year. Post-harvest, cotton plants were slashed and root-cut before the stalks were incorporated into the beds. The experiment was laid out as a randomised complete block with three replications and designed such that both cotton and rotation crop phases in T3 and T4 were sown every year, resulting in a total of 18 plots. Individual plots were 158-177 m long and 16 rows wide. The rows (beds) were spaced at 1 m intervals with vehicular traffic being restricted to the furrows. Conventional cotton was sown from 2002 to 2006, with GM varieties sown thereafter. Details of the experiment, its management and its impact on cotton agronomy, energy efficiency, soil quality, carbon dynamics and hydrology have been reported previously (Hulugalle et al., 2010; 2012; 2017; 2013). Further field details are outlined in Table 11.1.

2.2.3 Fields 3 and 4

The soil was a deep, uniform grey clay and classified as a fine, thermic, smectitic, Typic Haplustert (Soil Survey Staff 2014). At the 0-0.1 m depth it had a particle size distribution of 40 g 100 g^{-1} clay (<2 μm), 13 g 100 g^{-1} silt (2–20 μm) and 47 g 100 g^{-1} sand (20 μm–2 mm), was acid and had an average pH in 0.01 M $CaCl_2$ of 5.6 and was non-saline (electrical conductivity ($EC^{1:5}$) was 0.124 dS m^{-1}). Fields 3 and 4 were under conservation tillage for dryland cropping (the only operations were drilling seeds and fertilisers). During the 2019 winter cropping season (April sowing to November harvest) field 3 was sown with wheat and field 4 with chickpeas (*Cicer arietinum* L.). A starter fertiliser of Granulock® Z containing 11% N, 21.8% phosphorus, 4% sulfur and 1% zinc was drilled with an air seeder between 0.02-0.04 m before sowing. Post-harvest standing stubble was retained in both fields. Each field was considered as a treatment with three replications in each.

2.3 Sampling and analysis

Soil samples were taken 20 m from the head ditch and tail drain ends of each plot with a tractor-mounted hydraulic soil corer and divided into depths of 0-0.15, 0.15-0.3, 0.3-0.45 and 0.45-0.6 m in field C1 during 1993 and 2015 and 0-0.1, 0.1-0.3 and 0.3-0.6 m in field D1 during 2002 and 2015. Additional soil cores were taken during 2019 from field D1 at ACRI and in Fields 3 and 4 in Edgeroi using a Christie engineering post driver to drive steel coring tubes (0.042 m inside diameter) into the ground to be extracted with a tube puller. The cores from field D1 were taken in the tail drain, middle and head ditch end and bulked together at corresponding depths (0-0.02, 0.02-0.04, 0.04-0.06, 0.06-0.08 and 0.08-0.1 m) for each plot. Three soil cores were taken for each replication within a field and bulked together at corresponding depths (0-0.02, 0.02-0.04, 0.04-0.06, 0.06-0.08 and 0.08-0.1 m) from fields 3 and 4. Soils were air dried at 40°C. Samples from 1993 and 2002 were ground to pass through a 2 mm sieve by hand with a mortar and pestle. The samples from 2015 and 2019 were ground with a jaw crusher before being pulverised by hand with a mortar and pestle to pass through a 2 mm sieve. Head ditch and tail drain samples from each plot were mixed to produce a composite sample for each depth and archived as soon as possible after sampling and processing. In 2019 all the archived samples were analysed simultaneously for pH (1:5 soil:0.01 M $CaCl_2$) and electrical conductivity (1:5 soil:water suspension). Diethylenetriamine penta acetic acid (DTPA) analysis was used to remove Cu, Zn, Mn and Fe absorbed on solid phases, along with water-soluble constituents to simulate plant root uptake and act as an estimate of micronutrient plant availability (Rayment and Lyons, 2010). The analysis was performed for 2 h on air-dried soil at a soil:solution ratio of 1:2 and buffered to pH 7.3 (suited to alkaline soils in this experiment). DTPA Zn was not reported in 2015 due to the potential contamination of samples during processing which only impacted Zn. Consequently, the soil was re-sampled from selected plots (T2 – continuous cotton and T4 – cotton – wheat standing stubble) in 2020 from field D1 and analysed for DTPA Zn. The results from 2020 were compared with 2002 samples from the same treatments. Further analyses for total Cu, Zn, Mn, and Fe were conducted by scanning with a lab-mounted Bruker

Tracer III-SD portable X-ray fluorescence (pXRF) machine using settings calibrated for Vertisols (McLaren et al., 2012). The pXRF non-destructively measures the unique elemental characteristics of each micronutrient through the level of X-ray energy omitted by the element while irradiated by a source of excitation, thereby indicating the total amount of specific elements within a sample.

2.4 Statistical analysis

Each field's results were individually analysed by analysis of variance for a split-plot design, except field C1 in 2015 which was analysed as a split-split plot design to account for the introduction of the maize treatment as split-plots. Treatment was designated as the main-plot treatment and sampling depth as the sub-plot treatment for fields C1 and D1. For fields 3 and 4, field history was considered as treatment main plots and depth as subplots. Pairwise comparisons used the least significant difference conditional on significant ($p < 0.05$) effects detected by analysis of variance. Heterogeneity of variance and normal distributions for all responses were examined. Statistical analysis was performed using GenStat 20th Edition (VSN International Ltd).

3 Results and discussion

3.1 Whole profile micronutrient changes under varying tillage and crop rotations (0-0.6 m depth)

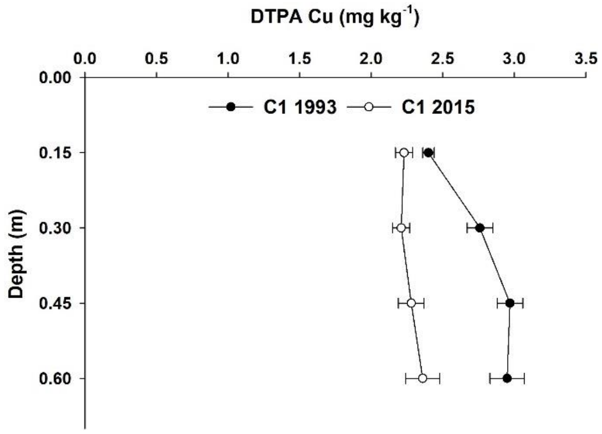
3.1.1 Whole profile XRF total micronutrients (0-0.6 m depth)

The XRF analysis did not show any evidence of declines in total micronutrients (supplementary data) within this experiment. Total Cu in field D1 (reported as XRF counts) increased by 4% from 2002 to 2015 ($p < 0.05$) in the 0-0.6 m depth, however, there was no evidence of stratification. Mean total Fe, Mn, and Zn (0-0.6 m depth) did not change with time. While the increase in total Cu could not be explained in this experiment, elsewhere it could be attributed to fungicide application or a trace element in a fertiliser product (Schneider et al., 2019; Wyszkowski and Brodowska, 2021).

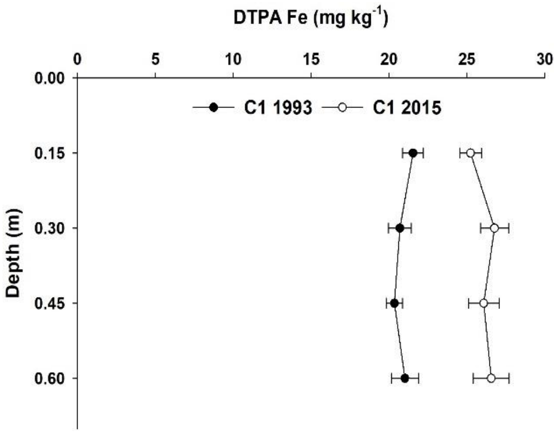
The Vertisols of north-west New South Wales are inherently fertile with rich nutrient status, although some of the other nutrients such as phosphorus are declining (Nachimuthu et al., 2022). Cropping on Australian soils has been relatively recent compared to most countries (Bellotti and Rochecouste, 2014). This study indicates that total micronutrient status has not been altered to a level which can be detected using current analytical methods. These two fields were under intensive cropping (22 and 13 years for fields C1 and D1, respectively) over the experimental period. There was no fertiliser application of any micronutrients (Cu, Fe, Mn, or Zn) during this experimental period despite nutrient export in harvested seeds in those years. This suggests that the micronutrient reserves in these cotton-growing Vertisols are not depleted and appropriate soil management to improve micronutrient availability will be the determinant factor of plant acquisition (Wei et al., 2006).

3.1.2 Changes in whole profile (0-0.6 m depth) DTPA-extractable micronutrient concentrations over the long term

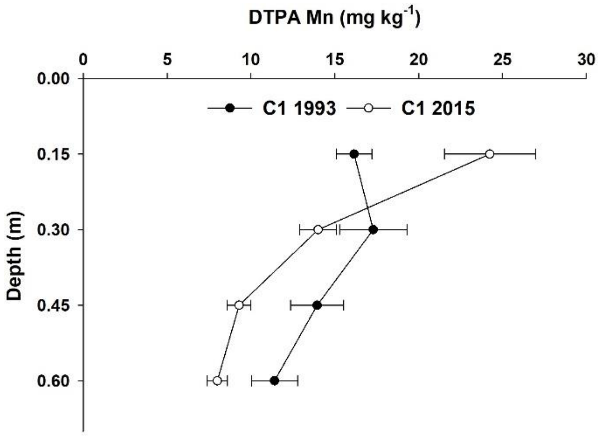
The results suggest that DTPA Cu concentrations declined by 18% ($p < 0.05$) and DTPA Fe increased by 23% ($p < 0.05$) over 22 years in field C1 (Figure 11.1A, 11.1B), averaged across 0-0.6 m depth. Over 13 years in field D1, there were no observed changes to mean DTPA Cu from 0-0.6 m while DTPA Fe declined by 36% ($p < 0.001$) (Figure 11.2A, 11.2B). Mean DTPA Mn remained similar in field C1 when compared from 1993 to 2015 and field D1 from 2002 to 2015 across 0-0.6 m depth, however, differed in field C1 in 2015 when separated by treatment ($p < 0.001$) (Table 11.2). There was no change in average DTPA Zn concentration in the 0-0.6 m depth (Figure 11.2D).



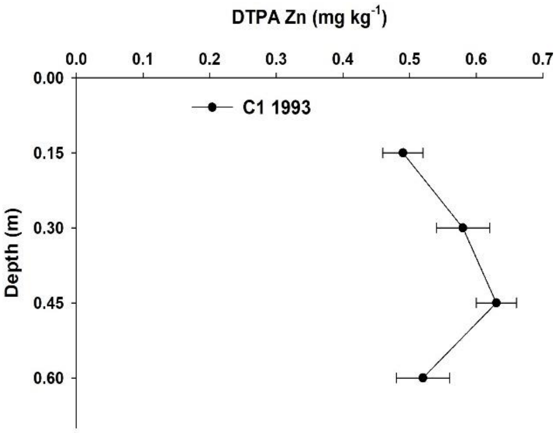
A)



B)

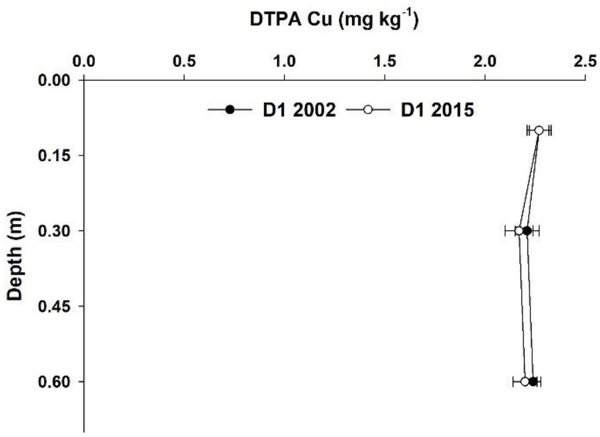


C)

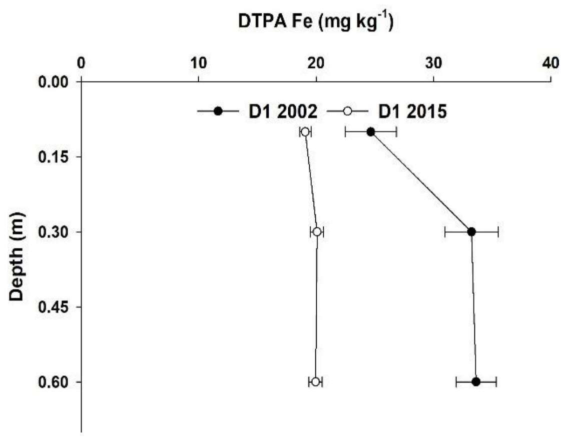


D)

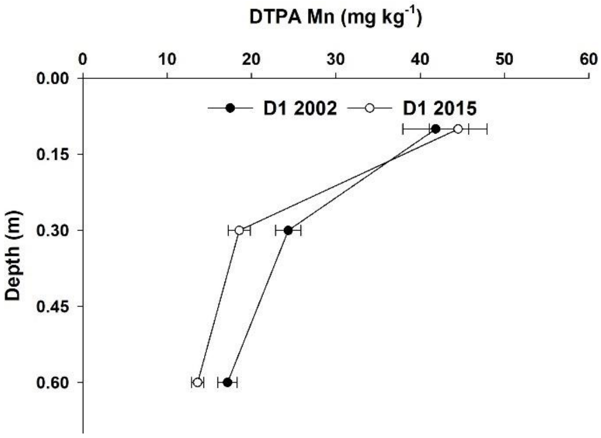
Figure 1.1 DTPA extractable micronutrient (Cu, Fe, Mn, Zn) concentration (mg kg^{-1}) of a Vertisol in field C1 (1993 and 2015) from 0-0.6 m depth. Error bars represent the standard error of the mean.



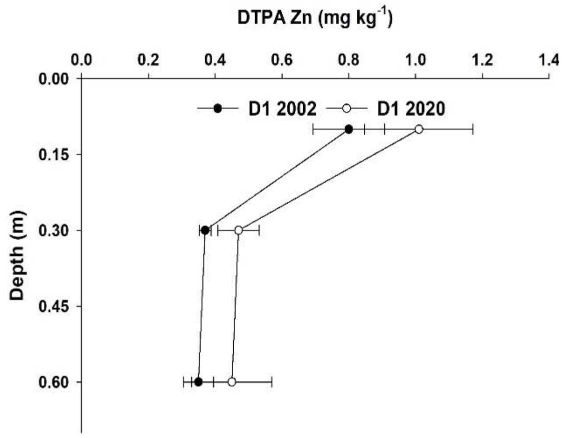
A)



B)



C)



D)

Figure 11.2 DTPA extractable micronutrient (Cu, Fe, Mn, Zn) concentration (mg kg^{-1}) of a Vertisol in field D1 (2002 and 2015 for Cu, Fe and Mn - 2002 and 2020 for Zn) from 0-0.6 m depth. Error bars represent the standard error of the mean.

Table 11.2 Average concentration (mg kg^{-1}) of DTPA Mn from 0-0.6 m depth over maximum (Max) and minimum (Min) tillage and continuous cotton (CC), cotton - maize (CM), wheat - cotton (WCF) and wheat - cotton - maize (WCM) crop rotations (LSD $p < 0.05$)

Treatment	0-0.15	0.15-0.3	0.3-0.45	0.45-0.6	Relative Mn stratification#
Max CC	16	12	8	7	76
Max CM	18	14	9	7	73
Min CC	25	15	9	7	134
Min CM	25	18	10	9	109
Min WCF	25	13	10	9	133
Min WCM	37	13	9	7	278
LSD Treatment			3.01		
LSD Depth			1.9		
LSD Treatment*Depth			4.9		

#Relative Mn stratification = ((DTPA Mn 0-0.15 m – DTPA Mn 0.15-0.6 m)/DTPA Mn 0.15-0.6 m) * 100

Mean DTPA Mn (0-0.6 m depth) concentrations were in the order of minimum tillage wheat – cotton – maize (67 mg kg^{-1}) > minimum tillage cotton – maize (61 mg kg^{-1}) > minimum tillage wheat – cotton (57 mg kg^{-1}) > minimum tillage continuous cotton (56 mg kg^{-1}) > maximum tillage cotton – maize (49 mg kg^{-1}) > maximum tillage continuous cotton (44 mg kg^{-1}). Therefore, DTPA Mn was higher under minimum than maximum tillage, and was higher when cereal crops (wheat or maize) were included in the rotation. As there were no changes in XRF Mn across treatments, the results suggest that Mn availability from 0-0.6 m depth was driven by changes in soil properties. DTPA Mn was positively correlated with soil organic carbon ($p < 0.001$, $R^2 = 0.7$), which has been observed in other studies (Cotter and Mishra, 1968; Reiss and Chifflard, 2015). Additionally, Terry et al. (2008) reported that cotton-wheat rotations increased SOC when compared to continuous cotton in irrigated Vertisols. Furthermore, including maize within continuous cotton and cotton–wheat systems increased surface SOC concentrations, compared to rotations without maize (Hulugalle et al., 2020). Hence DTPA-extractable Mn availability was likely driven by soil organic carbon, which in turn was influenced by tillage and crop rotation practices. In contrast to our results, Wright et al. (2007) found no influence of tillage on Mn availability in their 4-year nutrient stratification study under cotton rotations in an alkaline Texas silty clay loam. This may have been due to the short time frame of their study (4 years) whereas the duration of our study was 22 years. Unlike in our study, soil carbon results were not reported by Wright et al. (2007) and thus it is not possible to comment on the relationship between SOC and Mn availability in their study. Tillage and cropping system did not significantly affect mean DTPA Fe in field C1 (Figure 11.1B) or field D1 (Figure 11.2B) from 0-0.6 m depths. Similarly, there was no change in XRF Fe over time, indicating no change in total Fe, therefore the changes to DTPA Fe were due to temporal changes in soil properties that were unrelated to treatment, regulating plant availability. The three chemical processes which typically are responsible for Fe availability in soils are pH, chelation, and redox potential (Eh) during waterlogging (Fageria and Nascente, 2014; Husson, 2013; Lucena et al., 1987). The most easily observed of these factors is soil pH, which decreased from 7.5 in 1993 to 7.3 in 2015 (0-0.6 m depth) in field C1 and was negatively correlated with DTPA Fe ($R^2 = 0.34$, $p < 0.001$). Conversely, pH in field D1 increased over 13 years from 6.9 to 7.4 (0-0.6 m depth) but was also negatively correlated with DTPA Fe ($p < 0.05$). As soil pH decreases, the solubility of Fe increases (Fageria and Nascente, 2014; Haynes and Swift, 1985; Sarkar and Jones, 1982). Generally, root exudates increasing Fe availability in the rhizosphere play a significant role in Fe-deficient soils (Prasad, 2011). However, there was no Fe deficiency observed in either field C1 or D1 and it is unlikely that Fe chelation significantly affected changes to mean DTPA Fe from 0-0.6 m. While Fe is susceptible to state changes under the influence of redox and the experimental fields were flood irrigated (on average 6-7 times per growing season), there was no Fe-induced plant stress observed in this experiment due to anaerobiosis in the 0-0.6 m depth. This is despite research indicating that at least 48 hours is required for cotton root function to return in Vertisols after waterlogging (Dodd et al., 2013). While pH appears to be the main driver of DTPA Fe concentration changes in this experiment, it is important to note that there is an interconnected relationship between pH and Eh. The nature of this relationship is complex, and challenging to assess under field conditions, and the literature is often contradictory concerning its significance (de Mars and Wassen, 1999; Fiedler et al., 2007; Rabenhorst et al., 2009; Unger et al., 2008).

While there was no Fe toxicity observed in this study, Australian cotton-producing soils are predicted to acidify over the long term (Singh et al., 2003), which may lead to the over-availability of Fe in the future. The chemical reaction resulting from the application of N as urea or anhydrous ammonia may temporarily increase soil pH as NH_3 removes H^+ ions from the soil in conversion to NH_4^+, however as NH_4^+ converts to NO_3^- the H^+ ions will be released back to the soil, resulting in an overall pH decrease as this second reaction is more powerful (Janke et al., 2022). These risks are amplified by the over-application of N within Australian cotton systems and could therefore be mitigated by improved N use efficiency (Macdonald et al., 2018). Further, it is common practice in Australian irrigated cotton systems to deliver a top dressing of urea applied via irrigation water around peak flowering (Latimer, 2018). This could result in temporary pH flux and impact micronutrient availability at a time when crop micronutrient demand is high.

Despite the decline of mean DTPA Cu (0-0.6 m) in field C1 (Figure 11.1A), there was no influence of tillage or crop rotation observed. This decline contrasts with previous studies reporting increased Cu availability with decreasing soil pH (Fageria and Nascente, 2014; Oorts, 2013). Copper is considered to be the most easily bound by organic matter (Mengel et al., 2001) among the micronutrient cations in this study, however, the soil management practices for genetically-modified cotton require pupae busting, even for minimum tilled plots which may enhance breakdown of crop residues. As a result, the mass of residues retained may be insufficient to induce a measurable difference in binding the Cu and its availability. Copper availability can be complex. Brennan (1999) stated environmental factors, including temperature, light and water can all impact Cu availability to plants. The soil DTPA Cu concentration in fields C1 and D1 did not approach deficiency or toxicity levels.

3.2 Influence of tillage and crop rotation on patterns of micronutrient stratification

3.2.1 Patterns of stratification in XRF total micronutrients

Among the four micronutrients investigated in fields C1 and D1, only Fe and Cu in field C1 indicated a pattern of stratification. XRF Fe was observed in decreasing order of concentration from top depth (0-0.15 m) to lower depth (0.45-0.6 m) in both 1993 and 2015. XRF Cu in field C1 was significantly different across depths, but there was no change in the pattern of concentration between 1993 and 2015. Changes in XRF Fe and Cu were not influenced by tillage or crop rotation. There were no changes in XRF Mn or Zn. Despite 22 years of micronutrient removal via crop harvest, the unaltered total micronutrient levels suggest these Vertisols have a considerable total supply for the future.

3.2.2 Patterns of stratification in DTPA-extractable micronutrients

While stratification was observed in DTPA Cu, Zn and Mn at different times within fields C1 and D1, only DTPA Mn was influenced by tillage and crop rotation. There was no evidence of DTPA Fe stratification in this experiment.

Stratification of DTPA Cu was only observed in field C1 during 1993 as concentration was 20% lower in the 0-0.15 m depth than in the 0.15-0.6 m depth ($p < 0.05$) and was not seen in field C1 during 2015 (Figure 11.1A), or field D1 during 2002 or 2015 (Figure 11.2A). The decline of mean DTPA Cu from 1993 to 2015 in 0-0.6 m depth in field C1 may be responsible for the absence of surface stratification as it occurred mostly in the 0.15-0.6 m depths. As previously noted, Cu availability is complex (Brennan, 1999) and as there was no observed Cu toxicity or deficiency the drivers of availability within this experiment were not investigated further.

There was no evidence of DTPA Zn stratification in field C1 during 1993 (contaminated DTPA Zn results during 2015 not presented), however, DTPA Zn was stratified in field D1 during both 2002 and 2020 irrespective of crop rotation or soil management and the pattern of stratification remained similar between years (mean of 1.17 mg kg^{-1} in 0-0.1 m depth compared to 0.41 mg kg^{-1} in 0.1-0.6 m depth) (Figure 11.2D). The combination of minimum tillage in field D1 that did not disturb the soil below 0.1 m depth and the immobile nature of Zn is the likely cause of the stratified concentration in the 0-0.1 m depth. Furthermore, post-harvest crop residue mulching may have further concentrated Zn in the surface 0-0.1 m. DTPA Zn concentration in the subsoil (0.1-0.6 m) during both years was below 0.5 mg kg^{-1}, the proposed critical concentration for Zn deficiency (CRDC and CottonInfo, 2018; GRDC, 2013) and well below the values observed by Constable et al. (1988). Rochester et al. (2012) reported that 73% of Zn uptake in cotton occurred during peak flowering, which could highlight a risk of yield reduction if DTPA Zn is below the critical concentration within the extraction zone. While DTPA Zn concentration may indicate a potential deficiency, plant tissue tests are more accurate in confirmation and should be considered in conjunction with soil properties including pH and field history (Norton, 2014).

DTPA Mn was stratified in fields C1 and D1 over the 22 and 13-year experiments in each field, respectively. Both tillage and crop rotation influenced DTPA Mn stratification in field C1 (Table 11.2). When treatments in C1 during 2015 were separated by tillage (maximum compared to minimum tillage), results indicated a greater magnitude of stratification under minimum tillage (159% greater DTPA Mn concentration in the 0-0.15 m than in the 0.15-0.6 m depth) than maximum tillage (74% greater DTPA Mn concentration in the 0-0.15 m depth than in the 0.15-0.6 m depth). However, there was no influence of treatment in field D1. Mean DTPA Mn was 13% higher in the 0-0.15 m than in the 0.15-0.6 m depth ($p < 0.05$) and 103% higher in the 0-0.1 m depth than in the 0.1-0.6 m depth ($p < 0.05$) in fields C1 during 1993 (Figure 11.1C) and D1 during 2002 (Figure 11.2C), respectively. The magnitude of stratification increased over time in both fields as DTPA Mn concentration during 2015 in field C1 was 116% higher ($p < 0.05$) in the 0-0.15 m depth than in the 0.15-0.6 m depth, and 177% higher in the 0-0.1 m depth than in the 0.1-0.6 m depth in field D1. As stated in Section 3.1.2, during 2015 there was a positive correlation between SOC and DTPA Mn concentration in field C1, which was also observed in field D1 ($p < 0.001$, $R^2 = 0.68$). As soil carbon has a positive relationship with Mn availability, management practices that influence SOC are likely to influence DTPA Mn concentration. Cotton crops are mechanically mulched post-harvest, returning organic material to the surface soil. Under maximum tillage, the organic material is mixed through the top 0-0.3 m of soil, whereas minimum tillage concentrates organic material in the top 0-0.1 m depth. The accumulation of SOC in the topsoil under minimum tillage was also observed by Haddaway et al. (2017). As Mn is extracted from all depths this could explain the decline in concentration at depth, compared to the increase in the topsoil. The same can be said for the other micronutrients, however, within this experiment, other factors appear to have had a more significant influence on their DTPA-extractability.

3.3 Tillage effects on topsoil stratification

A requirement of growing Bt cotton in Australia is pupae busting tillage (a tillage pass to at least 0.1 m depth to facilitate the destruction of *Helicoverpa spp.* pupae) after cotton harvest if the crop has not been defoliated by March 31st (CottonInfo, 2018). For this reason, minimum-tilled irrigated cotton systems in Australia will often undergo an annual tillage operation, mixing soil to at least 0.1 m depth. To understand the impact of topsoil tillage on micronutrient stratification in irrigated cotton systems, we compared samples from two treatments (continuous cotton and cotton–wheat rotation) of field D1 with samples from two fields (fields 3 and 4) of a nearby broadacre farm of similar soil type, under conservation tillage for dryland cropping (the only operation is drilling seeds and fertilisers).

3.3.1 Tillage effects on XRF total micronutrient stratification in the topsoil

Total Fe (reported as XRF counts) was 59% lower in the dryland compared to the irrigated site averaged from 0-0.1 m depth ($p < 0.05$). XRF Fe at both sites followed a similar pattern of stratification showing a 4% higher concentration from 0-0.04 m, than in the 0.04-0.1 m depths ($p < 0.05$). Despite the difference in average XRF Fe between the irrigated and dryland sites, the similarities in stratification suggest this is likely due to the underlying soil geology and not differences in tillage practices. XRF Zn was stratified and followed the same pattern of stratification over both sites, being 8% higher in concentration in the 0-0.04 m than in the 0.04-0.1 m depth ($p < 0.05$). The concentration of XRF Zn was 33% higher in the irrigated compared to the dryland site in the 0-0.1 m depth ($p < 0.05$), which may be reflective of higher natural fertility at the irrigated site. There was no stratification or evidence of differences between the dryland and irrigated sites for XRF Cu or Mn (data not presented).

3.3.2 Tillage effects on DTPA-extractable micronutrient stratification in the topsoil

All DTPA micronutrients in this study were stratified in the 0-0.1 m depth of both fields 3 and 4 of the dryland site. Comparatively, in field D1 only DTPA Mn was stratified in both treatments, while DTPA

Fe stratification differed between treatments and there was no stratification observed in either DTPA Cu or Zn in the 0-0.1 m depth. The difference in stratification between DTPA Cu and Zn in the dryland compared to the irrigated site indicate the influence of tillage on these micronutrients, however, suggests that there was a reduced influence of tillage on DTPA Fe or Mn stratification in the topsoil.

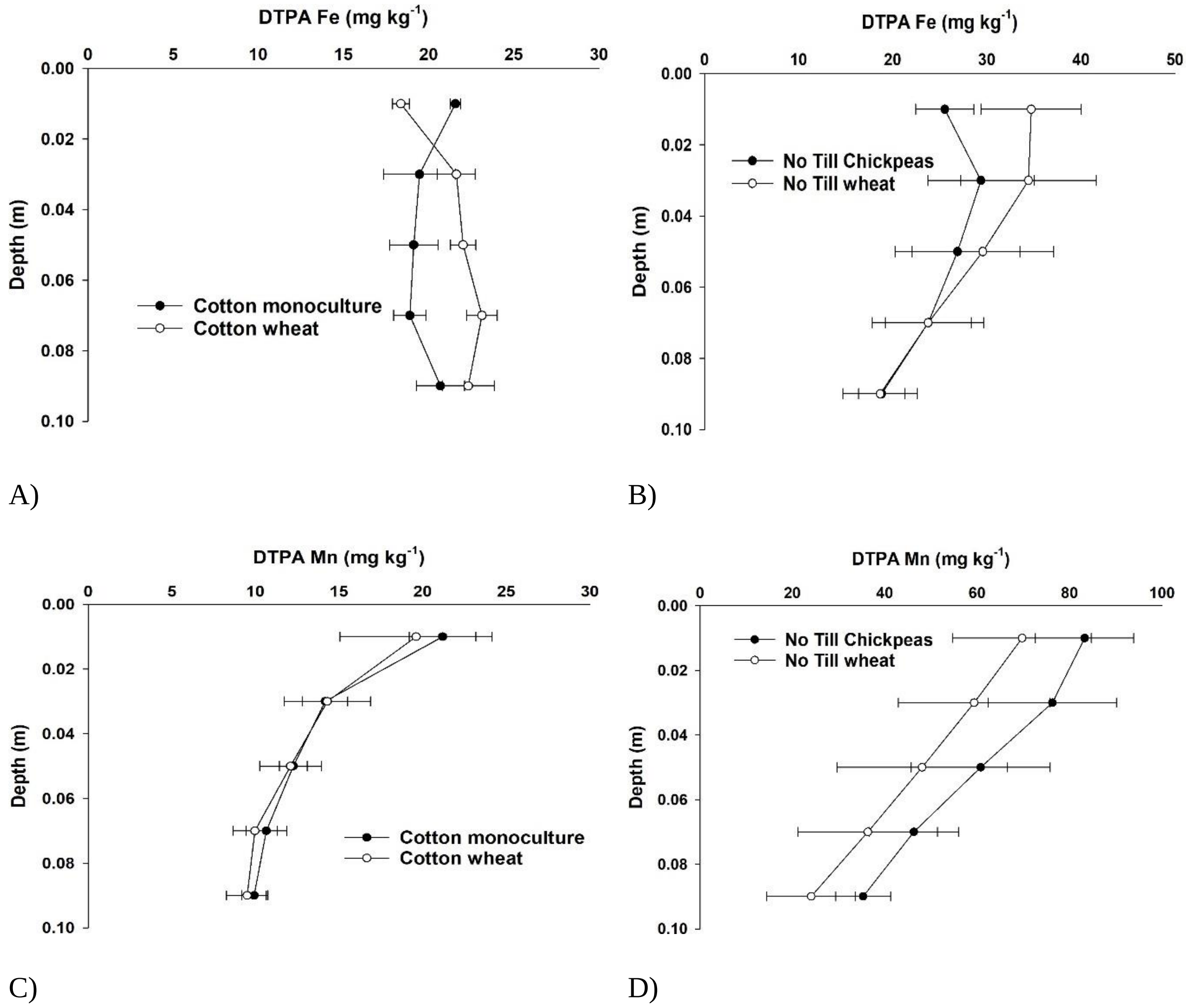
There was a negative correlation observed between DTPA Fe and soil pH ($p < 0.05$) across the combined treatments of the dryland and both treatments of the irrigated sites. While pH was a significant driver of Fe availability, relatively low correlation coefficients in the continuous cotton and cotton–wheat rotations (Table 11.3) suggest the influence of other factors. Table 11.3 shows that when comparing depth intervals below 0-0.02 m, DTPA Fe was always higher under cotton-wheat than continuous cotton rotations. Cereal monocots (i.e. wheat) are capable of exuding phytosiderophores, used to create zones of increased Fe availability within their rhizospheres (Rengel and Römheld, 2000; Wallace, 1981). This may translate to greater Fe uptake, and therefore greater plant availability of Fe in the form of post-harvest organic material returns in the wheat rotation than compared to continuous cotton.

Table 11.3 DTPA Fe concentration (mg kg^{-1}) and pH ($CaCl_2$) in dryland (average of chickpeas and wheat) compared to irrigated continuous cotton (CC) and cotton – wheat (CW) rotation from 0-0.1 m depth

	Dryland		Irrigated			
Depth (m)	DTPA Fe	pH	DTPA Fe CC	DTPA Fe CW	pH CC	pH CW
0-0.02	30	5.4	22	18	6.8	6.7
0.02-0.04	32	5.3	20	22	6.9	6.8
0.04-0.06	28	5.4	19	22	6.9	6.8
0.06-0.08	24	5.8	19	23	6.9	6.9
0.08-0.1	19	5.9	21	22	6.9	6.8
R^2	0.66		0.47	0.21		
LSD (p = 0.05) Treatment*Depth	34.62	2.05	5.22		0.17	

Stratification of DTPA Mn was observed regardless of tillage, with concentrations 61% and 73% higher in the dryland and irrigated sites, respectively when comparing the 0-0.04 m and 0.04-0.1 m depths (Figure 11.3C, 11.3D). The stratification of DTPA Mn was in contrast to XRF Mn, as there was no evidence of stratification or differences in concentration between the dryland and irrigated sites. Manganese concentration (DTPA extractable) was negatively correlated with pH in the no-till wheat ($p < 0.001$, $R^2 = 0.73$) and no-till chickpea ($p < 0.05$, $R^2 = 0.5$) rotations of the dryland site and the continuous cotton ($p < 0.05$, $R^2 = 0.32$) in the irrigated site. While this regression satisfactorily explains DTPA Mn concentration in dryland no-till wheat, the variance in the other crop rotations as well as the lack of relationship between DTPA Mn and pH in irrigated cotton wheat show that Mn availability was driven by additional factors under dryland and irrigated systems which need further investigation. As reported in previous Section 3.2.2, there was a positive correlation between DTPA Mn and SOC in the irrigated field in 2015 (4 years before the 2019 sampling event). This may account for DTPA Mn stratification in the irrigated treatments as these are under minimum tillage in this field, which suggests

SOC may also be stratified. Knezek and Greinert (1971) stated that as more Fe is introduced into the soil solution, Mn will become less plant available, however, our study found a positive correlation in dryland no-till chickpeas between DTPA Fe and DTPA Mn and no correlation in the other rotations. Kochian (1991) observed that a negative correlation between Fe and Mn availability had been widely reported and suggested that Mn availability may have been increased in Fe-deficient soils as this can induce some plant roots to exude chelating agents which alter the soil conditions of the rhizosphere. While the changes in soil conditions are targeting Fe solubilisation, Fe and Mn are often influenced by similar properties, thereby increasing Mn as well as Fe availability. The positive correlation between DTPA Fe and Mn in our study is likely reflective of similar soil properties driving their availability. Comparing the results of previous studies to ours highlights the complexity of micronutrient availability and the importance of soil properties in controlling micronutrient dynamics.



A) B) C) D)

Figure 11.3 DTPA extractable micronutrient (Fe, Mn) concentration (mg kg^{-1}) of Vertisols in field D1 under cotton monoculture and cotton wheat rotation and fields 3 and 4 under no-till chickpeas and no-till wheat from 0-0.1 m depth. Error bars represent the standard error of the mean.

Copper (DTPA extractable) within the dryland site was 13% higher in the 0-0.04 m depth, compared to the 0.04-0.1 m depth (Figure 11.4B) however there was no stratification at the irrigated site. Copper accumulation on the surface may have occurred due to the application of Cu-containing fungicides, additionally, there was a negative correlation between DTPA Cu and pH at the dryland site ($p < 0.001$, $R^2 = 0.36$).

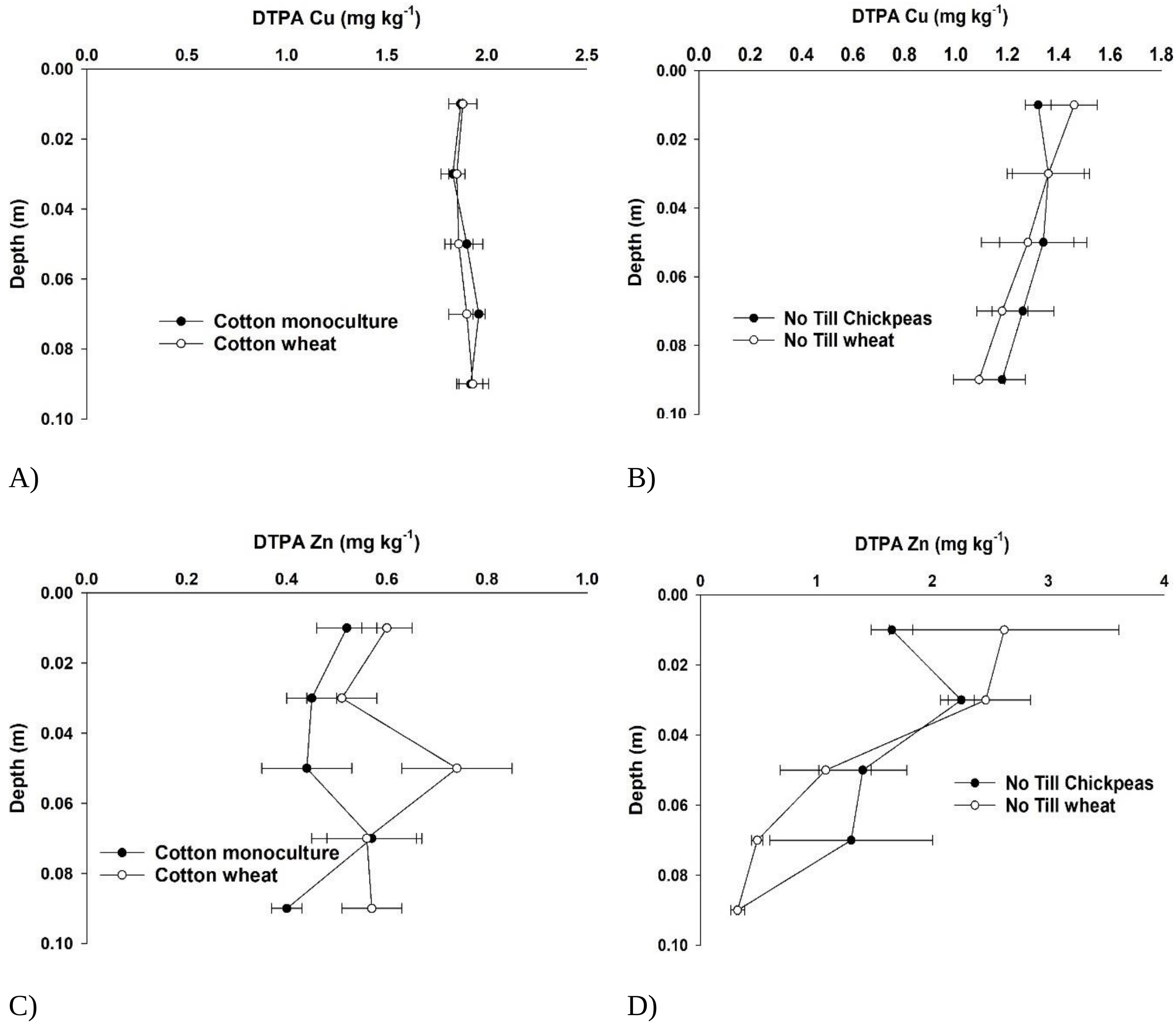


Figure 11.4 DTPA extractable micronutrient (Cu, Zn) concentration (mg kg^{-1}) of Vertisols in field D1 under cotton monoculture and cotton wheat rotation and fields 3 and 4 under no-till chickpeas and no-till wheat from 0-0.1 m depth. Error bars represent the standard error of the mean.

Although the stratification of DTPA Zn in the dryland compared to the irrigated site appears to be influenced by tillage, a major difference between the two sites is the dryland site regularly received a starting fertiliser containing Zn before winter crop planting. This is reflected in the concentration of DTPA Zn at the dryland site being 174% higher in the top 0-0.04 m depth, than the 0.04-0.1 m depth. It is evident that despite the use of a Zn-containing fertiliser, DTPA extractable Zn in the 0.08-0.1 m depth fell below the 0.5 mg kg^{-1} critical soil concentration at the dryland site, which may indicate potential Zn deficiency (CRDC and CottonInfo, 2018; GRDC, 2013). Similarly, within the irrigated site DTPA Zn concentration fell below 0.5 mg kg^{-1} between 0.02-0.04 m depth and 0.08-0.1 m depth. As mean DTPA Zn concentration from 0-0.1 m depth over these sites were 1.39 mg kg^{-1} and 0.54 mg kg^{-1} in dryland and irrigated sites respectively, the average concentration with usual commercial soil sampling increments (i.e. 0-0.1 m, 0.1-0.3 m, 0.3-0.6 m etc.), may not reflect the actual amount available to the plant at key times. Planting at a deeper depth to place the seed proximal to soil moisture is a common practice. In such instances, if the seeds are planted below 0.05 m depth where the Zn concentration levels were below the soil test critical value, the seedlings may suffer a Zn deficiency during early crop growth. To minimise these issues under no-till cropping systems, strategic tillage could offer a potential solution to distribute the stratified nutrients across the planting zones and minimise the risk of stratification (Dang et al., 2018).

4 Conclusion

There was no evidence of decline or changes in stratification of total micronutrients in intensively managed Vertisols. However, stratification and decline were observed in DTPA-extractable Mn, Cu, Fe and Zn in some tillage and crop rotation systems in long-term cotton experiments. Micronutrient extractability was related to changes in soil properties, specifically pH and SOC, rather than reduced total micronutrient status. Tillage frequency influenced soil properties and reduced topsoil stratification. Greater variation in micronutrient extractability in the topsoil (0-0.1 m depth), compared to the subsoil (below 0.1 m depth) was observed when sampling in 0.02 m increments, which would be masked if sampling in standard 0.1 m increments. Excepting Zn, DTPA-extractable Mn, Fe or Cu were not observed nearing critical deficiency concentrations, and therefore micronutrient stratification and decline in irrigated cotton-growing Vertisols are unlikely to be yield limiting, provided that surface soil properties are well managed. The findings of this study will be useful for benchmarking the micronutrient status after an extended period of cropping in the future and also for the soil management decisions (such as pH and SOC). Australian cotton growing regions are expanding, in some cases to areas of less fertile soil types, such as the duplex soils (Alfisols, Aridisols, Ultisols) of southern New South Wales. These soils require further investigation to determine the influence of micronutrient stratification and the decline in their productivity. Future research should also consider environmental impacts (temperature, light, oxygen exposure) on micronutrient speciation and the limitations of DTPA extraction in accurately replicating soil conditions.

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References

ABS, 2018. Land Management and Farming in Australia Vol. 2022. Australian Bureau of Statistics www.abs.gov.au (accessed 20 March 2022).

Armstrong, R. D., Perris, R., Munn, M., Dunsford, K., Robertson, F., Hollaway, G. J., Leary, G. J. O., 2019. Effects of long-term rotation and tillage practice on grain yield and protein of wheat and soil fertility on a Vertosol in a medium-rainfall temperate environment. Crop Pasture Sci. 70, 1-15. https://doi.org/10.1071/CP17437.

Basche, A. D., DeLonge, M. S., 2019. Comparing infiltration rates in soils managed with conventional and alternative farming methods: A meta-analysis. PLoS One 14, e0215702-e0215702. https://doi.org/10.1371/journal.pone.0215702.

Bellotti, B., Rochecouste, J. F., 2014. The development of Conservation Agriculture in Australia-Farmers as innovators. Int. Soil Water Conserv. Res. 2, 21-34. https://doi.org/10.1016/S2095-6339(15)30011-3.

BOM, 2020. Climate statistics for Australian locations. Bureau of Meteorology www.bom.gov.au (accessed 27 May 2022)

Bowles, T. M., Mooshammer, M., Socolar, Y., Calderón, F., Cavigelli, M. A., Culman, S. W., Deen, W., Drury, C. F., Garcia y Garcia, A., Gaudin, A. C. M., Harkcom, W. S., Lehman, R. M., Osborne, S. L., Robertson, G. P., Salerno, J., Schmer, M. R., Strock, J., Grandy, A. S., 2020. Long-term evidence shows that crop-rotation diversification increases agricultural resilience to adverse growing conditions in North America. One Earth 2, 284-293. https://doi.org/10.1016/j.oneear.2020.02.007.

Brennan, R. F., Best, E., 1999. Copper, in: Peverill, L.A., Reuter, D.J., (Eds.). Soil Analysis an Interpretation Manual, CSIRO Publishing, Clayton, Victoria, Australia, pp. 263.

Constable, G., Rochester, I., Cook, J., 1988. Zinc, copper, iron, manganese and boron uptake by cotton on cracking clay soils of high pH. Aust. J. Exp. Agr. 28, 351-356. https://doi.org/10.1071/EA9880351.

Cotter, D. J., Mishra, U. N., 1968. The role of organic matter in soil manganese equilibrium. Plant Soil 29, 439-448. https://doi.org/10.1007/BF01348975.

CottonInfo, 2018. Australian Cotton Production Manual, Cotton Research and Development Corporation, Narrabri, NSW, Australia. https://irec.org.au/wp-content/uploads/Australian-Cotton-Production-Manual-2018.pdf (accessed 4 November 2022).

CRDC, CottonInfo, 2018. NUTRIpak: A practical guide to cotton nutrition, Cotton Research and Development Corporation, Narrabri, NSW, Australia. https://www.cottoninfo.com.au/sites/default/files/documents/NUTRIpak%202018.pdf (accessed 4 November 2022).

Dang, Y. P., Balzer, A., Crawford, M., Rincon-Florez, V., Liu, H., Melland, A. R., Antille, D., Kodur, S., Bell, M. J., Whish, J. P. M., Lai, Y., Seymour, N., Carvalhais, L. C., Schenk, P., 2018. Strategic tillage in conservation agricultural systems of north-eastern Australia: why, where, when and how? ESPR 25, 1000-1015. https://doi.org/10.1007/s11356-017-8937-1.

Dang, Y. P., Moody, P. W., Bell, M. J., Seymour, N. P., Dalal, R. C., Freebairn, D. M., Walker, S. R., 2015. Strategic tillage in no-till farming systems in Australia's northern grains-growing regions: II. Implications for agronomy, soil and environment. Soil Tillage Res. 152, 115-123. https://doi.org/10.1016/j.still.2014.12.013.

de Mars, H., Wassen, M. J., 1999. Redox potentials in relation to water levels in different mire types in the Netherlands and Poland. Plant Ecol. 140, 41-51. https://doi.org/10.1023/A:1009733113927.

Dodd, K., Guppy, C. N., Lockwood, P. V., Rochester, I. J., 2013. Impact of waterlogging on the nutrition of cotton *Gossypium hirsutum* produced in sodic soils. Crop Pasture Sci. 64, 816-824, 9. https://doi.org/10.1071/CP13093.

Fageria, N. K., Baligar, V. C., Jones, C. A. 2010. Growth and mineral nutrition of field crops 3rd Ed. CRC Press, Boca Raton, Florida.

Fageria, N. K., Nascente, A. S., 2014. Management of soil acidity of South American soils for sustainable crop production. Adv. Agron., 128, 221-275. https://doi.org/10.1016/B978-0-12-802139-2.00006-8.

Fiedler, S., Vepraskas, M. J., Richardson, J. L., 2007. Soil redox potential: Importance, field measurements, and observations. Adv. Agron., 94, 1-54. https://doi.org/10.1016/S0065-2113(06)94001-2.

Filippi, P., Jones, E., Ginns, B., Whelan, B., Roth, G., Bishop, T., 2019. Mapping the depth-to-soil pH constraint, and the relationship with cotton and grain yield at the within-field scale. Agron. J. 9, 251. https://doi.org/10.3390/agronomy9050251.

Fleming, D., Musser, F., Reisig, D., Greene, J., Taylor, S., Parajulee, M., Lorenz, G., Catchot, A., Gore, J., Kerns, D., Stewart, S., Boykin, D., Caprio, M., Little, N., 2018. Effects of transgenic *Bacillus thuringiensis* cotton on insecticide use, heliothine counts, plant damage, and cotton yield: A meta-analysis, 1996-2015. PLos One., 13(7). https://doi.org/10.1371/journal.pone.0200131

GRDC, 2013. Micronutrients. https://grdc.com.au/__data/assets/pdf_file/0029/126497/grdc_fs_micronutrients_low-res-pdf.pdf.pdf (accessed 12 June 2022).

Haddaway, N. R., Hedlund, K., Jackson, L. E., Kätterer, T., Lugato, E., Thomsen, I. K., Jørgensen, H. B., Isberg, P.-E., 2017. How does tillage intensity affect soil organic carbon? A systematic review. Environ. Evid. 6, 30. https://doi.org/10.1186/s13750-017-0108-9.

Haynes, R. J., Swift, R. S., 1985. Effects of soil acidification on the chemical extractability of Fe, Mn, Zn and Cu and the growth and micronutrient uptake of highbush blueberry plants. Plant Soil 84, 201-212. https://doi.org/10.1007/BF02143184

Houx, J. H., Wiebold, W. J., Fritschi, F. B., 2011. Long-term tillage and crop rotation determines the mineral nutrient distributions of some elements in a Vertic Epiaqualf. Soil Tillage Res. 112, 27-35. https://doi.org/10.1016/j.still.2010.11.003.

Hulme, P. J., McKenzie, D. C., Abbott, T. S., MacLeod, D. A., 1991. Changes in the physical properties of a Vertisol following an irrigation of cotton as influenced by the previous crop. Aust. J. Soil Res. 29 (3), 425-442. https://doi.org/10.1071/SR9910425 .

Hulugalle, N., Weaver, T., Finlay, L. A., 2010. Soil water storage and drainage under cotton-based cropping systems in a furrow-irrigated Vertisol. Agr. Water Manage. 97, 1703-1710. https://doi.org/10.1016/j.agwat.2010.06.001.

Hulugalle, N., Weaver, T., Scott, F., 2005. Continuous cotton and cotton-wheat rotation effects on soil properties and profitability in an irrigated Vertisol. J. Sustain. Agric. 27, 5-24. https://doi.org/10.1300/J064v27n03_03.

Hulugalle, N. R., Finlay, L. A., Weaver, T. B., 2012. An integrated mechanical and chemical method for managing prostrate cover crops on permanent beds. Renew. Agric. Food Syst. 27, 148-156. https://doi.org/10.1017/S1742170511000226.

Hulugalle, N. R., Nachimuthu, G., Kirkby, K., Lonergan, P., Heimoana, V., Watkins, M. D., Finlay, L. A., 2020. Sowing maize as a rotation crop in irrigated cotton cropping systems in a Vertosol: effects on soil properties, greenhouse gas emissions, black root rot incidence, cotton lint yield and fibre quality. Soil Res. 58, 137-150. https://doi.org/10.1071/SR19242.

Hulugalle, N. R., Weaver, T. B., Finlay, L. A., 2006. Residual effects of cotton-based crop rotations on soil properties of irrigated Vertosols in central-western and north-western New South Wales. Soil Res. 44, 467-477. https://doi.org/10.1071/SR05141.

Hulugalle, N. R., Weaver, T. B., Finlay, L. A., 2017. Soil structure in permanent beds under irrigated cotton-based cropping systems in a Vertisol. Soil Tillage Res. 165, 107-112. https://doi.org/10.1016/j.still.2016.08.002.

Hulugalle, N. R., Weaver, T. B., Finlay, L. A., 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. https://doi.org/10.1071/CP12374.

Husson, O., 2013. Redox potential (Eh) and pH as drivers of soil/plant/microorganism systems: a transdisciplinary overview pointing to integrative opportunities for agronomy. Plant Soil 362, 389-417. https://doi.org/10.1007/s11104-012-1429-7.

Jalota, S. K., Buttar, G. S., Sood, A., Chahal, G. B. S., Ray, S. S., Panigrahy, S., 2008. Effects of sowing date, tillage and residue management on productivity of cotton (*Gossypium hirsutum* L.)–wheat (*Triticum aestivum* L.) system in northwest India. Soil Tillage Res. 99, 76-83. https://doi.org/10.1016/j.still.2008.01.005.

Janke, C., Moody, P., Fujinuma, R., Bell, M., 2022. The impact of banding polymer-coated urea on nitrogen availability and distribution in contrasting soils. Soil Sci. Plant Nutr. https://doi.org/10.1007/s42729-022-00869-x.

Knezek, B. D., Greinert, H., 1971. Influence of Soil Fe and MnEDTA interactions upon the Fe and Mn nutrition of bean plants1. J. Agron 63, 617-619. https://doi.org/10.2134/agronj1971.00021962006300040031x.

Kochian, L. V., 1991. Mechanisms of micronutrient uptake and translocation in plants, in: Micronutrients in Agriculture. Soil Science Society of America, Madison, WI, pp. 229-296.

Kottek, M. G., J., Beck, C., Rudolf, B., Rubel, F., 2006. World map of the Köppen-Geiger climate classification updated Meteorol. Zeitschrift. 15, 259-263. https://doi.org/10.1127/0941-2948/2006/0130.

Latimer, J., 2018. Pitfalls in water-running urea, in: Optimising irrigation & nitrogen: research tour. CRDC, Narrabri, Australia, p. 11. https://www.cottoninfo.com.au/sites/default/files/documents/Irrigation%20and%20N%20tour%20booklet%20-%20FINAL.pdf (accessed 16 June 2022).

Longpaddock, 2020. SILO - Australian climate data from 1889 to yesterday Vol. 2020. Queensland Government. https://www.longpaddock.qld.gov.au/silo/point-data/ (accessed 3 June 2022).

Lucena, J. J., GÁRate, A., Carpena, O., 1987. Iron-chelates evaluation in a calcareous soil. Plant Soil 103, 134-138. https://doi.org/10.1007/BF02370679.

Macdonald, B. C. T., Latimer, J. O., Schwenke, G. D., Nachimuthu, G., Baird, J. C., 2018. The current status of nitrogen fertiliser use efficiency and future research directions for the Australian cotton industry. J. Cotton Res. 1, 15. https://doi.org/10.1186/s42397-018-0015-9.

McLaren, T. I., Guppy, C. N., Tighe, M. K., Forster, N., Grave, P., Lisle, L. M., Bennett, J. W., 2012. Rapid, nondestructive total elemental analysis of Vertisol soils using portable X-ray fluorescence. Soil Sci. Soc. Am. J 76, 1436-1445. https://doi.org/10.2136/sssaj2011.0354.

Mengel, K., Kirkby, E. A., Kosegarten, H., Appel, T., 2001. Soil copper, in: Mengel, K., Kirkby, E. A., Kosegarten, H., Appel, T. (Eds.), Principles of Plant Nutrition, Springer Netherlands, Dordrecht, pp. 599-611.

Nachimuthu, G., Hulugalle, N. R., Watkins, M. D., Finlay, L. A., McCorkell, B., 2018. Irrigation induced surface carbon flow in a Vertisol under furrow irrigated cotton cropping systems. Soil Tillage Res. 183, 8-18. https://doi.org/10.1016/j.still.2018.05.011.

Nachimuthu, G., Schwenke, G., Mercer, C., Bischof, C., Hulme, P., Bell, M., 2022. A review of phosphorus nutrition in irrigated cotton farming systems of Australia. J. Cotton Res. 5. https://doi.org/10.1186/s42397-022-00114-x.

Norton, R., 2014. What's new with Zinc; maybe just some critical reminders? GRDC, Canberra, Australia. https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2014/02/whats-new-with-zinc-maybe-just-some-critical-reminders (accessed 7 April 2022).

Oorts, K., 2013. Copper, in: Alloway, B.J. (Eds.), Heavy metals in Soils: Trace Metals and Metalloids in Soils and their Bioavailability. Springer Netherlands, Dordrecht, pp. 367-394.

Polain, K., Knox, O., Wilson, B., Pereg, L., 2020. Subsoil microbial diversity and stability in rotational cotton systems. Soil Syst. 4, 44. https://doi.org/10.3390/soilsystems4030044.

Prasad, R., 2011. Aerobic rice systems. Adv. Agron. 111, 207-247. https://doi.org/10.1016/B978-0-12-387689-8.00003-5.

Pretty, J., Bharucha, Z. P., 2014. Sustainable intensification in agricultural systems. Ann. Bot. 114, 1571-1596. https://doi.org/10.1093/aob/mcu205.

Rabenhorst, M. C., Hively, W. D., James, B. R., 2009. Measurements of soil redox potential. Soil Sci. Soc. Am. J. 73, 668-674. https://doi.org/10.2136/sssaj2007.0443.

Ramanjaneyulu, A., Prasad, B., Nagula, S., Umarani, E., Chandupatla, P., Vijay, J., Jagadeeshwar, R., 2021. Crop residue management in cotton. CBM 5, 01-08. http://www.pphouse.org/cbm-article-details.php?cbm_article=21 (accessed 20 March 2022).

Rayment, G. E., Lyons, D. J., 2010. Soil Chemical Methods – Australasia. CSIRO Publishing, Collingwood, Australia.

Reiss, M., Chifflard, P., 2015. Depth function of manganese (Mn) concentration in soil solutions: Hydropedological translocation of trace elements in stratified soils. Eurasian J. Soil Sci. 4, 169-177. https://doi.org/10.18393/ejss.2015.3.169-177.

Rengel, Z., Römheld, V., 2000. Root exudation and Fe uptake and transport in wheat genotypes differing in tolerance to Zn deficiency. Plant Soil 222, 25-34. https://doi.org/10.1023/A:1004799027861.

Rochester, I. J., 2010. Phosphorus and potassium nutrition of cotton: interaction with sodium. Crop Pasture Sci. 61, 825-834. https://doi.org/10.1071/CP10043.

Rochester, I. J., 2011. Assessing internal crop nitrogen use efficiency in high-yielding irrigated cotton. Nutr. Cycl. Agroecosys. 90, 147-156. https://doi.org/10.1007/s10705-010-9418-9.

Rochester, I. J., 2012. Using seed nitrogen concentration to estimate crop N use-efficiency in high-yielding irrigated cotton. Field Crop Res. 127, 140-145. https://doi.org/10.1016/j.fcr.2011.11.018.

Rochester, I. J., Bange, M., 2016. Nitrogen fertiliser requirements of high-yielding irrigated transgenic cotton. Crop Pasture Sci. 67, 641-648. https://doi.org/10.1071/CP15278.

Rochester, I. J., Constable, G. A., 2015. Improvements in nutrient uptake and nutrient use-efficiency in cotton cultivars released between 1973 and 2006. Field Crop Res. 173, 14-21. https://doi.org/10.1016/j.fcr.2015.01.001.

Rochester, I. J., Constable, G. A., Oosterhuis, D. M., Errington, M., 2012. Nutritional requirements of cotton during flowering and fruiting in: Oosterhuis, D.M., Cothren, T.J. (Eds.), Flowering and Fruiting in Cotton, Vol. Eight. The Cotton Foundation, Cordova, Tennessee, pp. 35-50.

Sarkar, A. N., Jones, R. G. W., 1982. Effect of rhizosphere pH on the availability and uptake of Fe, Mn and Zn. Plant Soil 66, 361-372. https://doi.org/*10.1007/BF02183802.*

Schneider, M., Keiblinger, K. M., Paumann, M., Soja, G., Mentler, A., Golestani-Fard, A., Retzmann, A., Prohaska, T., Zechmeister-Boltenstern, S., Wenzel, W., Zehetner, F., 2019. Fungicide application increased copper-bioavailability and impaired nitrogen fixation through reduced root nodule formation on alfalfa. Ecotoxicology 28, 599-611. https://doi.org/10.1007/s10646-019-02047-9.

Schwenke, G., McPherson, A., 2022. Banded urea placement did not affect nitrous oxide emission from furrow-irrigated Vertisols. Nutr. Cycl. Agroecosys. 122. https://doi.org/10.1007/s10705-021-10177-y.

Shah, K. K., Modi, B., Pandey, H. P., Subedi, A., Aryal, G., Pandey, M., Shrestha, J., 2021. Diversified crop rotation: An approach for sustainable agriculture production. Adv. Agric. 2021, 8924087. https://doi.org/10.1155/2021/8924087.

Singh, B., Odeh, I., McBratney, A., 2003. Acid buffering capacity and potential acidification of cotton soils in northern New South Wales. Aust. J. Soil. Res. 41. https://doi.org/10.1071/SR02036.

Soil Survey Staff, 2014. Keys to Soil Taxonomy, 12th Edition. Natural Resources Conservation Service of the United States. Department of Agriculture, Washington DC.

Somasundaram, J., Chaudhary, R. S., Awanish Kumar, D., Biswas, A. K., Sinha, N. K., Mohanty, M., Hati, K. M., Jha, P., Sankar, M., Patra, A. K., Dalal, R., Chaudhari, S. K., 2018. Effect of contrasting tillage and cropping systems on soil aggregation, carbon pools and aggregate-associated carbon in rainfed Vertisols. Eur. J. Soil Sci. 69, 879-891. https://doi.org/10.1111/ejss.12692.

Su, B., Zhao, G., Dong, C., 2018. Spatiotemporal variability of soil nutrients and the responses of growth during growth stages of winter wheat in northern China. PLoS One 13, e0203509-e0203509. https://doi.org/10.1371/journal.pone.0203509.

Terry, J., Tan, D., Hulugalle, N., Field, D., Weaver, T., Knox, O., 2008. Cotton yield and soil carbon under continuous cotton, cotton-corn, cotton-vetch-corn and cotton-wheat rotations, in: Unkovich, M. (Ed.), Global Issues – Paddock Action, Proc. 14th Australian Agronomy Conference, 21-25 September 2008, Adelaide, SA. Australian Society of Agronomy, Adelaide, SA. http://agronomyaustraliaproceedings.org/images/sampledata/2008/concurrent/evaluating-systems/5595_terryjh.pdf (accessed 1 April 2022).

Unger, I. M., Muzika, R. M., Motavalli, P. P., Kabrick, J., 2008. Evaluation of continuous in situ monitoring of soil changes with varying flooding regimes. Commun. Soil Sci. Plan. 39, 1600-1619. https://doi.org/10.1080/00103620802071788.

Vervoort, R. W., Cattle, S., Minasny, B., 2003. The hydrology of Vertosols used for cotton production: I. Hydraulic, structural and fundamental soil properties. Aust. J. Soil Res. 41, 1255-1272. https://doi.org/10.1071/SR02154.

Wallace, A., 1981. Some physiological aspects of iron deficiency in plants. J. Plant Nutr 3, 637-642. https://doi.org/10.1080/01904168109362866.

Weaver, T., Rochester, I., Gordon, K., Bange, M., 2022. Importance of timing N application for meeting irrigated cotton demands, in: Bell, L., Bhagirath, C. (Eds.), Systems Solutions for Complex Problems, Proc. 20th Australian Agronomy Conference. 18-22 September, Toowoomba, Qld. Australian Society of Agronomy, Toowoomba, QLD. https://www.agronomyaustraliaproceedings.org/images/sampledata/2022/NutrientsAndFertility/ASAweaver_t_563s.pdf (accessed 29 July 2022).

Wei, X., Hao, M., Shao, M., Gale, W. J., 2006. Changes in soil properties and the availability of soil micronutrients after 18 years of cropping and fertilization. Soil Tillage Res. 91, 120-130. https://doi.org/10.1016/j.still.2005.11.009.

Wollmer, A.-C., Pitann, B., Mühling, K.-H., 2019. Timing of waterlogging is crucial for the development of micronutrient deficiencies or toxicities in winter wheat and rapeseed. J. Plant Growth Regul. 38, 824-830. https://doi.org/10.1007/s00344-018-9893-9.

Wortmann, C. S., Dang, Y. P., 2020. Strategic tillage for the improvement of no-till farming systems, in: Dang, Y. P., Dalal, R. C., Menzies, N. W. (Eds.), No-till Farming Systems for Sustainable Agriculture: Challenges and Opportunities. Springer International Publishing, Cham, Switzerland, pp. 155-171.

Wright, A. L., Hons, F. M., Lemon, R. G., McFarland, M. L., Nichols, R. L., 2007. Stratification of nutrients in soil for different tillage regimes and cotton rotations. Soil Tillage Res. 96, 19-27. https://doi.org/10.1016/j.still.2007.02.005.

Wyszkowski, M., Brodowska, M. S., 2021. Potassium and nitrogen fertilization vs. trace element content of maize (*Zea mays* L.). Agriculture 11, 96. https://doi.org/10.3390/agriculture11020096

Chapter 12: Cotton strip assay detects soil microbial degradation differences among crop rotation and tillage experiments on Vertisols

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Abstract

The cotton strip assay (CSA) is a simple and inexpensive method of evaluating management effects on soil microbial decomposition. The average loss of tensile strength of cotton strips buried 3 to 35 days in soils from two long-term tillage and crop-rotation experiments was of the order: cotton-wheat rotation > minimum-tillage cotton monoculture > maximum-tillage cotton monoculture. The study suggests CSA can be an effective indicator to delineate microbial activity, soil organic carbon or crop biomass as influenced by agricultural practices in cotton fields.

Keywords: Loss of tensile strength, decomposition, soil health, cotton systems, assay

1 Introduction

Soil biological functions are key components of soil health. Microbial breakdown of organic matter is a fundamental soil ecosystem process that enhances nutrient cycling. The Cotton Strip Assay (CSA) is a practical ecological indicator tool (Nachimuthu *et al.*, 2007; Tiegs *et al.*, 2013; Carballeira *et al.*, 2020; Jabiol *et al.*, 2020). A standard cotton cloth is buried in the soil and the loss of cotton fibre strength over time is used as an indirect measure of cellulose degradation by soil microbes (Correll *et al.*, 1997).

The mechanical harvest of cotton crops often results in incomplete recovery of the lint produced (Faulkner *et al.*, 2011), thus the microbial communities of cotton-producing soils are habituated to the decomposition of cellulose in the form of cotton fibres. Therefore, the CSA should be particularly well suited to detect changes in soil microbial activity as a result of soil management. Soil microbial functions in soils used to grow cotton have previously been conducted using detailed laboratory-based analyses (Polain *et al.*, 2021), but here we aimed to evaluate the sensitivity of the simple and inexpensive CSA to detect the effects of various cotton cropping systems treatments on microbial decomposition of cotton in soils cropped with cotton.

2 Materials and Methods

Two incubation experiments were conducted using surface soils (0–10 cm) sampled from two long-term field experiments on Vertisols- the dominant cotton-growing soils in Australia. The soil characteristics for both experiments are described in Nachimuthu *et al.* (2018) and Hulugalle *et al.* (2013), respectively. Experiment 1 (ongoing since 1985) included soils collected from six cropping systems: (1a) minimum-tillage cotton-monoculture, (1b) minimum-tillage cotton-maize, (1c) maximum-tillage cotton-monoculture, (1d) maximum-tillage cotton-maize, (1e) minimum-tillage cotton-wheat, (1f) minimum-tillage cotton-wheat-maize. Maximum and minimum tillage practices include soil disturbance to 30 and 10 cm respectively. Experiment 2 (ongoing since 2002) included four crop-sequences under minimum tillage: (2a) cotton-oats cover crop, (2b) cotton monoculture, (2c) cotton-wheat ~ standing stubble, (2d) cotton-wheat ~ stubble incorporated.

Soils were sampled two weeks before incubation and air-dried under aerobic conditions (19-32 ^{0}C). After stones and large organic debris were removed, the soil was broken into small clumps by hand and homogenised. The standard cotton strips (60 mm x 60 mm x 0.65 mm) used (Mittal International, 2022) had a thread count of 38/cm to ensure the same number of threads were broken in the tensometer (as described in Nachimuthu *et al.* (2007)) during later measurement of tensile strength. Soils were incubated in 80 mm tall plastic containers (110 mm diameter) with three holes in the bottom to ensure the draining of excess water. First, soil was added to a depth of 20 mm and a cotton strip was placed on the soil. Then, another 20 mm of the same soil was added, followed by another cotton strip and another 20 mm of the soil. Total air-dried (6% moisture) soil weight was 365 grams. Deionised water (200 ml) was added to saturate the soil (mimicking flood irrigation conditions used for growing cotton in Australia). The excess water drained leaving the soil moisture content at the drained upper limit (soil water content at potentials of -10 kPa for this soil was about 0.42 m^3/m^3 (Hulugalle *et al.*, 2017)). The incubation experiment was conducted under controlled temperature (26°C average) with cotton strips destructively retrieved after 3, 7, 12, 18, 25 and 35 days. Each treatment was replicated three times with two cotton strips in each container as described above. The extracted strips were rinsed in distilled water, air-dried (40 °C) for 48 hours, then broken in the tensometer to measure the tensile strength (Nachimuthu *et al.*, 2007). The tensometer was calibrated using a digital tension balance. The results indicated every 10 mm movement of the counter balance was equal to 1 kg weight. The control strips (unburied) were broken as a reference for determining loss of tensile strength (LTS) as below,

LTS (%) = (((kg to break control strip) – (kg to break sample strip))/ kg to break control strip) * 100

The above ground shoots were removed from 2 m of plant row in each plot at maximum biomass stage and dry weight measured after drying them at 70 °C until constant weight. The bolls and vegetative components were partitioned to obtain vegetative and total dry biomass. The soil organic carbon was measured using Walkley Black method as described in Nachimuthu *et al.* (2018).

Statistical analysis was carried out using Genstat Version 21.1.1.2 (VSN International Ltd) by treating experiment 1 as a split-plot design with the historical cropping system as main plots and maize rotation as sub plots. Experiment 2 was analysed as a randomised block design.

3 Results and Discussion

The LTS results from experiment 1 was of the order of cotton-wheat systems (55.3) > minimum-tillage cotton-monoculture (52.3) > maximum-tillage cotton-monoculture (47.1) (Figure 12.1, LSD at $P<0.05=2.90$). Senapati *et al.* (2014) observed a similar trend for the long-term average yields and carbon inputs for these three systems. Likewise, the same trend was observed for the vegetative biomass of cotton grown in these three treatments during the 2020–21 season (Table 12.1). The preseason soil organic carbon levels suggest cotton-wheat systems > maximum- tillage cotton-monoculture (Table 12.1).

The LTS results from soils of crop sequencing experiment (experiment 2) showed lower microbial degradation in the cotton-oats cover crop (2a) (55.8%) than in the cotton- wheat stubble incorporated system (2d) (62.2%) ($P=0.077$). The observed result could be due to the greater volume of fresh residues in the cover crop system competing with the cotton strips for microbial decomposition. Changes in the quantity and quality of carbon compounds supplied to the soil has the potential to modify the activity of microbial communities, its composition and impact organic matter decomposition by the priming effect (Osanai *et al.*, 2020). Degradation over time (extraction days) was significantly different in both the experiments (Figure 12.2, $P<0.001$).

The observed LTS results indicate that this technique was sensitive enough to delineate microbial degradation differences among treatments in a laboratory environment using soil from agricultural field experiments. It is also less expensive than using a laboratory respirometer to measure microbial activity at a single point in time (Nachimuthu *et al.*, 2007). Our study suggests CSA has potential to be used as a soil biological activity indicator in field experiments. Currently, the only visual indicator of soil biology recommended by the FAO, when assessing soil health, is the number of earthworms per square meter (Shepherd *et al.*, 2008). The CSA has excellent potential to be deployed as a simple technique to monitor soil biological activity in warmer semi-arid environments where earthworms are rare, and could be added to the recommended FAO-visual soil assessment methods. Soil health is the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans (Lehmann *et al.*, 2020). Interest in soil health across the Australian cotton farming and school community has recently been boosted by the Australian cotton industry extension network in the form of a 'soil your undies' campaign (CottonInfo, 2022). Expanding the efforts of the engagement generated by this campaign to the use of cotton cloth degradation to assess the improvement in soil health from differences induced by soil management and crop rotation would be both possible and meaningful, based on the findings from these CSA experiments.

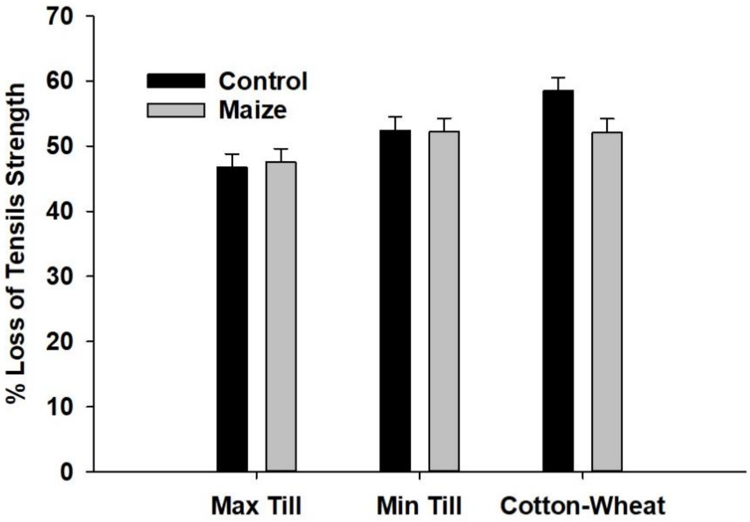
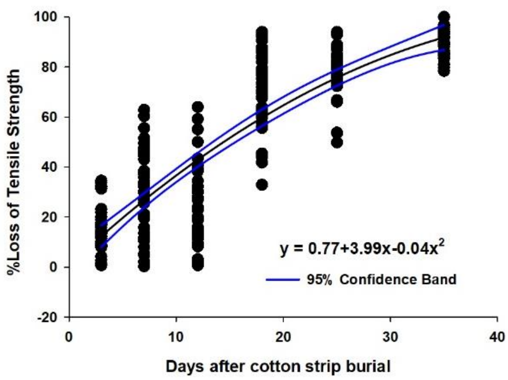


Figure 12.1. Percentage loss of tensile strength as influenced by tillage and crop rotation (Experiment 1, Max Till- Maximum tillage cotton monoculture, Min Till- Minimum tillage cotton monoculture, Cotton-Wheat- Minimum tillage cotton wheat). All data were averaged across six retrieval times for each system. The error bars denote standard error of differences of means for cropping system x maize rotation. The LSD (0.05) for cropping system main effect was 2.90).

A)



B)

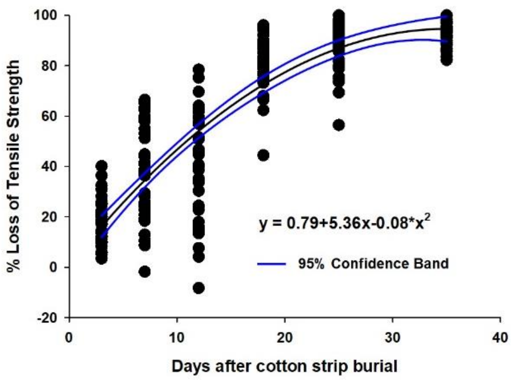


Figure 12.2. The loss of tensile strength of cotton strips over the incubation period (35 days) for soil samples from (A) experiment 1 (n=36 at each extraction days) and (B) experiment 2 (n=36 at each extraction days) (all treatments combined). The fitted quadratic function is described by the equation (solid line with confidence interval).

Table 12.1. Cotton plant dry-biomass and soil organic carbon levels as influenced by tillage and crop rotation during 2020-21 season

Treatments	Soil organic carbon (g/100 g) (0-15 cm)	Plant total dry-biomass (t ha^{-1})	Vegetative dry-biomass (t ha^{-1})
Maximum tillage cotton monoculture	0.89	13.13	5.66
Minimum tillage cotton monoculture	0.92	14.59	6.41
Minimum tillage cotton wheat	0.97	16.84	8.05
P value	0.010	<0.001	<0.001
LSD (0.05)	0.046	0.982	0.621

Acknowledgement

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References

Carballeira, C., Villares, R., Mata-Rivas, B., Carballeira, A., 2020. The cotton-strip assay as an environmental surveillance tool for ecological integrity assessment of rivers affected by WWTP effluents. Water Research 169, 115247. https://doi.org/10.1016/j.watres.2019.115247

Correll, R.L., Harch, B.D., Kirkby, C.A., O'Brien, K., Pankhurst, C.E., 1997. Statistical analysis of reduction in tensile strength of cotton strips as a measure of soil microbial activity. Journal of Microbiological Methods 31, 9-17. https://doi.org/10.1016/S0167-7012(97)00080-8

CottonInfo, 2022. Soil your undies. https://cottoninfo.com/soilyourundies. CottonInfo team, Narrabri.

Faulkner, W.B., Wanjura, J.D., Boman, R.K., Shaw, B.W., Parnell, C.B., Jr, 2011. Evaluation of Modern Cotton Harvest Systems on Irrigated Cotton: Harvester Performance. Applied Engineering in Agriculture 27, 497-506. https://doi.org/10.13031/2013.38196

Hulugalle, N.R., Weaver, T.B., Finlay, L.A., 2013. Soil water storage, drainage, and leaching in four irrigated cotton-based cropping systems sown in a Vertosol with subsoil sodicity. Soil Research 50, 652-663. https://doi.org/10.1071/SR12199

Hulugalle, N.R., Weaver, T.B., Finlay, L.A., 2017. Fallow soil evaporation in a grey Vertisol under contrasting wheat stubble management practices in cotton cropping systems. Soil and Tillage Research 165, 41-45. https://doi.org/10.1016/j.still.2016.07.011

Jabiol, J., Colas, F., Guérold, F., 2020. Cotton-strip assays: Let's move on to eco-friendly biomonitoring! Water Research 170, 115295. https://doi.org/10.1016/j.watres.2019.115295

Lehmann, J., Bossio, D.A., Kögel-Knabner, I., Rillig, M.C., 2020. The concept and future prospects of soil health. Nature Reviews Earth & Environment 1, 544-553. 10.1038/s43017-020-0080-8

Mittal International, 2022. Mittal International-World's premier textile manufacturers. Huda, Panipat - 132103, India.

Nachimuthu, G., Hulugalle, N.R., Watkins, M.D., Finlay, L.A., McCorkell, B., 2018. Irrigation induced surface carbon flow in a Vertisol under furrow irrigated cotton cropping systems. Soil and Tillage Research 183, 8-18. https://doi.org/10.1016/j.still.2018.05.011

Nachimuthu, G., King, K., Kristiansen, P., Lockwood, P., Guppy, C., 2007. Comparison of methods for measuring soil microbial activity using cotton strips and a respirometer. Journal of Microbiological Methods 69, 322-329. https://doi.org/10.1016/j.mimet.2007.02.002

Osanai, Y., Knox, O., Nachimuthu, G., Wilson, B., 2020. Increasing soil organic carbon with maize in cotton-based cropping systems: Mechanisms and potential. Agriculture, Ecosystems & Environment 299, 106985. https://doi.org/10.1016/j.agee.2020.106985

Polain, K., Knox, O., Wilson, B., Guppy, C., Lisle, L., Nachimuthu, G., Osanai, Y., Siebers, N., 2021. Distribution of subsoil microbial activity and biomass under Australian rotational cotton as influenced by system, crop status and season. Soil Research 59, 547-558. https://doi.org/10.1071/SR19335

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 and Tillage Research 143, 38-49. https://doi.org/10.1016/j.still.2014.05.009

Shepherd, G., Stagnari, F., Pisante, M., Benites, J., 2008. Visual Soil Assessments- Annual Crops. Food and Agriculture Organisation of the United Nations, Rome.

Tiegs, S.D., Clapcott, J.E., Griffiths, N.A., Boulton, A.J., 2013. A standardized cotton-strip assay for measuring organic-matter decomposition in streams. Ecological Indicators 32, 131-139. https://doi.org/10.1016/j.ecolind.2013.03.013

Chapter 13: The tensile strength of a soil-buried cotton strip is related to its loss of weight during burial

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Key findings

- There is a relationship between loss of tensile strength and weight loss of cotton fabric when buried in the soil to assess microbial activity
- The weight loss method is a cost-effective means of predicting the rate of cotton-strip degradation—a surrogate indicator of soil biology in Vertosols used for cotton growing

1 Introduction

A simple and easy method of soil biology measurement will enable the impacts of agricultural activities on soil health to be readily assessed. The Cotton Strip Assay (CSA) is a valuable tool that has been used over several decades as an ecological indicator. The assay is a simple assessment of the loss of cotton fibre strength as an indirect measure of soil microbial degradation of cellulose in a standard strip of cotton cloth. Recent investigations have emphasised that CSA can be an effective indicator to describe management effects on microbial activity, soil organic carbon or crop biomass in cotton fields (Nachimuthu et al., 2022). However, the need for an expensive tensometer precludes the greater uptake of this technique by researchers and interested farmers. An earlier experiment compared the standard CSA measurement using a tensometer with a scanning technique (Nachimuthu et al., 2007) but scanning method was not adopted due its limitations. This report details an incubation experiment that compared the CSA using a tensometer with a simple weight loss method, which could make the CSA more user-friendly and more widely adopted.

2 Methods

An experiment was conducted using surface soils (0-10 cm) sampled from the long-term experiment as described in Nachimuthu et al. (2018). Four of six cropping systems were examined in this experiment: (1c) maximum-tillage cotton-monoculture, (1d) maximum-tillage cotton-maize, (1e) minimum-tillage cotton-wheat, (1f) minimum-tillage cotton-wheat-maize. Each treatment was replicated 6 times with two strips buried in each replicate (a total of 96 strips buried on day 0 in total). A total of 12 strips per treatment with a cumulative total of 48 strips were extracted on day 15 and a similar number of strips were extracted on day 25 after incubation. Altogether, a total of 96 strips were extracted and brushed for soil particles and washed gently with deionised water and dried at 40°C in a dehydrator overnight. The dried strips were weighed (WS), then measured for tensile strength using a tensometer. The tensometer was calibrated using a digital tension balance. Every 10 mm movement of the counterbalance was equal to 1 kg of extra weight. The control strips (unburied) were also broken on the tensometer as a reference for determining loss of tensile strength (LTS) as below,

LTS (%) = (kg to break control strip – kg to break sample strip) / kg to break control strip * 100

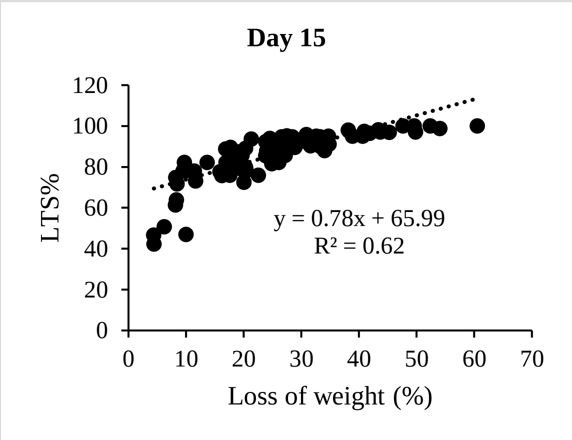
The control strips were also washed and weighed (WC). Loss of weight (%) of cotton strips as a result of degradation was calculated as below,

Loss of weight (%) = ((WC – WS) / WC) * 100

Statistical analysis was carried out using Genstat Version 21.1.1.2 (VSN International Ltd). Simple linear regression was used to analyse the relationship between LTS% and loss of weight (%) for each treatment.

3 Results and discussion

The two CSA methods were positively correlated (Figure 13.1) with r^2 ranging from 0.62 (15 day) and 0.71 (25 day) averaged over four different cropping systems. The relationship was also significant for all four systems analysed individually (*P<0.001*). The level of correlation between the two CSA methods indicates that the weight loss method has the potential to be used for measuring microbial activity in the Vertosols. The correlation on day 15 (Figure 13.1) and also analysing the data individually for each cropping systems (Figure 13.2) suggest, the weight loss method may be inaccurate below 10% weightloss and needs further refinement. However, delaying the extraction of strips reduced the number of strips below 10% weight loss. The positive correlation between weightloss method and loss of tensile strength across across maximum and minimum tillage systems under different rotations suggest, weightloss method could be used under range of soil management and crop rotation systems.



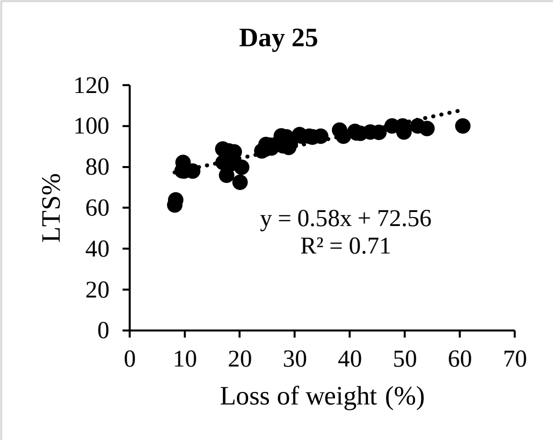


Figure 13.1. Correlation (r^2) between loss of tensile strength and loss of weight of cotton strips incubated in soils at 15 and 25 days after incubation. Measurements presented were from four different cropping systems at each day of extraction. The solid line represents the linear regression and the circle dots represent the individual data points.

Although the weight loss method showed a correlation with the tensometer method, further refinements of this method can be suggested. Washing the soil adhering to the strips before weighing is a delicate job and there is the potential to introduce a small error during this process. On some cotton strips, fine-cleaning the soil particles may prove a challenge and could slightly increase the weight if they are not removed and introduce a minor error. However, the presence of any soil particles would not have contributed to tensile strength measurements. Careful brushing of the strips before washing could minimise the error. Other similar methods such as the tea bag index to measure organic matter degradation have also reported minor errors (Mori, 2022). CSA using tensometers is also not without errors. The tensile strength of cotton strips can be increased by fungi (Latter et al., 1988). Therefore, both the methods of CSA in this study using weight loss or tensometer quantification need careful practice and attention to detail.

The mechanical harvest of cotton crops often results in incomplete recovery of the lint produced (Faulkner et al., 2011), thus the microbial communities of cotton-producing soils are habituated to the decomposition of cellulose in the form of cotton fibres. Therefore, the CSA should be ideally suited to detect changes in soil microbial activity as a result of soil management in cotton fields. CSA weight loss can be adopted for measuring overall biological activity by cotton growers with a scope for further refinement by scientists especially under less than 10% weight loss. In addition, the only visual indicator of soil biology currently recommended by the FAO, when assessing soil health, is the number of earthworms per square meter (Shepherd et al., 2008). The current study, along with the recent study (Nachimuthu et al., 2022) in Australian cotton soils suggest that the CSA has excellent potential to be deployed as a simple technique to monitor soil biological activity in warmer semi-arid environments where earthworms are rare and could be added to the recommended soil quality assessment methods.

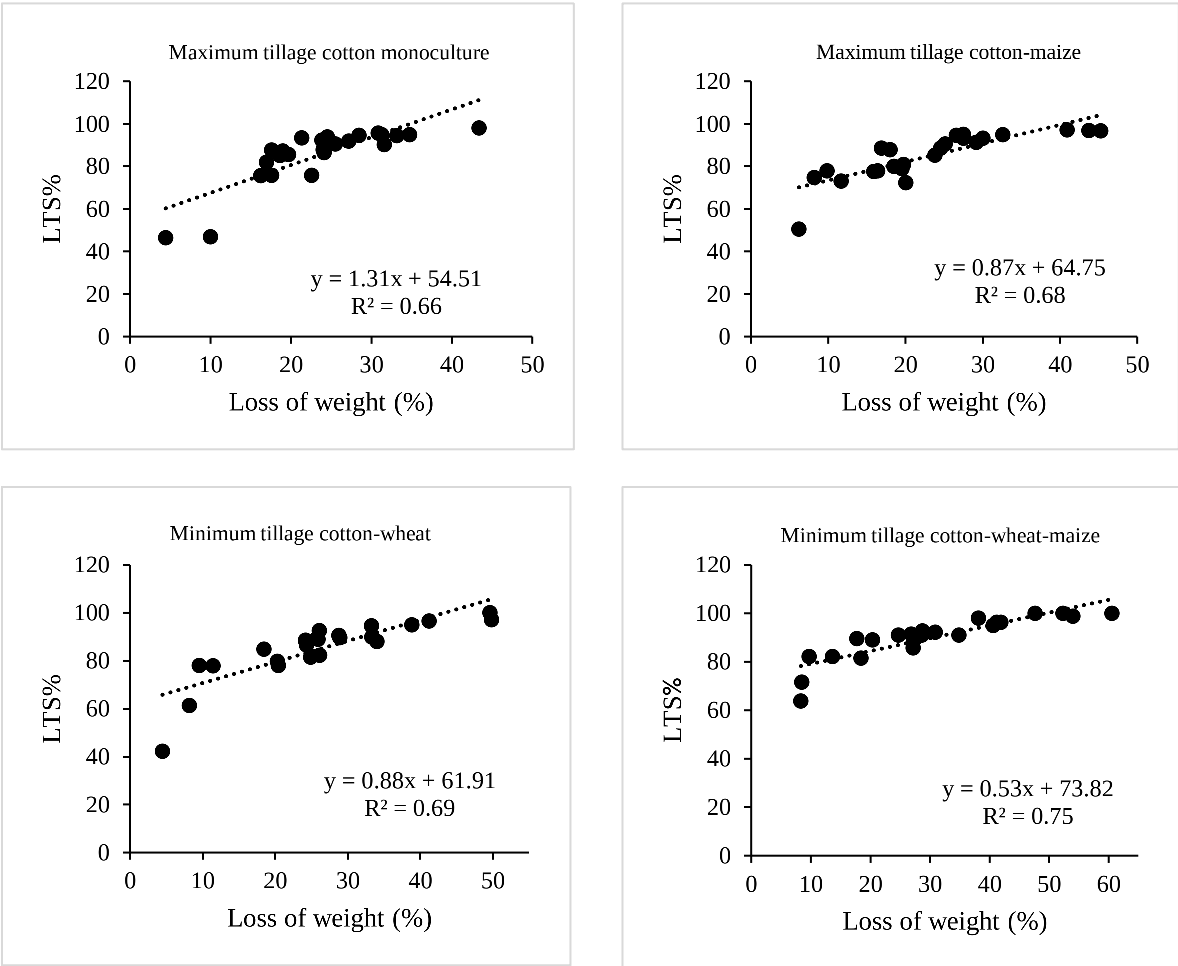


Figure 13.2. Correlation (r^2) between loss of tensile strength and loss of weight of cotton strips incubated in soils from four different cropping systems. Measurements were recorded at 15 and 25 days after incubation. The solid line represents the linear regression and the circle dots represent the individual data points.

4 Conclusions

The weight loss method is a simpler and cheaper means of assessing the loss of tensile strength of a standard cotton strip after burial in the soil than breaking the strip with a tensometer. Assessing the soil biology status in Australian cotton-growing soils does not require specialised laboratory equipment, just attention to detail when preparing and a reliable balance for weighing, thus increasing the potential for wider adoption of the CSA.

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References

Faulkner, W.B., Wanjura, J.D., Boman, R.K., Shaw, B.W., Parnell, C.B., Jr, 2011. Evaluation of Modern Cotton Harvest Systems on Irrigated Cotton: Harvester Performance. 27, 497-506.

Latter, P.M., Bancroft, G., Gillespie, J., 1988. Technical aspects of the cotton strip assay in soils. 24, 25-47.

Mori, T., 2022. Validation of the Tea Bag Index as a standard approach for assessing organic matter decomposition: A laboratory incubation experiment. 141, 109077.

Nachimuthu, G., Hulugalle, N.R., Watkins, M.D., Finlay, L.A., McCorkell, B., 2018. Irrigation induced surface carbon flow in a Vertisol under furrow irrigated cotton cropping systems. 183, 8-18.

Nachimuthu, G., Hundt, A., Palmer, B., Schwenke, G.D., Knox, O.G.G., 2022. Cotton strip assay detects soil microbial degradation differences among crop rotation and tillage experiments on Vertisols. 200, 106558.

Nachimuthu, G., King, K., Kristiansen, P., Lockwood, P., Guppy, C., 2007. Comparison of methods for measuring soil microbial activity using cotton strips and a respirometer. 69, 322-329.

Shepherd, G., Stagnari, F., Pisante, M., Benites, J., 2008. Visual Soil Assessments- Annual Crops. Food and Agriculture Organisation of the United Nations, Rome.

Chapter 14: Can loss of tensile strength measurements able to predict the difference in microbial degradation resulting from cover crop rotation and land use?

Measurement of soil biology is important to understand soil health. Cotton Strip Assay (CSA) was a valuable tool used over several years as an ecological indicator. This concept is a simple assessment of loss of cotton fibre strength as an indirect measure of soil microbial degradation of cellulose in the standard cotton cloth. However, whether this method is capable of predicting soil management differences within the cotton field was not investigated earlier. Several investigations were carried out this summer at across multiple cotton valleys. Standard cotton cloths from a single standard fabric were cut to 6 cm x 6 cm and they were buried 5 cm below the soil surface and were excavated at periodical intervals in each trial. The excavated strips were rinsed with rain or deionised water and air dried. The air-dried strips were measured for tensile strength using a tensometer. The loss of tensile strength was calculated by breaking unburied cotton strips and the results were expressed as percentage (%) loss in tensile strength. Cotton Strip Assay provides metrics for comparison among management systems. Comparison of cotton fields and native site were conducted for soil biology using.

The on-farm cover crop experiment at Southern NSW suggests the loss of tensile strength as an indirect measure of microbial degradation was able to detect the differences between crop cover crop rotation systems. An investigation in an on-farm cover crop field trial at southern NSW (2020-2021 season) in collaboration with CottonInfo indicates the loss of tensile strength is of the order Wheat>Barley>Control (Figure 14.1). This again emphasises not only the crop rotation benefits on soil biology but the ability of CSA to predict the soil microbial differences between management systems.

The results from Gwydir cotton valley indicate, there is no clear pattern in differences in the loss of tensile strength between native vegetation sites and cotton fields (Figure 14.2) and similar results were observed in Darling Downs. The cotton strips assay conducted in Western Downs region of Queensland resulted in complete decomposition of strips in 4 weeks (Figure 14.3). The observed result is a function of soil moisture where the cotton fields are irrigated and native sites are not and the variability in rainfall across different sites resulted in difference in microbial degradation of strips. Overall, the cotton growing soil and native sites are biologically active.

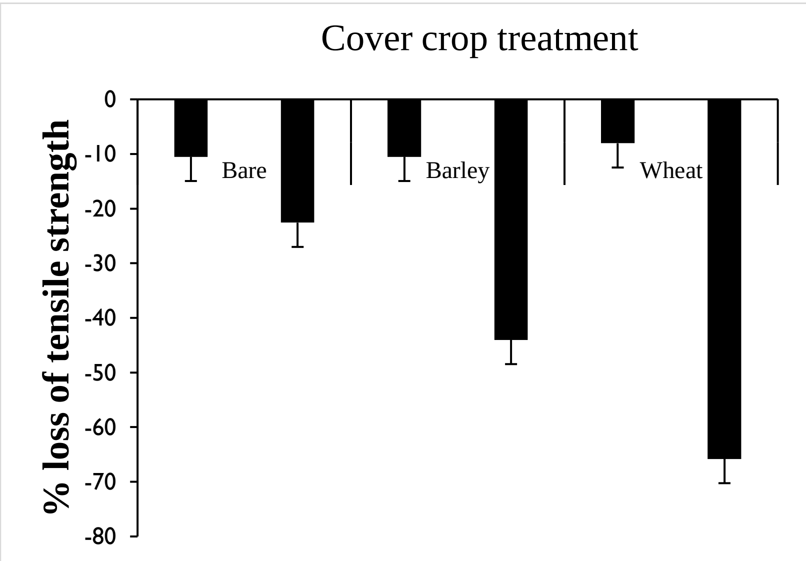

Figure 14.1. Percentage loss of tensile strength as influenced by cover crop rotation in Southern NSW at 2 and 4 weeks after burial (The error bars denote standard error of the mean).

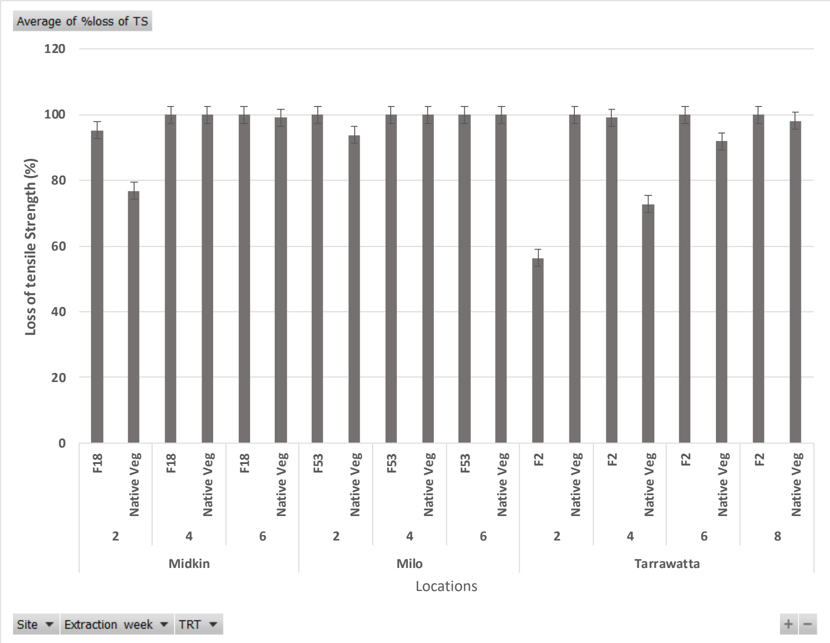

Figure 14.2. Percentage loss of tensile strength between cotton fields and native sites from Gwydir valley (The error bars denote standard error of mean).

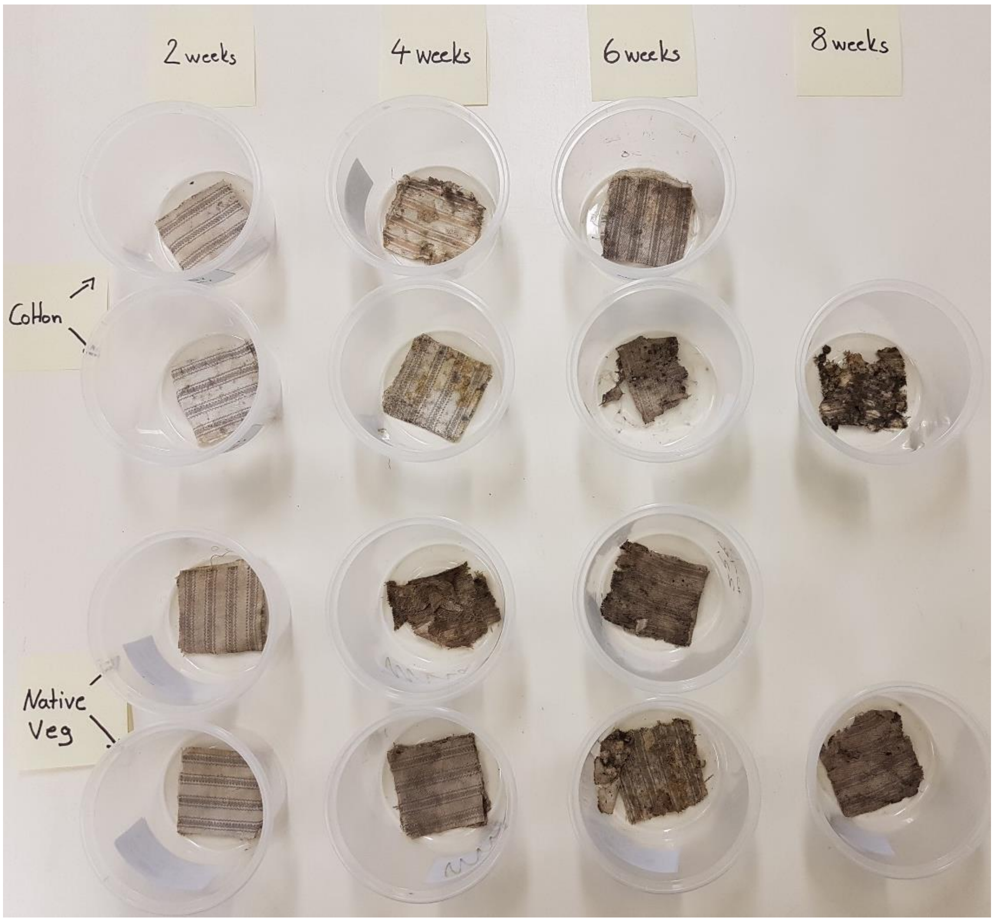

Figure 14.3. Cotton strips degradation at various time intervals after burial (Darling Downs, QLD).

Chapter 15: Biochar and manure affect rates of cotton strip degradation in a Vertosol

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Key findings

- Biochar decreased the rate of cotton strip degradation in Vertosols
- Manure accelerated the degradation of cotton strips in Vertosols

1 Introduction

Measurement of soil biological processes is important to understanding how management practices affect soil health. The Cotton Strip Assay (CSA) is a valuable tool that indicates the rate of soil microbial activity and has been used over several years in ecological studies. This assay is a simple measurement of the loss of cotton fibre strength which correlates with the level of microbial degradation of the cellulose within the standard cotton cloth used. Recent investigations demonstrated that CSA can be an effective indicator to assess the influence of agricultural practices on microbial activity, soil organic carbon or crop biomass in cotton fields (Nachimuthu et al., 2022). In the current study, the CSA was used to evaluate the effect of biochar and manure amendments on soil microbial activity in a commercial cotton-growing Vertosol (cracking clay soil) near Moree NSW.

2 Methods

The experiments were conducted at 'Keytah' (29° 28^1 E, 149° 35^1 S) in the Gwydir River valley near Moree, NSW. The experiment had a randomised block design with four manure rates and three biochar rate combinations resulting in 12 treatment combinations. However, for the purpose of this investigation using CSA, only two manure (control and 15 t/ha of manure) and two biochar (control and 1000 kg/ha of biochar) combinations were studied, resulting in four treatment combinations as below

1. Control

2. Biochar only (1000 kg/ha)

3. Manure only (15 t/ha)

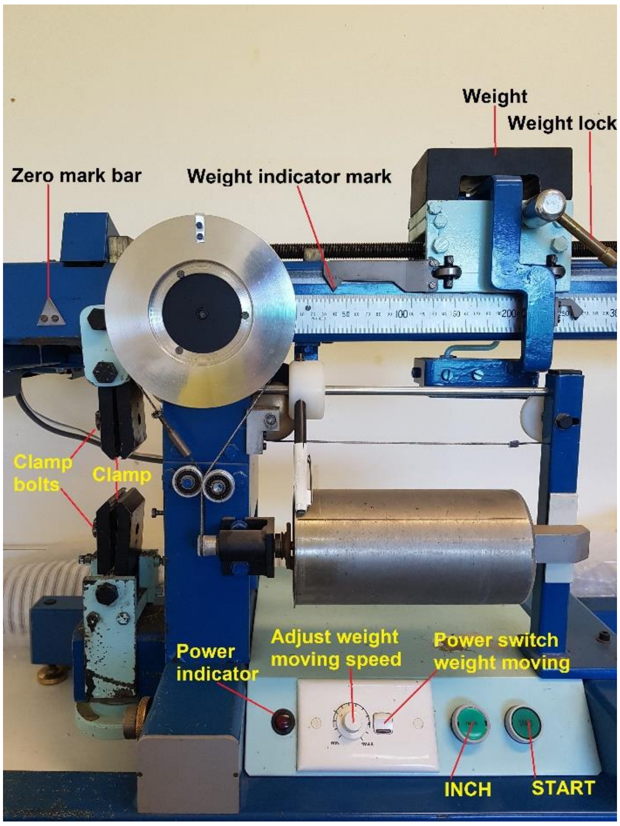
4. Manure (15 t/ha) and Biochar (1000 kg/ha)

Each treatment had four replicate plots arranged randomly within the trial area. Standard cotton cloths from a single standard fabric were cut to 6 cm x 6 cm strips, buried 5 cm below the soil surface (Figure 15.1), then excavated after set time intervals. Fifteen strips were buried in each treatment plot and 3 strips were excavated at each extraction time (2, 4, 6 and 8 weeks after burial). The excavated strips were rinsed with rain water or deionised water then air-dried. The air-dried strips were measured for tensile strength using a tensometer. The tensometer was calibrated using a digital tension balance whereby every 10 mm movement of the counter balance was equal to 1 kg weight. Several unburied reference strips were also broken with results used in the formula for determining loss of tensile strength (LTS) as below,

LTS (%) = (((kg to break reference strip) – (kg to break sample strip))/ kg to break reference strip) * 100

Statistical analysis was carried out using Genstat Version 21.1.1.2 (VSN International Ltd) by treating the experiment as a factorial design with manure and biochar as two factors. The treatment effects with a probability of <5% were considered as significant effects. In such cases, the least significant difference ($P < 0.05$) was used to compare treatment means.

A) Cotton strips burial



C) Tensometer with parts

B) Cotton strips extraction

D) Tensometer

Figure 15.1. Cotton strips burial (A: Photo show the strips placed before cover with 5 cm of soil on top) and excavation (B: Photo show the strips during extraction after removing the top 5 cm of soil in the field). Tensometer (C: Photo describe the main parts using to measure loss of tensile strength, D: Tensometer)

3 Results and discussion

The results showed no measurable microbial activity during the first two weeks after burial (data not presented as there was no loss of tensile strength of strips extracted two weeks after burial compared to reference strips). This was mainly due to a lack of moisture as there was no irrigation or rainfall between burial and excavation in this time. However, after four weeks burial (with an incrop irrigation @1 ML /ha), the manure-treated soil showed the highest amount of microbial degradation (loss of tensile strength), with the combined manure and biochar treatment slightly less than this (Figure 15.2). Averaged across treatments, the biochar constrained the rate of cellulose degradation, while manure increased the rate. The possible reason for this trend is, that the availability of manure as a nutrient source for microbes might have resulted in a higher microbial population compared to the biochar which had less nutritive content. The negative impact of biochar was also observed after 6 weeks burial, although this trend was not statistically different as most strips were largely decomposed by this time. Similarly, most strips were decomposed eight weeks after burial.

The negative impact of biochar on the degradation of cotton strips might indirectly indicate a decline in the rate of breakdown of soil organic matter in the plots applied with biochar. However, this needs further investigation using a range of organic matter sources (eg. different crop stubbles), biochar combinations and soil organic carbon measurements. Soil organic carbon is reported to decline in the cotton farming systems of Australia (Hulugalle et al., 2013; Nachimuthu et al., 2018). Identifying a combination of biochar and crop stubble that mitigates soil organic carbon decline will assist growers with their efforts to manage soil fertility in this challenging environment of Australia.

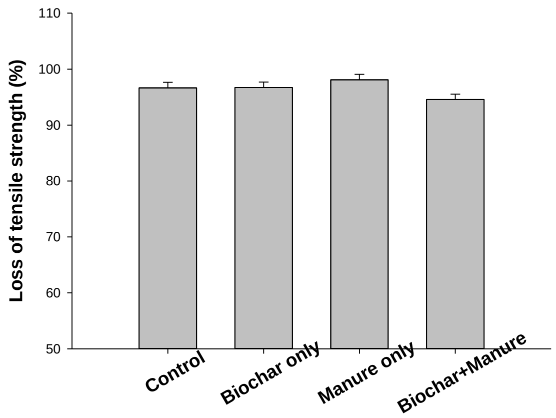


Figure 15.2. Loss of tensile strength of cotton strips as influenced by treatments (4 weeks after burial)

4 Conclusions

Biochar negatively influenced the cotton strip degradation and manure enhanced the degradation of cotton strips. Future research on various combinations of biochar and various crop stubbles in cotton-growing soils will inform the potential of possible crop stubble type-biochar combinations in reducing the soil organic carbon decline in Australian cotton farming systems.

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References

Hulugalle, N.R., Weaver, T.B., Finlay, L.A., 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. 64, 799-805.

Nachimuthu, G., Hulugalle, N.R., Watkins, M.D., Finlay, L.A., McCorkell, B., 2018. Irrigation induced surface carbon flow in a Vertisol under furrow irrigated cotton cropping systems. 183, 8-18.

Nachimuthu, G., Hundt, A., Palmer, B., Schwenke, G.D., Knox, O.G.G., 2022. Cotton strip assay detects soil microbial degradation differences among crop rotation and tillage experiments on Vertisols. 200, 106558.

Chapter 16: Limitations and options to address the yield variability in cotton

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1 Introduction

Cotton is an important fibre crop worldwide but lint yields vary widely between countries. In Australia, the average cotton lint yield is higher than the world's average lint yield (CRDC and Cotton Australia, 2020). However, there is still significant yield variability between regions, farms and fields. Cotton fields within the same farm, despite having the same management and weather conditions, often vary considerably in yield, due to a diverse range of factors including: timing of operations, water supply, soil constraints, climate, nutrition, pests, diseases, and weeds (Constable and Bange, 2015). Lint yield is impacted by both the individual factors listed above and their complex interactions. While long-term experiments can improve the understanding of the causal factors for yield differences, the significant investment required in resources and time preclude replicating such research sites in multiple areas of the Australian industry. Modelling is an alternative approach that allows investigation of a range of climatic and growing condition scenarios, but the model first needs to be validated using actual field data to maximise its predictive potential.

2 Identifying yield performance zones within or between fields

In Australia, the cotton developed largely on highly fertile Vertosols (cracking clay soils) of New South Wales and Queensland but has since expanded onto other soil types and into other states (Northern Territory and Western Australia). Recent NSW studies indicate a decline in soil fertility (Nachimuthu et al., 2022; Palmer et al., 2023) which could create additional limitations for realising the yield potential. In addition, the new areas being developed often include soils that are less fertile than the traditional cotton-growing areas or have some inherent soil chemical or physical properties that constrain optimum crop prodution. Electromagnetic (EM) induction mapping is one approach to identifying soil variability, although the resultant map needs to be ground-truthed with soil testing of the various zones identified by the EM readings (Zare et al., 2020; Zare et al., 2021). Another approach is to integrate multiple years of normalised difference vegetation index (NDVI) images to map long-term high and low-yielding areas of paddocks. The latter approach has recently been developed as an online tool (Constraint ID: Grains) for grain growers in Australia (Dang et al., 2021).

There are limitations in using the NDVI maps to predict cotton lint yield as the direct relationship between NDVI and cotton lint yield is poor (Baio et al., 2018; Ballester et al., 2017). However, cotton is usually grown as one crop in a rotational cropping system (Hulugalle et al., 2017; Nachimuthu et al., 2019; Rochester, 2011). The NDVI of rotation crops can be used to classify the field zones with different yield levels for cereal rotation crops using Constraint ID: Grains (Dang et al., 2021). The cotton yield map is also a useful tool to identify the high and low-yielding zones within the cotton field (Filippi et al., 2022; Leo et al., 2021) and can help to identify unmet yield potential (yield gap). The current commercial service providers in the Australian cotton industry e.g., PCT AgCloud (PCT, 2023) and Data farming (Datafarming, 2023) are capable of mapping variable yield zones within cotton fields. Though precision cropping techniques, such as variable-rate fertiliser or ameliorant applications, are suggested as remedies to address the variabilities in the field, they need to be tested prior to broadscale use to make sure the yield-inhibiting issue is actually being addressed. If the inputs are not matched to the problem, costly remedies may not improve yields and expenses will be wasted. Instead, a gradual step by step approach is recommended to identify the yield constraints, address the issue and confirm the response. A targeted ground-truthing exercise utilising soil testing is needed to base this approach on and improve the understanding of soil constraints affecting cotton lint yield and its ameliorative management.

3 Limitation to address yield variability in cotton

The paired-field approach conducted in this project was limited to a single-year investigation as a result of drought. However, it provided an opportunity to identify the soil properties that are potentially limiting cotton lint yield (Chapter 1). The paired field approach works best if whole fields have uniform soil characteristics, but the use of geo-located sampling points within fields also helps to assess the variability in properties within each field. We accessed grower's historical yield data for this study, but some crop management records were incomplete making it difficult to analyse long-term yield differences between closeby fields. Long-term benchmarking of cotton lint yield, crop management and seasonal stresses (biotic e.g. pest, disease, weeds and abiotic e.g. compaction) will assist with the efforts to understand the causes of yield variability. Soil moisture probes can also be a useful tool to understand the crop water use pattern and relate it with environmental and biotic stresses. Similarly, canopy sensors could provide time-series data on crop stress. However, there are practical limitations with the number of soil moisture probes or canopy sensors in Australian cotton fields due to the large field sizes and costs involved. As a result, growers and agronomists are usually limited to just a few probes or sensors for each field. Long-term benchmarking of yield with crop management must be accompanied by the appropriate tools and training for growers and advisors to capture and store the same parameters of on-farm data every season.

4 Can strip trials be an option to identify and address the causal factors of yield variability?

Farmer-friendly approaches are needed to identify the factors causing yield variability and ways to address them. A recent report on other cropping industries in Australia emphasised the need for 'grower-centric' on-farm experimentation and it is becoming increasingly evident that digital tools and precision agriculture technologies are becoming the enablers of on-farm investigations (Bramley et al., 2022). In cotton systems, the yield map is a useful digital output that assists with identifying the performance of the field zones. An investigation using the grower machinery and associated tools or implements will be more grower-centric and will assist with documenting useful information over the long term. The strip trial approach proposed by Lawes and Bramley (2012) is notable and could be a good start for on-farm investigations within cotton fields to identify the factors causing yield variability and address those constraints. Growers, agronomists and researchers could adopt strip trials for ease of crop operations and possibly divide the strips into multiple zones (each zone as a plot or sampling or sensor point for investigation (Figure 16.1) based on their experience or with the supporting datasets such as yield maps, EM maps or Constraint ID etc. Multi-year and multi-location grower-driven strip trials with the involvement of researchers to document the key data will build the dataset required to interpret and improve the understanding of yield variability. Building a dataset is the first key step in addressing variability. However, the development of a centrally- managed database (e.g. CRDC or CSD or a common cotton industry body similar to GRDC's Better Fertiliser Decision for Cropping (BFDC) or grains on-farm trial database (https://www.farmtrials.com.au/) or Soil CRC's Visualising Australasia's soils database (https://data.soilcrc.com.au/map/about)) could enable the data capture from all the on-farm trials and support the efforts to understand and address the cotton yield variability. The data needs to be screened to make sure it followed proper quality assurance protocols and has enough supporting meta-data for it to be useful for future interpretation. Such effort should be accompanied by ongoing maintenance of the database.

5 Future research

Future research needs to focus on on-farm experiments to identify and address the constraints for yield variability using grower centric strip trial approach. The strip trial approach could encompass but is not limited to

1. Identifying the causes of yield variability (soil properties, disease incidence)
2. Single strip amendments (e.g compost, gypsum etc) or fertilisers to address constraints
3. Single-strip foliar sprays of growth regulators or nutrients (growth and/or yield response study)
4. Tillage, stubble management for soil health and disease control etc.
5. Strip trial for decision-making of sensor placement point within the field

The strip trial output needs to be accompanied by documentation and uploading of data to a common database managed by a common cotton industry organisation.

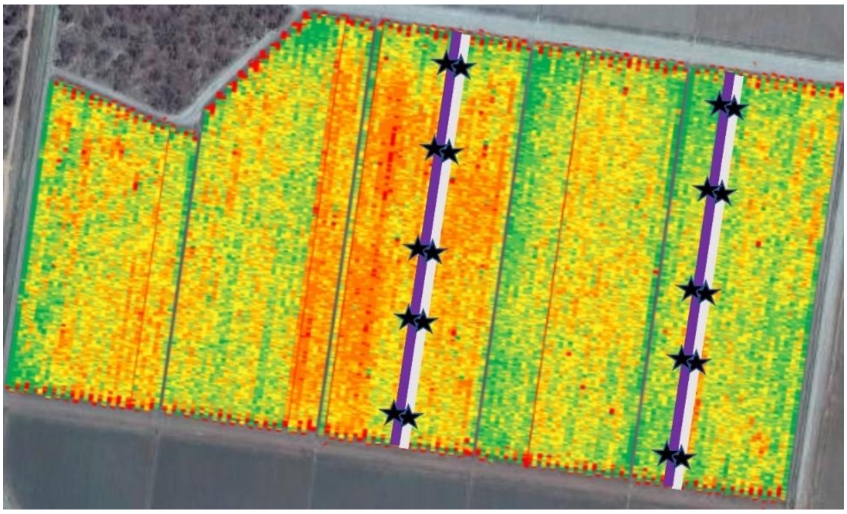

Figure 16.1. A model strip trial with control and an example treatment with stars showing multiple sampling or sensor points of interest for investigation. The figure is showing the cotton yield map (green, yellow and orange) in the background (Map acknowledgement- DeBortoli farm, Riverina, NSW).

References

Baio, F.H.R., Neves, D.C., Campos, C.N.d.S., Teodoro, P.E., 2018. Relationship between cotton productivity and variability of NDVI obtained by landsat images. 34, 197-205.

Ballester, C., Hornbuckle, J., Brinkhoff, J., Smith, J., Quayle, W., 2017. Assessment of In-Season Cotton Nitrogen Status and Lint Yield Prediction from Unmanned Aerial System Imagery. 9, 1149.

Bramley, R.G.V., Song, X., Colaço, A.F., Evans, K.J., Cook, S.E., 2022. Did someone say “farmer-centric”? Digital tools for spatially distributed on-farm experimentation. 42, 105.

Constable, G.A., Bange, M.P., 2015. The yield potential of cotton (Gossypium hirsutum L.). 182, 98-106.

CRDC and Cotton Australia, 2020. Australian Cotton Sustainability Report 2019, In: Australian Cotton Industry's Sustainability working group (Ed.). Cotton Research and Development Corporation and Cotton Australia, Narrabri & Sydney.

Dang, Y., Orton, T., McClymont, D., Menzies, N., 2021. ConstraintID – a free web-based tool to identify areas where soil constraints are most likely to be limiting crop yields.

Datafarming, 2023. Data Farming. DataFarming Pty Ltd – Australia, P.O.Box 253, Highfields, Qld 4352.

Filippi, P., Whelan, B.M., Vervoort, R.W., Bishop, T.F.A., 2022. Identifying crop yield gaps with site- and season-specific data-driven models of yield potential. 23, 578-601.

Hulugalle, N.R., Weaver, T.B., Finlay, L.A., 2017. Fallow soil evaporation in a grey Vertisol under contrasting wheat stubble management practices in cotton cropping systems. 165, 41-45.

Lawes, R.A., Bramley, R.G.V., 2012. A Simple Method for the Analysis of On-Farm Strip Trials. 104, 371-377.

Leo, S., De Antoni Migliorati, M., Grace, P.R., 2021. Predicting within-field cotton yields using publicly available datasets and machine learning. 113, 1150-1163.

Nachimuthu, G., Schwenke, G., Mercer, C., Bischof, C., Hulme, P., Bell, M., 2022. A review of phosphorus nutrition in irrigated cotton farming systems of Australia. 5, 6.

Nachimuthu, G., Watkins, M.D., Hulugalle, N.R., Weaver, T.B., Finlay, L.A., McCorkell, B.E., 2019. Leaching of dissolved organic carbon and nitrogen under cotton farming systems in a Vertisol. 35, 443-452.

Palmer, B., Guppy, C., Nachimuthu, G., Hulugalle, N., 2023. Changes in micronutrient concentrations under minimum tillage and cotton-based crop rotations in irrigated Vertisols In Press.

PCT, 2023. Precision Cropping Technologies. PCT Agcloud Pty Ltd, Narrabri, New South Wales.

Rochester, I.J., 2011. Sequestering carbon in minimum-tilled clay soils used for irrigated cotton and grain production. 112, 1-7.

Zare, E., Arshad, M., Zhao, D., Nachimuthu, G., Triantafilis, J., 2020. Two-dimensional time-lapse imaging of soil wetting and drying cycle using EM38 data across a flood irrigation cotton field. 241, 106383.

Zare, E., Li, N., Arshad, M., Nachimuthu, G., Triantafilis, J., 2021. Time-lapse imaging of soil moisture using electromagnetic conductivity imaging: Wetting phase. 85, 760-775.