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RESEARCH ARTICLE

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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 to 3700 kg/ha, but yields vary substantially between farms and also 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 help optimize inputs and improve profits. During the 2018–2019 summer cotton-growing season, a paired-field comparison approach was used to investigate and improve the understanding of soil property-induced irrigated cotton yield differences within five farms across three regions of NSW, Australia. The paired fields at each farm recorded an average lint yield difference of >284 kg/ha (measured in 2018–2019 or 5-year average lint yield). Several soil properties differed between the paired fields at each farm comparison. The soil organic carbon stocks were higher in the higher-yielding fields at all the farm comparisons and the normalized 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 comparisons. Results for most soil nutrient tests were above the recommended critical concentrations for Australian cotton production. A stepwise linear regression excluding soil nutrients that were above soil test critical values for crop response and below crop toxicity levels indicated the lint yield was positively correlated with SOC stocks and negatively correlated with sodicity and bulk density. No earthworms were detected during visual soil assessment or soil sampling across all the sites. Visual soil assessment was not 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 strip comparison approach could be adopted for within-field variability by dividing the fields into discrete performance zones and assessing the soil properties of each zone separately.

KEYWORDS
cotton, lint yield, paired field, soil

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 high variability in lint yields across the industry and even 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 & Bange, 2015). In-field variations 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, the significant resources and time required often limit the number of such experiments possible across various climatic regions. Simulations of varying climate scenarios, crop management practices and soil characteristics are one approach to investigating the relative impact of these factors, but actual field data on cause and effect information is essential to construct and validate models and improve their predictive capabilities.

In Australia, cotton has been traditionally grown on Vertosols (Isbell & National Committee on Soil and Terrain, 2021) with high water holding capacity. 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, Schwenke, Mercer, et al., 2022; 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 (e.g. Northern Australia) 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 in improving their understanding of soil property-induced yield differences. Previous research in the USA compared the soil property differences (0–20 cm) between high- and average-yielding soybean areas (Adams et al., 2017, 2018) and identified properties such as soil organic carbon and extractable phosphorus levels that were higher in selected high-yielding soybean fields. There have been no such comparative studies on cotton fields in Australia.

Understanding the soil's physical, chemical and biological properties and their contributions to yield variability is important. Soil-test-based nutrient recommendations are part of commercial agronomic services prevalent in cropping industries including cotton in Australia and elsewhere in the world. Such tests predominantly include chemical properties. Soil physical properties are not measured regularly despite the use of heavy machinery that can cause soil compaction (Jamali et al., 2021). Soil biological properties are often perceived as time-consuming and difficult to measure, although new commercial biological tests are emerging to fill the gap (Predicta B, 2023). A visual soil assessment was proposed by the United Nations Food and Agriculture Organization (Shepherd et al., 2008) as a universal indicator of soil health. 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 account for yield differences is yet to be investigated. A paired field approach in the USA suggested no-till systems increasing soil organic carbon only in topsoil (Blanco-Canqui & Lal, 2008).

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. A sub-sample of three paired sites (six fields) was assessed using the Visual Soil Assessment to examine whether its use added any further insight into the yield differences. In this on-farm study across the Australian cotton industry, we hypothesised that cotton lint yield differences were related to differences between soil properties at the field scale. We used both the five-year average cotton lint yield and single-year measurements to explore the potential relationship between soil properties, such as sodicity (an intrinsic soil attribute that remains constant from year to year) and yield. In addition, we utilized single-year yield measurements to investigate whether year-to-year management practices induced soil constraints such as soil compaction (bulk density), influenced crop yield.

2 | MATERIALS AND METHODS

2.1 | Study location and site selection

The farms investigated were located in the Gwydir Valley, Macquarie and Riverina cotton-growing regions of New South Wales, Australia. Fields were selected in discussion with the CottonInfo team (Australian Cotton Industry's extension agronomists), leading cotton growers and commercial agronomists. The locations of each farm (Figure 1, Table 1) are described in Section 2.2. Soils in the Gwydir Valley irrigation area are relatively uniform and were mostly formed from alluvial sediments (Aus Gov, 2023; NSWDOI, 2018). 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 & 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 ranges from light clay (Riverina) to heavy clay (Gwydir) (Table 2). The soil classification is presented in Table 2.

The annual average rainfall of the case study regions varied from 395 mm in Riverina to 569 in Gwydir regions (Table A3 (Jeffrey et al., 2001), Supporting Information). The average monthly mean maximum and minimum temperatures declined from Gwydir (Northern latitudes) to the Riverina region (Southern latitudes) (Table A3, Supporting Information).

2.2 | Field comparisons

A total of 10 fields were investigated with five within-farm paired-field comparisons made. Historical cotton lint yields (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. Where historical cotton lint yield information was not available (Riverina A and B comparisons (Table 1)), yield assessment in the 2018–2019 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). The Gwydir, Macquarie-A and Macquarie-B fields were also compared using the FAO Visual Soil Assessment (Shepherd et al., 2008) to compare the soil quality (Sections 2.4 and 3.6).

2.2.1 | Gwydir Valley

Two fields located in the Gwydir Valley in Northwest NSW were selected for comparative analysis. The basal fertilizer application in the 2018–2019 season included 290, 32.5 and 50 kg of N, P and K, respectively. The soil type in this valley is predominantly Vertosol with >50% clay

FIGURE 1 Location of cotton farms selected for investigation in this study.

TABLE 1 Details of paired field comparisons and basic management information including in-crop rainfall during the study (All the fields were planted with cotton variety Sicot 748 B3F).

Comparison	Field	GPS coordinates		Rainfall (mm)	Tillage depth	Irrigation type	Irrigation volume (mega litres)	Year of laser levelling
Gwydir	1	−29.298°	149.761°	140	>20 cm	Furrow-siphon	8.9	NK#
	2	−29.301°	149.749°	140	>20 cm	Furrow-siphon	8.9	NK#
Macquarie-A	3	−31.769°	147.708°	219	10–20 cm	Furrow-siphon	10.24	2005
	4	−31.803°	147.704°	219	10–20 cm	Furrow-siphon	10.24	2005
Macquarie-B	5	−31.750°	147.710°	219	10–20 cm	Furrow-siphon	11.25	2005
	6	−31.713°	147.717°	219	10–20 cm	Furrow-siphon	10.24	2000
Riverina-A	7	−34.536°	146.216°	181	>20 cm	Bankless	10.00	NK#
	8	−34.539°	146.211°	181	>20 cm	Bankless	10.00	NK#
Riverina-B	9	−34.539°	146.189°	181	>20 cm	Bankless	10.00	2017
	10	−34.539°	146.186°	181	>20 cm	Bankless	10.00	2017

Note: #NK-Not Known: Current grower was not aware of the year when the field was laser levelled.

TABLE 2 Soil texture of paired fields at each comparison.

		0–30 cm			30–60 cm			Soil type (Isbell & National Committee on Soil and Terrain, 2021)
Comparison	Field	%Clay	%Silt	%Sand	%Clay	%Silt	%Sand	
Gwydir	1	56	17	27	60	18	22	Self mulching, Endohypersodic, Grey Vertosol
	2	58	19	23	61	18	21	Self mulching, Endohypersodic, Grey Vertosol
Macquarie-A	3	50	18	32	49	16	35	Self mulching, Haplic, Grey Vertosol
	4	45	20	35	38	18	44	Self mulching, Haplic, Grey Vertosol
Macquarie-B	5	50	18	32	53	11	35	Self mulching, Haplic, Grey Vertosol
	6	54	21	25	58	20	23	Self mulching, Haplic, Grey Vertosol
Riverina-A	7	47	9	44	52	10	39	Hypocalcic, Mottled, Grey or Brown Dermosol
	8	48	8	44	55	10	34	Hypocalcic, Mottled, Grey or Brown Dermosol
Riverina-B	9	48	7	45	64	7	29	Hypocalcic, Mottled, Grey or Brown Dermosol
	10	54	10	36	62	7	31	Hypocalcic, Mottled, Grey or Brown Dermosol

(Table 2). 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 | 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 these fields was also Vertosols (Table 2). Both adjacent field comparisons received basal fertilizer application in the 2018–2019 season (150, 44 and 25 kg/ha of N, P and K). An additional 160–200 kg/ha of N was applied in-crop as a water-run fertilizer application for both pairs. All four fields have been harvested using round bale module pickers since 2011 and were under similar management.

2.2.3 | 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 pairs. In 2018–2019, lint yields were measured by hand harvesting at each of the soil sampling locations. Both the pairs had a bankless channel irrigation system.

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

The history of rice production in these fields renders soil classification more difficult as there is evidence of both eluviation and earthworks, however, the clay type (mix of brown and grey clays) and behaviour (lack of cracking and slickensides) suggest an underlying Dermosol profile (Isbell & National Committee on Soil and Terrain, 2021).

2.3 | Yield estimation

Cotton was handpicked from 1 m^2 per soil 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 (for the fields in Riverina) in 2018–2019 was used to derive a normalized lint yield percentage. To normalize yield, the lint yield at the low-yielding field was divided by the yield at the higher-yielding field and multiplied by 100 to give a percentage for each paired comparison.

2.4 | Soil sampling and analysis

Soil samples were taken from 0 to 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°C and samples were weighed. A sub-sample of each soil sample was oven-dried at 105°C to determine the air-dried soil moisture content. The bulk density of the soil samples at each depth increment was calculated by dividing the oven-dry mass (105°C) of the soil at each depth by the volume of the extracted soil core. Soil samples were ground to <2 mm then homogenized and sub-sampled using a riffle splitter for each depth increment in every core. The methods used for soil chemical analysis were all drawn from Rayment and Lyons (2010), specifically Methods 3A1, 4A1 and 4B4, 6A1, 7C2b, 9B and 18A1, 10D1, 12A1, 12C2 and 15E2. The soil available P was measured as Colwell P (Colwell, 1963). Soil organic carbon (SOC) and mineral N stocks were calculated by multiplying the soil organic carbon and mineral N concentrations adjusted for air-dried soil moisture by the bulk density at the respective depths. SOC stocks (t/ha) = (SOC concentration % × bulk density (g/cm^3) × soil depth (cm))/100 and Mineral N stocks (kg/ha) = (Nitrate N (mg/kg) + Ammonium N (mg/kg)) × bulk density (g/cm^3) × soil depth (cm)/10.

2.5 | Visual soil assessment

Visual soil assessment (Shepherd et al., 2008) was undertaken for Gwydir, Macquarie A and B comparisons. The top 20 cm of soil was 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 compared 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 | 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. We acknowledge the limitations associated with the randomisation and replication in this approach; nevertheless, it serves as a valuable method for comparing two neighbouring cotton fields on a commercial farm. The approach earlier adopted by Blanco-Canqui and Lal (2008) was used in our study except using two factors. *p-values* were presented in Table 5 and Table S1. Mean separation values (Least significant differences (LSD)) at $p < .05$ for the effects of field and soil depth on selected soil properties measured were presented in Tables S1 and S2. With the exception of Mineral N and SOC, we applied soil test critical values for crop response and toxicity to eliminate the soil nutrient data for stepwise linear regression. Subsequently, a stepwise linear regression was conducted for the remaining factors, encompassing exchangeable sodium percentage (sodicity), soil organic carbon stocks, mineral N stocks, pH ($CaCl_2$) and bulk density.

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 a 284 kg/ha (1.25 bales/ha) lint yield difference between fields 3 and 4 and a 624 kg/ha (2.75 bales/ha) difference between fields 5 and 6. The measured yield difference between the fields for the Riverina A comparison was 356 kg lint/ha (1.57 bales/ha) and that of the Riverina B comparison was 806 kg lint/ha (3.55 bales) (Table 3). The 2018–2019 season had extreme and extended hot conditions (Dowling, 2019) experienced by the Australian cotton industry and yields for Gwydir and Macquarie comparisons deviated from the 5-year average trends. Due to the extreme climate-induced growing conditions (Table A1, Supporting Information), it was proposed that the yields at Gwydir and Macquarie comparisons in this season were likely influenced by non-soil factors rather than by soil properties. The deviation from the 5-year average trend in 2018–19 can be attributed to the increased occurrence of nights with temperatures above 26°C (Table A1, Supporting Information). This led to a shift in plant response, as they likely utilized energy during the night time instead of assimilating it for growth (Loka & Oosterhuis, 2010). Consequently, this extreme weather had a more significant impact on growth and crop yield than the soil constraints during this season. The potential soil factor impacting the yield for Macquarie B comparison in 2018–2019 (fields 5 and 6) is discussed in Section 3.2.

3.2 | Bulk density, soil pH and Colwell P

There were differences in bulk density between the fields in each comparison except the Riverina B comparison. The stepwise linear regression indicated a negative correlation between the lint yield and bulk density across depths of 0–15, 0–30 and 0–60 cm (Table 4). The bulk density of the soil is related to its soil type and its moisture content (Indoria et al., 2020). The soils of southern NSW exhibit strong colour contrast between horizons with Parna (aeolian deposits) and fluvial deposits layered over each other. There was a slight increase in clay content from 0–30 to 30–60 cm depth (Table 2). Laser levelling

TABLE 3 Lint yield (5-year average preceding the 2018–2019 season) and soil organic carbon and mineral nitrogen stocks for the paired sites.

Comparison	Field	Average lint yield (kg/ha)[a]	Soil organic carbon stock (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	54.8	118
	10	2068	49.3	201

[a]The average lint yields reported are based on the grower survey for fields 1–6 and the measured average yield in 2018–2019 near sampling points for fields 7–10.

TABLE 4 Stepwise linear regression for lint yield (LY) from all fields and individual sites.

Comparison	Field numbers	Regression equation for lint yield	% Variance accounted for	*p* Value
All fields (0–15 cm depth)	1–10	LY = 3254 − 1030 × bulk density + 42.4 × SOC stocks	10.7	<.001
All fields (0–30 cm depth)	1–10	LY = 2881 − 48.5 × ESP + 19.9 × SOC stocks − 368 × bulk density	7.3	<.001
All fields (30–60 cm depth)	1–10	LY = 3138 − 37.9 × ESP + 50.6 × SOC stocks − 543 × bulk density	20	<.001
All fields (all depths)	1–10	LY = 2454 − 22.2 × ESP + 19 × SOC stocks	8	<.001
Gwydir (all depths)	1 & 2	LY = 3007 + 37.7 × SOC stocks − 34.2 × ESP − 2.4 × Mineral N stocks	40	<.001
Macquarie-A (all depths)	3 & 4	LY = 2540 − 23.6 × ESP + 8.7 × SOC stocks	29	<.001
Macquarie-B (all depths)	5 & 6	LY = 4475 − 307.3 × pH ($CaCl_2$)	20	<.001
Riverina-A (all depths)	7 & 8	No relationship	–	NS
Riverina-B (all depths)	9 & 10	LY = 2772 − 69.1 × ESP	47	<.001

Note: Factors included in this analysis include exchangeable sodium percentage (ESP or sodicity), soil organic carbon (SOC) stocks, mineral N stocks, pH ($CaCl_2$) and bulk density.

to alter the landscape for irrigation and rice production in the past has resulted in a mixture of these layers making drainage characteristics uneven and thus influencing their bulk density. The irrigated cotton-growing soils of the Gwydir Valley are predominantly cracking clays (Vertosols) with uniform clays up to and exceeding 1 m in 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 the previous season likely influencing the bulk density differences among the fields in each comparison (Table 5). 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). However, in the Macquarie Valley, the bulk density in fields 4 and 6 of this case study was distinctly higher compared to their pairs and thus showed signs of compaction. The measured lint yield in field 6 was significantly lower than field 5, however, fields 3 and 4 recorded similar yields in the 2018–19 season (Figure 2). The magnitude of bulk density changes between 0–15 cm and 15–30 for fields 3 and 4 was 0.2 g/cm^3. However, the magnitude of bulk density changes for the same depths for fields 5 and 6 were 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 in this comparison. A recent study reported a 27% reduction in lint yield as a result of an 86% reduction in soil water recharge and a 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 fields (Table 5) except fields 7–10 in Riverina where the soil pH was acidic in the top 30 cm and neutral to alkaline from 30 to 90 cm depth (Table 5). The stepwise linear regression suggested the soil pH ($CaCl_2$) was negatively related to lint yield at Macquarie-B comparison (Table 4). The five-year average lint yield (Table 3) suggests, the higher soil pH resulted in lower lint yields in field 5. The higher soil pH in field 5 likely influenced the soil nutrient availability and subsequent plant uptake of, for example, phosphorus (Barrow & Hartemink, 2023). This inference is supported by significantly lower Colwell P values observed in field 5 compared to field 6, as detailed in Table A6 of the Supporting Information. Specifically, the Colwell P levels at depths of 15–30 cm in field 5 fell below the critical Colwell P value of 7 mg/kg, as established by Dorahy et al. (2004) for depths of 0–30 cm. It is possible, that these lower Colwell P values were attributed to the higher soil pH levels. In soils with elevated pH, the efficiency of applied fertilizer phosphorus (P) is likely reduced, as indicated by recent studies highlighting the inconsistent response to applied P fertilizer in alkaline soils (Bell, 2014; Griffith & Guppy, 2015; Nachimuthu, Schwenke, Baird, et al., 2022; Nachimuthu, Schwenke, Mercer, et al., 2022).

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 across all depths, whereas Riverina-B indicated a clear difference in SOC at 0–30 cm depths (Figure 3). There was also a trend of higher

TABLE 5 Selected soil properties for all the paired fields measured (Values are means of 9 replicates).

Depth (cm)	0–15		15–30		30–45		45–60		60–90		Level of significance		
Field (F)	**F1**	**F2**	**F1**	**F2**	**F1**	**F2**	**F1**	**F2**	**F1**	**F2**	**Field**	**Depth**	**Field × depth**
Bulk density (g/cm^3)	1.1	1.0	1.3	1.2	1.3	1.3	1.3	1.3	1.4	1.3	**	***	NS
SOC Conc. (%)	0.73	0.57	0.56	0.44	0.49	0.41	0.45	0.37	0.38	0.34	*	***	*
pH ($CaCl_2$)	7.4	7.2	7.7	7.5	7.8	7.6	7.8	7.7	7.8	7.8	NS	***	NS
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	NS	***	NS
SOC stock (t/ha)	12	9.1	12	8.6	10	8.3	10	7.5	17	14	*	***	NS
Field (F)	**F3**	**F4**	**F3**	**F4**	**F3**	**F4**	**F3**	**F4**	**F3**	**F4**			
Bulk density (g/cm^3)	1.1	1.4	1.3	1.6	1.4	1.7	1.4	1.8	1.5	1.9	***	***	NS
SOC Conc. (%)	0.63	0.71	0.48	0.49	0.42	0.40	0.36	0.32	0.30	0.24	NS	***	**
pH ($CaCl_2$)	7.7	7.3	7.8	7.4	7.9	7.6	8.0	7.5	8.1	7.7	**	***	NS
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	NS	***	*
Field (F)	**F5**	**F6**	**F5**	**F6**	**F5**	**F6**	**F5**	**F6**	**F5**	**F6**			
Bulk density (g/cm^3)	1.2	1.1	1.4	1.5	1.4	1.7	1.4	1.7	1.5	1.7	***	***	NS
SOC (%)	0.56	0.62	0.37	0.43	0.31	0.30	0.29	0.23	0.25	0.20	NS	***	**
pH ($CaCl_2$)	7.6	7.0	7.7	7.2	7.9	7.5	8.0	7.7	8.0	7.8	*	***	**
Sodicity (ESP) %	0.3	0.8	1.4	1.6	3.1	3.2	5.2	5.8	9.8	9.6	NS	***	NS
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	NS	***	*
Field (F)	**F7**	**F8**	**F7**	**F8**	**F7**	**F8**	**F7**	**F8**	**F7**	**F8**			
Bulk density (g/cm^3)	1.2	1.4	1.4	1.5	1.6	1.6	1.6	1.5	1.5	1.6	NS	***	*
SOC (%)	0.92	0.92	0.72	0.61	0.47	0.34	0.32	0.24	0.20	0.15	NS	***	NS
pH ($CaCl_2$)	6.3	5.9	6.0	6.1	6.7	6.9	7.4	7.7	8.0	7.8	NS	***	**
Sodicity (ESP) %	1.4	1.0	1.2	1.3	2.9	2.6	3.1	2.2	2.8	2.0	NS	***	NS
Mineral N stock (kg/ha)	72	124	343	405	58	35	22	31	40	70	NS	***	NS
SOC stock (t/ha)	17	19	16	14	11	8	8	6	9	7	NS	***	**
Field (F)	**F9**	**F10**	**F9**	**F10**	**F9**	**F10**	**F9**	**F10**	**F9**	**F10**			
Bulk density (g/cm^3)	1.4	1.3	1.5	1.4	1.5	1.5	1.5	1.5	1.6	1.5	NS	**	NS
SOC (%)	0.90	0.75	0.58	0.54	0.41	0.39	0.29	0.25	0.16	0.15	NS	***	***
pH ($CaCl_2$)	5.1	5.4	5.0	6.0	6.4	7.0	7.2	7.7	7.7	7.7	*	***	***
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	NS	***	*
SOC stock (t/ha)	19	15	13	12	10	9	7	6	8	7	NS	***	***

Note: *, ** and *** indicates significance of the factor at 5%, 1% and 0.1% levels, respectively.

Abbreviation: NS, not significant.

SOC in topsoil (0–15 cm) and also the whole profile SOC stocks of high-yielding fields in all comparisons (Table 5). There was a positive correlation between SOC stocks and normalised yield ($p < .05$) (Figure 4). The stepwise linear regression suggested SOC stocks were positively related to lint yield across all the sites when analysed for SOC stocks at 0–15, 0–30, 30–60 and 0–90 cm depths (Table 4). The SOC stocks of high-yielding fields were 2.5–12.3 t/ha higher than their low-yielding paired fields, which, at a typical C:N ratio of 10:1, means these fields also had an additional 250–1230 kg/ha of organic N—a benefit for potential N mineralisation and thus less reliance on mineral fertilizer 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 (Hulugalle et al., 2013; Nachimuthu et al., 2018;

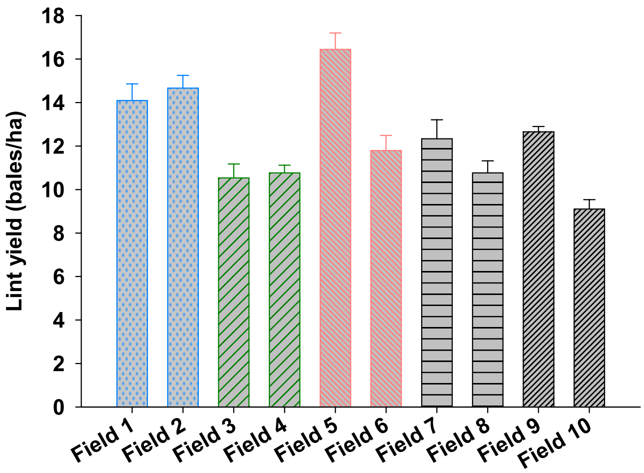

FIGURE 2 Lint yield (bales/ha; 1 bale = 227 kg of ginned lint) of paired sites measured during the 2018–2019 season. The error bars indicate the standard error of the mean. Each paired site is presented in the same colour and pattern. (Differences between fields 5 and 6, 7 and 8 and 9 and 10 are significantly different).

Osanai et al., 2020; Rochester, 2011). The three long-term research 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.

The stepwise linear regression suggested a negative relationship with lint yield only for the Gwydir comparison (Table 4). Mineral N stocks in this study tended to be higher than in recent research studies (Schwenke et al., 2022). This could be a result of the timing of the soil sampling that occurred after fertilizer application and before crop uptake. Overall, there was no relationship between early-season mineral N stock and cotton lint yield ($r^2 = .04$). However, Rochester and Bange (2016) reported lint yield was positively correlated with pre-sowing soil nitrate in unfertilised plots and all the fields in this study received N fertilizer. The lack of relationship between cotton lint yield and soil mineral N in our study suggests the combined fertilizer N and soil N stock were higher than soil nitrate N reported by Rochester and Bange (2016) and there is potential to rationalize the N input. Previous research found that cotton plants often derive more N from soils than from applied fertilizer (Macdonald et al., 2017; Rochester & Bange, 2016). 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 the slightly high industry average N application rate (176 kg N/ha) (CRDC, 2023). 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

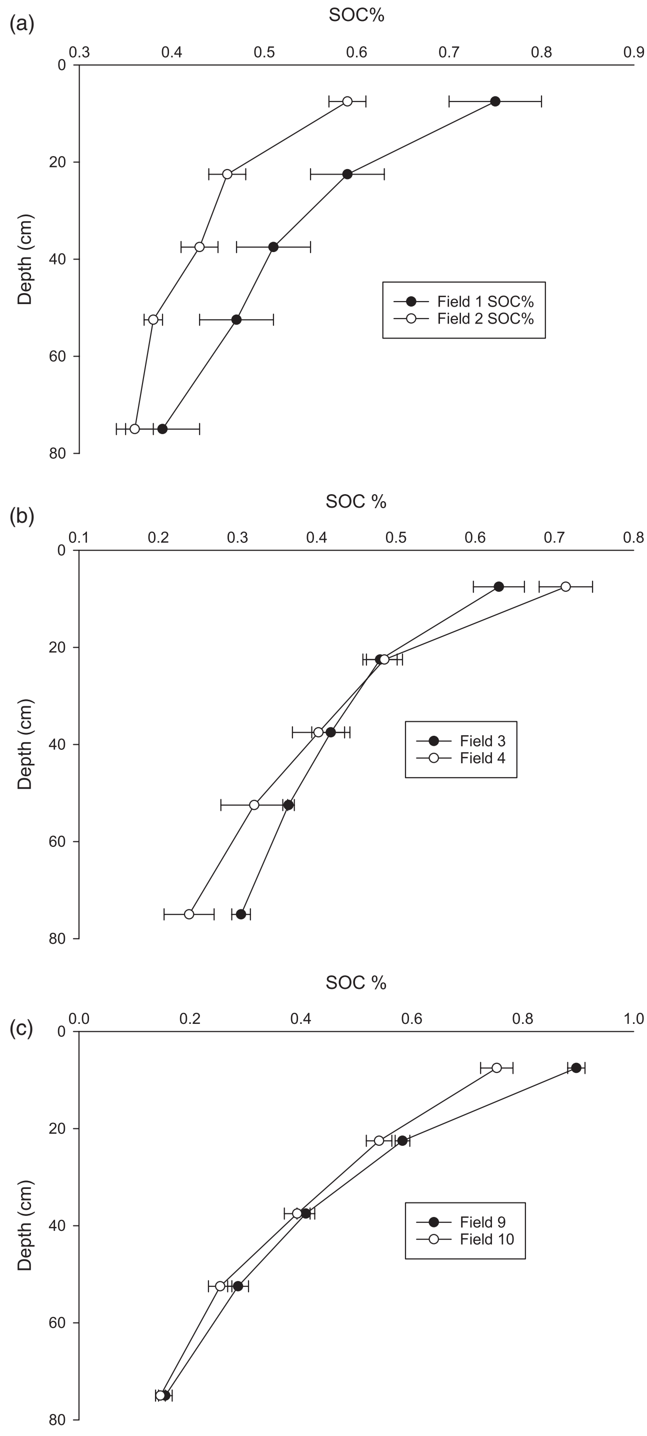

FIGURE 3 Soil organic carbon (%) at different depths in fields 1 and 2 (Gwydir), 3 and 4 (Macquarie-A) and 9 and 10 (Riverina-B). The error bars indicate the standard error of the mean.

Research Institute and higher than the paired fields investigated in this study (Figure 3). Higher SOC stocks in high-yielding fields could also be related to other soil properties (e.g. low sodicity, Section 3.5) resulting in higher biomass return leading to higher SOC. Future studies on nutrient response comparing soils of various

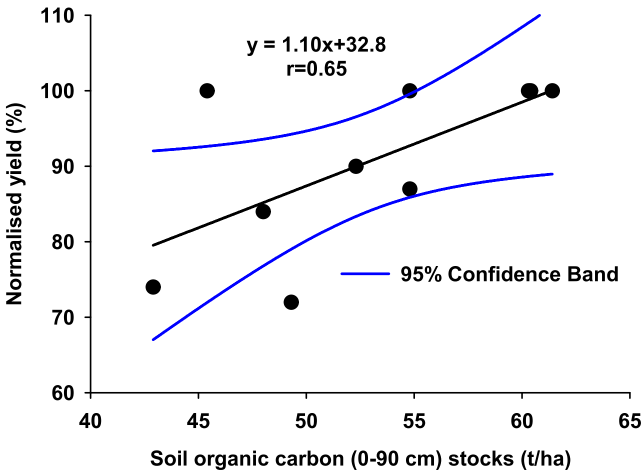

FIGURE 4 Relationship between soil organic carbon stocks (t/ha) and normalised lint yield across 10 fields. Normalised lint yield % = (The lint yield at the low yielding field/the yield at the higher yielding field) × 100.

SOC stocks will unravel the capacity of the soil to satisfy the plant nutrient demand and assist with optimising nutrient inputs.

3.4 | Sodicity

Sodicity (ESP) was significantly different between paired fields for Gwydir, Macquarie-A and Riverina-B comparisons (Table 5, Figure 5). 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 clay dispersion which impedes drainage through the soil profile (Dodd et al., 2013). Poorly drained soils 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 5). Sodicity is either ameliorated by gypsum application and leaching or else farmers can adjust their nutrition inputs to suit a lower yield potential. The annual cotton industry consultant survey (CRDC and CCA, 2023) and grower management records within this study suggested that soil surface crusting resulting in poor seedling establishment and subsequent yield impact, was observed in Macquarie Valley.

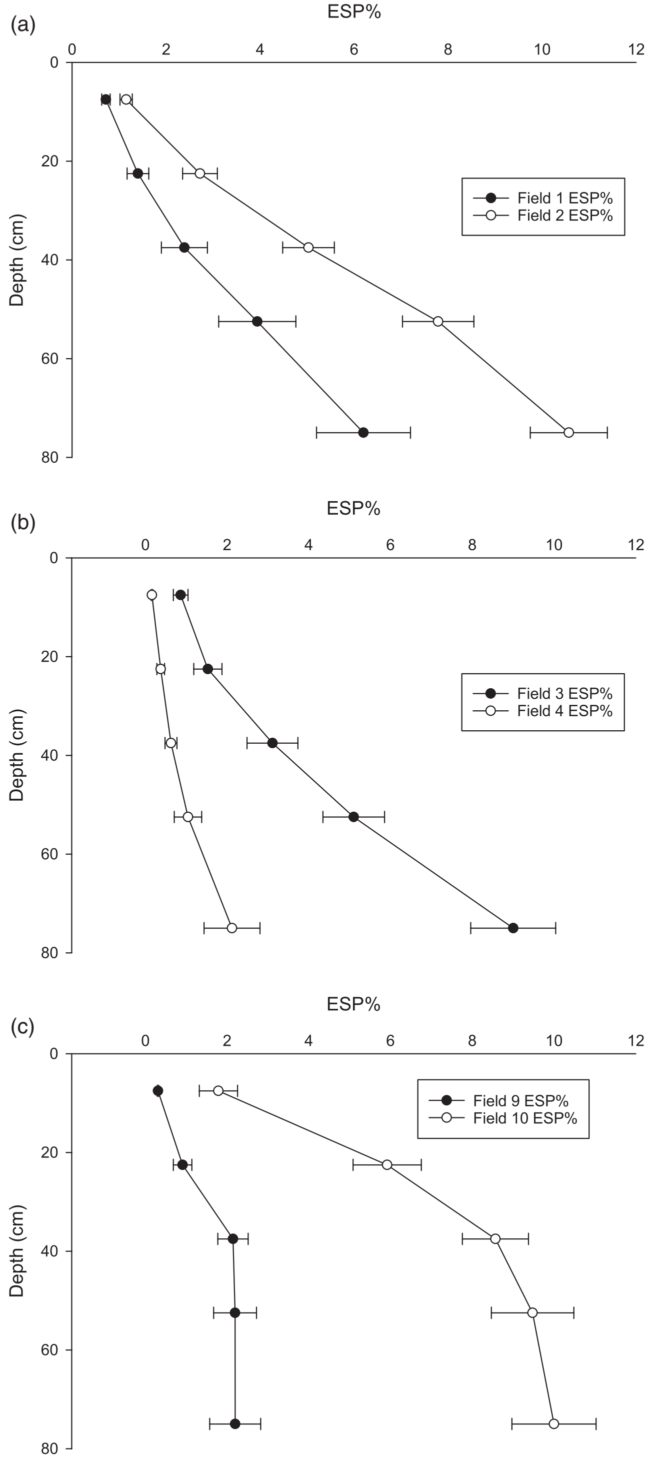

FIGURE 5 Exchangeable sodium percentage (ESP) at different depths in fields 1 and 2 (Gwydir), 3 and 4 (Macquarie-A) and 9 and 10 (Riverina-B). The error bars indicate the standard error of the means.

3.5 | Micronutrients

All DTPA-extractable micronutrients (Cu, Zn, Fe and Mn) were above recommended critical values for crop response in topsoil (NUTRIpak, 2018) across all the sites (Tables S1,S2, A4–A8). The lower-yielding fields in both Macquarie A and B comparisons had lower Zn levels in topsoil (Tables S1,S2, A4,A5, Supporting Information) 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 (Tables S1,S2, A4–A8, Supporting Information). 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).

3.6 | Visual soil assessment

The soil quality index score of fields 1–6 was above 30 and classified as 'good'. Many cotton farms in Australia were developed on medium–heavy cracking clay soils, with shrink-well properties acting to self-repair physical damage (Pillai-McGarry et al., 1994). In addition, soil management has improved over time by adopting controlled 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—currently the highest in the world (Constable & 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 & Bange, 2015). There are other soil constraints, such as subsoil compaction induced by heavy machinery (not 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 & Scott, 2008) and nutritional fertility (Rochester, 2011; Rochester et al., 2001). While the soil quality was 'good' using the visual soil assessment method, there are still opportunities for improvement with soil management practices such as minimising tillage and tactical stubble management.

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 in any of the fields in this study. 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, Hundt, Palmer, et al., 2022), which documents organic matter degradation under cotton-growing conditions. Apart from 'drainage' and 'rooting depth', most parameters of the visual soil assessment method only deal with the topsoil. Therefore, the current assessment method may not be sensitive enough to predict cotton crop performance in cotton-growing Vertosols of Australia and needs further refinement. Incorporating McKenzie's (2001a, 2001b) visual soil compaction assessment into the FAO visual soil assessment approach would improve the method's sensitivity, thereby improving its efficacy in predicting cotton crop growth. Subsoil dispersion is one of the factors causing poor drainage and subsequently impacting cotton growth in Australian cotton-growing soils, an aggregate dispersion test, such as ASWAT (Field et al., 1997) could be a metric that needs to be incorporated into visual soil quality indices.

4 | CONCLUSION

This paired field case study identified some differences in soil properties that may account for yield variation. Soil organic carbon stocks were positively correlated with normalised lint yield percentage (five-year average yield), whereas early season soil mineral N stocks did not correlate with current season yield. Soil sodicity was negatively related to lint yield at selected sites across all three valleys. The visual soil quality index was not a sensitive predictor of cotton crop performance. This case study focussed on understanding between the two fields at each site. A similar approach of strip comparison could be undertaken to improve understanding of within-field yield variability by dividing the field into several zones and assessing each zone individually.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the Supporting Information of this article.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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