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SOIL RESEARCH

Soil and fertiliser nitrogen performance indicators for irrigated cotton in Australia

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ABSTRACT

Context. Current cotton industry nitrogen (N) performance indicators have been developed in a narrow geographic region and do not represent production in southern Queensland (SQld) and southern New South Wales (SNSW), Australia. **Aims.** To benchmark soil and fertiliser N use efficiency (NUE) in irrigated cotton crops in these production areas, and to determine whether the current industry benchmarks are relevant in these regions. **Methods.** Eight field experiments were conducted over three growing seasons on commercial farms in SQld and SNSW. Experiments applied rates of urea-N to fields using surface or overhead irrigation. **Key results.** The industry partial factor productivity for N and internal N use efficiency (*i*NUE) benchmarks were not suitable NUE targets for these experiments because of variations in soil types, background soil N and other constraints to crop yield. Crops grown with soil N alone accumulated crop N and lint yield at 75% and 79% of crops producing 95% of site maximum lint yield (Y_{95}). At fertiliser rates producing Y_{95}, apparent N budgeting indicated only 25–30% of the potentially available soil and fertiliser N was present in crop biomass and soil mineral N at the end of season. **Conclusions.** Improving fertiliser N efficiency in irrigated cotton will require an understanding of site-specific factors that influence N availability, crop N demand and the ability of the crop to produce lint from N accumulated in biomass. **Implications.** Further research is required to develop the understanding of regional factors that influence crop N performance for the industry to improve its NUE.

Keywords: agronomic efficiency, cotton, fertiliser nitrogen uptake efficiency, internal nitrogen use efficiency, nitrogen, nitrogen fertiliser, nitrogen use efficiency, soil nitrogen uptake efficiency.

Introduction

Nitrogen (N) is the mineral nutrient required in the greatest amounts to support plant growth and its availability is a major factor limiting productivity in many farming systems (Kraiser *et al.* 2011). Its importance to the Australian cotton industry is highlighted by a sustained 50-year research and development investment that has underpinned increases in fibre and oil productivity (Macdonald *et al.* 2018). Indeed, Australia has the highest recorded cotton lint yield in the world (Constable and Bange 2015) and there is general recognition that N fertiliser applications are a critical success factor to achieve the crop N uptake required to produce high lint yields (Rochester and Bange 2016).

Fertiliser N management in the Australian cotton industry has been based on the concept of economic optimum fertiliser application rates since at least the early-mid 1990s (Rochester *et al.* 1997). However, most of the research upon which these optima have been based has been derived from research conducted in a relatively small geographic area on or around the Australian Cotton Research Institute in Narrabri NSW, primarily on Vertosol soils (Isbell 2016) and under siphon-furrow irrigation. The Australian industry has expanded geographically, with ~60% of the Australian crop grown outside the areas in which the industry N benchmarks were established (Cotton Australia Limited 2021). The implications of this diversified production base on fertiliser N requirements have not been determined, but differences in soil type/properties, crop yield potential, climatic conditions and management practices like overhead irrigation are all likely to impact various aspects of crop N management. Even with the limited geographic spread of historical fertiliser N research, lint yield responses to N fertiliser have varied considerably from season-to-season and location-to-location over the many years these experiments have been conducted (Constable and Rochester 1988; Rochester 2011; Rochester and Bange 2016). For example, changing from surface application to placement of fertiliser in the soil profile increased apparent fertiliser recovery from 5% to 60% (Rochester *et al.* 1993); variation in crop rotation and N fertiliser application rate produced apparent fertiliser recoveries ranging from 15% to 73% (Hearn 1986); changing the timing of fertiliser N application from all upfront (pre-season) to a combination of upfront and in-crop increased apparent recoveries from 25% to 45%, depending on season and the actual application timing (Constable and Rochester 1988); and at fertiliser application rates corresponding to the economic optimum, apparent fertiliser N recovery ranged from 0% to 98% depending on season and crop rotation, with the lower recoveries generally associated with larger amounts of soil mineral N (Rochester and Bange 2016). This variability suggests there are site and/or season-specific factors that impact on N demand from the cotton crop and/or the efficiency with which applied fertiliser is able to meet that demand, and yet the industry applies a single set of NUE benchmarks across all production regions. These benchmarks consist of a target band for Partial Factor Productivity of applied N (PFPN) that ranges from 13 to 18 kg lint kg of applied N^{-1} and an internal crop Nitrogen Use Efficiency (*i*NUE) target of 12.5 (±0.2) kg lint kg crop N uptake^{-1} (Rochester 2011; Rochester and Gordon 2014). It is recognised in other industries (e.g. the dairy industry – de Klein *et al.* (2017)) that setting universal performance indicators to drive improvements in the conversion of N inputs into agricultural products is unrealistic due to variation between production regions. Similar concerns have been reported in the cotton industry (Constable and Bange 2015), but as yet there have been no reports assessing the applicability of these indicators to the other cotton production regions.

The research reported in this manuscript systematically explored fertiliser N responses in eight irrigated cotton crops grown in either southern Queensland (SQld, three sites) or southern New South Wales (SNSW, five sites), Australia, over three growing seasons. The objectives of this work were to: (1) determine fertiliser N application rates that produced lint yield derived from fertiliser applied at rates delivering 95% of the maximum site yield (Y_{95}) at each location; (2) investigate the relationship between background soil N status and Y_{95}; and (3) compare physiological and agronomic N indicators to the current industry NUE benchmarks for the first time in these areas. This study also provided an opportunity to test other indicators of NUE such as those recently proposed by Antille and Moody (2021).

These studies will contribute to the knowledge base of the industry by gaining understanding of crop responses to soil and fertiliser N outside the intensively researched northern NSW production area. They also establish new N performance indicators against which subsequent studies can explore interactions between various crop management variables (irrigation strategies, timing of fertiliser N application and choice of fertiliser N product) on NUE of irrigated cotton crops in Australia.

Materials and methods

Field experiment sites

The data was collected from a total of eight field experiments conducted at three sites in southern Queensland (designated Qld Site 1–Qld Site 3) in the 2014/15 growing season and five in southern New South Wales (designated NSW Site 1–NSW Site 5), Australia, over the 2016/17 and 2017/18 growing seasons. Crops were grown using the most common irrigation systems used for cotton production in each region; that is, overhead and siphon-furrow irrigation in southern Queensland and bankless channel and siphon-furrow irrigation in southern New South Wales. Both siphon-furrow and bankless channel irrigation systems represent surface irrigation systems. The former applies water from a supply channel via siphons, with water traversing the length of the field in defined furrows and infiltrating soil between the furrows. Bankless channel systems are somewhat similar although without the requirement for siphons and associated labour, as water is applied via a channel that has one side level with the bottom of each furrow and as the channel fills, water flows out of the channel and traverses the length of the field in defined furrows.

Five of the eight field sites were planted as back-to-back cotton from the previous cropping season. Qld Site 1 was grown following maize in the previous summer cropping season; NSW Site 2 was grown following a fallow period of approximately 18 months after a maize crop, during which time the irrigation layout was developed; and NSW Site 3 was planted following ryegrass dominant pasture of approximately two and a half years. The pasture was sprayed out in August before paddock preparation for the cotton crop commenced.

The crop was grown on flat ground with overhead irrigation at Qld Site 1, and at the other two Qld sites and all the NSW sites the crops were grown on 1.8 m wide beds with two rows of cotton per bed with a 1-m spacing between the plant rows and irrigated using surface irrigation (either siphon-furrow or bankless channel).

Site locations and seasonal information are summarised in Table 1.

Pre-season soil samples were taken to a depth of 90 cm and analysed in 30 cm increments down the profile (0–30 cm, 30–60 cm, 60–90 cm) at all sites. Soil samples were analysed

Table 1. Cropping season, regional location and selected soil chemical properties (0–30 cm) for the eight field experiments used in the nitrogen response experiments for benchmarking nitrogen use efficiency in irrigated cotton crops.

Site	Region	Location	Soil type[A]	Irrigation system	Previous crop	pH_w	CEC (cmol(+) kg^{-1})	Soil organic C (%)
2014/15								
Qld Site 1	SQld	Brookstead (27°76′S 151°45′E)	Grey Vertosol	Overhead	Maize	8.1	61.0	2.30
Qld Site 2	SQld	Dalby (27°19′S 151°27′E)	Grey Vertosol	Siphon-furrow	Cotton	8.7	46.6	0.99
Qld Site 3	SQld	Dalby (27°19′S 151°27′E)	Grey Vertosol	Siphon-furrow	Cotton	8.6	46.8	0.73
2016/17								
NSW Site 1	SNSW	Whitton (34°51′S 146°18′E)	Grey Vertosol	Bankless Channel	Cotton	7.7	27.9	0.60
NSW Site 2	SNSW	Coleambally (34°79′S 145°89′E)	Red Chromosol	Bankless Channel	Fallow	6.8	16.4	0.88
NSW Site 3	SNSW	Yanco (34°60′S 146°41′E)	Red Chromosol	Siphon-furrow	Pasture (grass)	7.5	16.4	0.90
NSW Site 4	SNSW	Darlington Point (34°57′S 146°00′E)	Grey Vertosol	Siphon-furrow	Cotton	7.7	31.2	0.80
2017/18								
NSW Site 5	SNSW	Darlington Point (34°57′S 146°00′E)	Grey Vertosol	Siphon-furrow	Cotton	7.3	28.8	0.90

[A]Source: Isbell (2016).

using standard methods described in detail in Rayment and Lyons (2011), with the soil classification (Isbell 2016) and selected soil chemical characteristics are in Table 1. Specifically, the 0–30 cm sample was analysed for Colwell P (Method 9B2) and Phosphorus Buffering Index (PBI; Method 912b); pH in water (Method 4A1) and $CaCl_2$ (Method 4B1); exchangeable cations – NH_4OAc (Method 15D1) and exchangeable Al^{3+} (KCl) – Method 15G1; electrical conductivity and chloride (1:5 soil/water) – Method 3A1; and Walkley and Black organic carbon (Method 6A1). Soil mineral N (the sum of NH_4^+ and NO_3^- - N) concentrations were quantified for all depth layers using KCl extractions (Method 7C2b) (Table 2). Two soil samples were collected in the upper slope and lower slope positions (four in total) of all surface irrigated fields and analysed separately, to identify any trends associated with slope and position and the impact of water run during irrigation, with average mineral N concentration calculated for each site and depth. At the overhead irrigated site, two soil samples were collected from two locations (four in total) that were selected randomly within the field area identified for the field experiment. These samples from each field site were then bulked together for analysis. The pre-season and post-season mineral N concentrations were converted to a mass (kg N ha^{-1}) for each profile layer using estimated site bulk densities and then summed to provide profile totals in the top 90 cm, both prior to fertilising and sowing of the crop and also post-harvest for selected N rates (Table 2).

Field experiment site management

Variety selection was made by the co-operator at each site, with variety 74BRF sown at Qld Site 1 and 3, variety 75BRF sown at Qld Site 2 and the variety 746B3F sown at all sites in SNSW. The SQld sites were planted during mid to late October 2014, while NSW Sites 1 to 4 were planted

Table 2. Pre- and post-season mineral N content (kg N ha^{-1}), and apparent net *in situ* N mineralisation during growth (kg N ha^{-1}) in the 0–90 cm soil profile at the field sites across southern Queensland and southern New South Wales.

Site	Pre-season mineral N	Upfront N application rates	In-crop N application rate	Post-season mineral N	Apparent net *in situ* N mineralisation
Qld Site 1	100	0, 25, 50, 75, 100, 125, 200, 300	60	39	80
Qld Site 2	110	0, 40, 80, 120, 160, 200, 280, 360	50	20	63
Qld Site 3	57	0, 40, 80, 120, 160, 200, 280, 360	20	31	52
NSW Site 1	67	0, 50, 100, 150, 200, 400	0	67	81
NSW Site 2	161	0, 50, 100, 150, 200, 400	30	48	138
NSW Site 3	78	0, 25, 50, 75, 100, 125, 150, 200, 300, 400	0	59	125
NSW Site 4	148	0, 50, 100, 150, 200, 400	0	51	37
NSW Site 5	176	0, 100, 200, 400	0	71	60

Post-season samples used in the calculation of apparent net *in situ* N mineralisation were taken from the plots where no fertiliser N was applied.

late October/mid-November in 2016, and NSW Site 5 was planted in early October 2017. Pest and weed control at each site were managed with consideration of the insect thresholds within the industry's Insecticide Resistance Management Strategy and herbicide application limitations within the Bollgard Resistance Management Plans (CottonInfo 2020). Application of plant growth regulators and timing of defoliation was determined through the monitoring of Vegetative Growth Rate, estimation of cut-out and determination of nodes above cracked boll (CottonInfo 2020).

Field experiment design

Six field experiments were established using randomised complete block (RCB) designs in which each block consisted of either four, six or eight fertiliser N application rates ranging from zero to very low (from the result of in-crop application of fertiliser of between 20 and 60 kg N ha^{-1}), to supra-optimal, to establish the linear and curvilinear components of the N response surface at each location. Exceptions were at NSW Sites 3 and 5, where a split-plot design was utilised, with the duration of irrigation applications as the main plots and fertiliser treatments (10 and four fertiliser N application rates, respectively) as the sub-plots. Only the effects of fertiliser rate from NSW Sites 3 and 5 are reported in this paper, with irrigation and other fertiliser treatment effects to be reported elsewhere (authors' unpubl. data). Each field experiment consisted of five or six replicate blocks.

All sites received fertiliser N as granular urea applied upfront (i.e. prior to cotton planting) with the rates of fertiliser N applied shown in Table 2. At four sites there was an additional small in-crop application of N made to the whole field by the local co-operator at approximately first flower, with urea dissolved in water and applied using the surface (water-run) or overhead (fertigation) irrigation systems.

Plant sampling and nitrogen analysis

Sampling to determine crop biomass and N uptake was conducted on at least four of the N rate treatments in each experiment and always included the treatments with the lowest and the highest N rates applied. More intensive sampling was conducted on NSW Site 3, where the 0, 50, 100, 150, 200 and 400 N rates were sampled.

Crops had leaves removed through chemical defoliation when 60–65% of the bolls were open (Bange 2013), with up to four chemical defoliant applications required in SNSW. Biomass samples were collected from all replicates in the week prior to the initial chemical defoliant applications, with 1 m of plant row from the selected N fertiliser rates collected from each replicate plot on each occasion. The pre-defoliation sample was used to estimate maximum crop N accumulation.

Whole plants were cut at the cotyledon node, dried and weighed to determine total dry biomass (kg ha^{-1}). Dried samples had lint removed from bolls to allow effective grinding, with representative sub-samples selected and analysed for total N using Dumas combustion and a LECO analyser (Rayment and Lyons 2011). The lint that had been removed to facilitate sample grinding has been shown to contain a negligible amount of N (Macdonald *et al*. 2017) and so was assumed to not contribute to total above-ground crop N content.

The two central rows of each plot were harvested (picked) using a two-row mechanical picker (Rochester and Bange 2016). Seed-cotton (a combination of cotton seed and lint) weights were recorded for each plot and a subsample (approximately 500 g) taken for the determination of the proportions of lint and seed in the sample (turnout) using a 20-saw gin (Constable and Hodgson 1990). The seed from this sample was analysed for total N using Dumas combustion and a LECO analyser (Rayment and Lyons 2011) to calculate the seed N exported from the crop.

Nitrogen performance indicators

The N performance indicators were based on those reported by Antille and Moody (2021) but adapted to include soil N indicators.

Apparent net nitrogen mineralisation

The soil N mineralisation rates (kg ha^{-1}) at each site were determined using an equation adapted from Brackin *et al.* (2019) in the treatments where no N fertiliser had been applied. At sites where there had been small amounts of in-crop N application, post-season soil mineral N with no applied N was estimated by extrapolation from the relationship between the rates of fertiliser N applied and the measured post-season soil mineral quantities:

$$\text{Apparent net mineralised N} = (U + \text{N}_{\text{POST}}) - \text{N}_{\text{PRE}}$$

where U is the N taken up in crop biomass and $\text{N}_{\text{POST}}/\text{N}_{\text{PRE}}$ are the quantities of mineral N measured in the soil profile (0–90 cm) at the end of and prior to the cotton season, respectively.

Available soil N (N_S)

The N_S was defined as: pre-sowing mineral N + apparent N mineralisation + fertiliser N rate.

Soil N indicators

Soil nitrogen uptake efficiency (NU_PE_S)

This indicator measures the efficiency with which soil N was taken up in crop biomass. It was calculated as:

$$\text{NU}_{\text{P}}\text{E}_{\text{S}} = \frac{U}{\text{N}_{\text{S}}}$$

where U is the crop biomass N uptake due to available soil N (N_S kg ha^{-1}). At sites where there had been small amounts of in-crop N application, crop N uptake from soil mineral N at sowing was estimated by extrapolating from the relationship between the lower rates of fertiliser N applied and crop N uptake to determine crop N with no N applied. This method was used to estimate the condition with no N applied in all subsequent index calculations.

Data for the crop N content with no applied N was used to also estimate the quantity of plant N that may have been derived from in-season mineralisation or organic N sources in the unfertilised treatments at each site.

Agronomic efficiency of soil N (AE_S)

This indicator measures the efficiency with which soil N was used to produce lint yield. It was calculated as:

$$AE_S = \frac{Y}{N_S}$$

where Y is the yield (kg ha^{-1}) of harvested product (lint) due to available soil N (N_S, kg ha^{-1}).

Fertiliser N indicators

Fertiliser nitrogen uptake efficiency (NU_PE)

This indicator measures the efficiency with which applied N was taken up in crop biomass. It was calculated as:

$$NU_PE = \frac{\Delta U}{\Delta N_R}$$

where ΔU is the increase in crop biomass N uptake (kg ha^{-1}) due to an increment of applied N (ΔN_R, kg ha^{-1}) of N fertiliser above nil applied N.

Agronomic efficiency of applied fertiliser nitrogen (AE)

This indicator measures the efficiency with which fertiliser is used to produce crop yield. It was calculated as:

$$AE = \frac{\Delta Y}{\Delta N_R}$$

where ΔY is the yield increase (kg ha^{-1}) of harvested product (lint) due to an increment of applied fertiliser N (ΔN_R, kg ha^{-1}) above nil applied N.

Whole-crop N performance indicators

Partial factor productivity of applied N (PFP_N)

This indicator measures the yield produced (kg ha^{-1}) from a specified rate of applied fertiliser (kg ha^{-1}). It was calculated as:

$$PFP_N = \frac{Y_N}{N_R}$$

where Y_N is the yield obtained from a specified rate (N_R) of fertiliser N. This indicator represents one of the current Australian industry benchmarks, with a target range of 13–18 kg lint kg applied N^{-1} (Rochester and Gordon 2014).

Internal nitrogen use efficiency (*i*NUE)

This indicator measures the yield (kg ha^{-1}) produced from the N accumulated in crop biomass (kg ha^{-1}). It was calculated as:

$$iNUE = \frac{Y}{U}$$

where Y is the yield obtained from the N taken up in crop biomass (U). This is the other Australian industry benchmark, with a target of 12.5 (±0.2) kg lint kg crop N $uptake^{-1}$ (Rochester 2011).

Crop nitrogen balance (N balance)

This indicator describes the balance between N inputs and N removal for the cotton crop, and is calculated as:

$$\text{Apparent N balance} = N_R - \text{Seed } N_R$$

where N_R is the specified rate of fertiliser N applied and Seed N_R is the N removed in the seed fraction of seed-cotton at harvest for the specified fertiliser N rate. Macdonald *et al.* (2017) determined that N removed in lint represented <3% of plant removal of N and was assumed to negligible in this study.

Partial nitrogen budget (N budget)

The partial N budget for the cropping season was calculated using mass balance.

$$\text{N budget} = (N_S + N_R) - (U + N_{POST})$$

where N_S is the available soil N pre-sowing, N_R is the specified rate of fertiliser N, U is the N taken up in crop biomass and N_{POST} is the quantity of mineral N measured in the soil profile (0–90 cm) after crop harvest at the end of the cotton season.

Statistical analysis

Statistical analysis was conducted using Genstat 19th edition (VSN International 2015). To test for differences in crop N uptake and lint yield resulting from the application of fertiliser N at all Queensland sites and NSW Sites 1, 2 and 4, a general analysis of variance (ANOVA) was used for each of the sites separately. At NSW Sites 3 and 5 the Residual Maximum Likelihood method was utilised to conduct the analysis because of the factorial design at these sites that incorporated irrigation treatments. A two-sample *t*-test was used to determine if differences in crop N uptake and lint yield between SQld and SNSW were statistically significant.

Regression analyses were performed using Genstat 19th edition (VSN International 2015). This program was also used to fit the curves to the lint yield data and Sigmaplot (Systat Software 2017) was used to fit curves for the other relationships described in the paper. An optimum lint yield (Y_{95}) was used as a point of comparison across the sites and was defined as 95% of the maximum yield for each site estimated using the derived response surface determined from the regression analysis. Quadratic functions have been used previously by Rochester and Bange (2016) to describe the relationships between lint yield or crop N uptake and rate of applied N, but this function did not adequately describe the response surfaces at all sites in this study. Exponential, quadratic and linear functions best defined the crop N uptake and lint yield responses to fertiliser N application at the different sites.

Results

Regional crop performance

The experiments in SQld and SNSW produced cotton crops that were typical of the irrigated production in each region (Table 3). In the presence of adequate N, there was a similar range in lint yields (2400–3000 kg ha^{-1} in SQld and 2000–3000 kg ha^{-1} in SNSW) across both regions, although the crop N contents (130–175 kg N ha^{-1} in SQld and 170–250 kg N ha^{-1} in SNSW) were generally higher in SNSW. There was a significant difference in the mean yield of treatments receiving no N fertiliser prior to planting between the two production regions (an average of 2350 kg ha^{-1} in SQld vs 1870 kg ha^{-1} in SNSW), and this higher yield in SQld was despite less crop N uptake (i.e. 124 kg N ha^{-1} in SQld and 154 kg N ha^{-1} in SNSW; Table 3). The relatively high crop N content in the unfertilised treatments in SNSW suggests that agronomic factors that impact boll/lint production rather than simple N availability were the cause of the lower lint yields in those experiments.

Crop response to soil N

The quantity of soil N used for the calculation of N performance indicators in this study is derived from the measured mineral N in the soil prior to fertiliser application plus an *in situ* assessment of net N that had mineralised during the growing season. The estimated quantity of N mineralised during the season ranged from 25 to 160% of the profile mineral N determined from pre-season samples (Table 2), and there was no relationship between net N mineralised and either soil organic C or pre-season mineral N across the sites. The sites with the highest net in-season mineralisation (NSW Sites 2 and 3) had not been cropped in the preceding year, while those that had been cropped to cotton the previous year showed low and fairly similar rates of net N mineralisation (i.e. 40–60 kg N ha^{-1}).

Soil N played an important role in the productivity of crops at all sites, with the N accumulated in unfertilised crops representing an average of 75% of the crop N uptake and sustaining an average of 79% of the lint yield of that recorded at fertiliser rates that delivered Y_{95} (Table 3). Crop N content without fertiliser application was positively correlated to soil mineral N with crops accumulating on average 75% of the available soil N across the range from 109 to 299 kg N ha^{-1} across all sites (Fig. 1). However, the same relationship was not evident with lint yield (data not

Table 3. Crop N uptake and lint yield (kg ha^{-1}) with no fertiliser N applied, the additional crop N uptake and lint yield derived from fertiliser applied at rates delivering 95% of the maximum site yield (Y_{95}) and N exported from the crop in seed.

Site	Soil N				Fertiliser N applied to achieve Y_{95}				
	Crop N uptake	Lint yield	% of Y_{95} yield	Seed N	Fertiliser N rate	Additional N uptake	Additional lint yield	Y_{95} lint yield	Seed N
Qld Site 1	140	2660	87	128	64	17	381	3046	134
Qld Site 2	151	2400	83	125	156	23	488	2885	154
Qld Site 3	82	1980	81	83	78	47	468	2445	108
NSW Site 1	78	1380	53	98	316	96	1213	2593	161
NSW Site 2[A]	250	2400	100	158	0	0	0	2400	158
NSW Site 3	143	2210	72	119	163	66	850	3063	161
NSW Site 4	134	1540	77	114	208	36	472	2009	124
NSW Site 5	163	1840	76	86	197	70	596	2436	135
Mean	143 (±19)	2051 (±195)	79	114 (±9.0)	148 (±35)	44 (±11)	559	2610 (±129)	142 (±7.0)
SQld	124 n.s.	2347*	84	112 n.s.	99*	29*	446	2792*	132*
SNSW	154	1874	76	114	176	54	626	2500	148

Standard error of the means are shown in parentheses. The significance of the difference in means between SQld and SNSW is indicated: *$P \leq 0.05$; n.s., not significant.
[A]The data for NSW Site 2 is for the point of maximum lint yield, not Y_{95}, due to the declining response following application of fertiliser N.

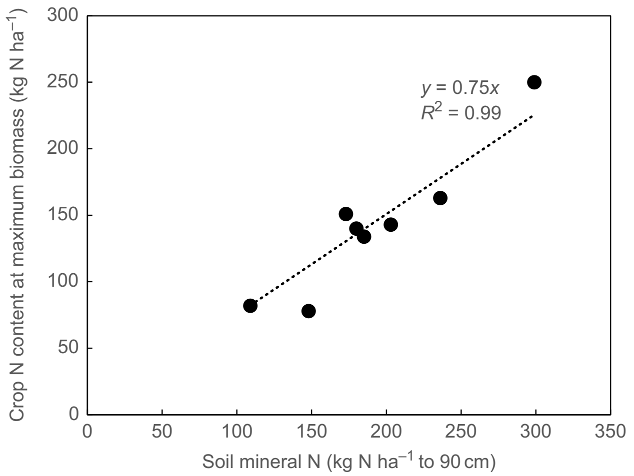

Fig. 1. The relationship between soil mineral N (determined through measurement of soil mineral N at the start of the cotton season and an estimated *in situ* mineralisation of N throughout the crop growing season) and crop N content at defoliation where no fertiliser N had been applied.

shown; $r = 0.16$, $P > 0.05$), suggesting that factors other than N availability were influencing the production of lint.

Crop responses to fertiliser N

The N accumulated in crop biomass from soil and applied fertiliser is shown for all sites in SQld and SNSW sites (Fig. 2). Apart from the NSW Site 2, which showed no change in crop N content as fertiliser rates increased from 30 to 430 kg N ha^{-1}, all other crops showed increases in N contents of 50–100 kg N ha^{-1} due to fertiliser N application in responses that were either linear or curvilinear. The quantities of additional N accumulated in crop biomass in response to fertiliser N rates that delivered Y_{95} were much smaller than the rates themselves. While the rate of increase in crop N content may have decreased at the higher N rates in some sites, it was only at NSW Site 1 where crop N content appeared to plateau, albeit at rates >300 kg N ha^{-1}.

The continued increase in crop N with increasing N application rate was in marked contrast to the crop response in terms of lint yield increase (Fig. 3), where yield reached a maximum at relatively low rates of N application and then plateaued despite higher rates of N application and increasing crop N uptake.

Lint yield increased significantly as fertiliser N application rate increased across all sites in SQld and four of the five sites in SNSW ($P < 0.05$; Fig. 3). The lint yield response surface across the seven sites was best described using an exponential function with an initial rapid increase as the fertiliser N application increased from the minimum, and then a defined plateau in the response that defined maximum lint yield. The lint yield response surfaces were similar in SQld despite different varieties being grown

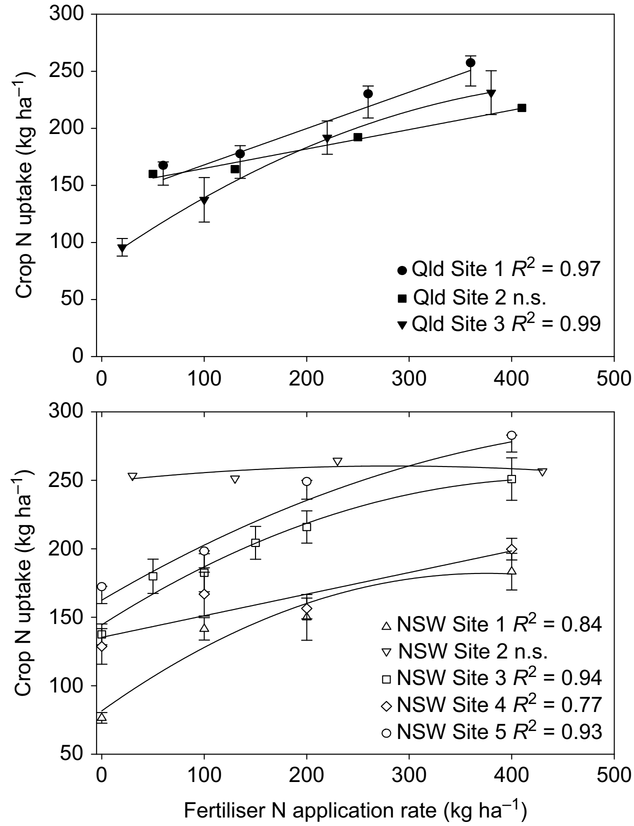

Fig. 2. The relationships between applied fertiliser nitrogen (N) application and the crop N uptake across three sites in southern Qld (solid symbols) during the 2014/15 season and five sites in southern NSW (open symbols) during the 2016/17 and 2017/18 seasons. The error bars represent the standard error for each fertiliser N application rate at each site.

across the sites. Management of the Qld sites appears to have had a larger impact than variety choice with the same variety indicating high (Qld Site 1) and low (Qld Site 3) yield potential in response to fertiliser application. The fertiliser rate that delivered Y_{95} was chosen as the point at which to quantify the impact of fertiliser N on crop N uptake, lint yield and N performance indicators. There was a wide range in fertiliser N rates required to reach Y_{95} across the eight experiments, with the NSW sites representing both ends of the range (from 0 kg N ha^{-1} at NSW Site 2 to >300 kg N ha^{-1} at NSW Site 1 – Table 3). The Qld sites also exhibited a wide range (64–156 kg N ha^{-1}) but generally required less fertiliser N to achieve Y_{95}. On average, the SNSW sites required significantly more fertiliser N (176 kg N ha^{-1} compared with 99 kg N ha^{-1}) to achieve Y_{95} (Table 3). An important note with the fertiliser response surfaces for lint yield across sites in both regions was that due to the curvilinear responses to increasing N rates (Fig. 3), yields increased by only 1–2 kg lint for each additional kg N fertiliser applied between Y_{90} (90% maximum lint yield) and Y_{95}.

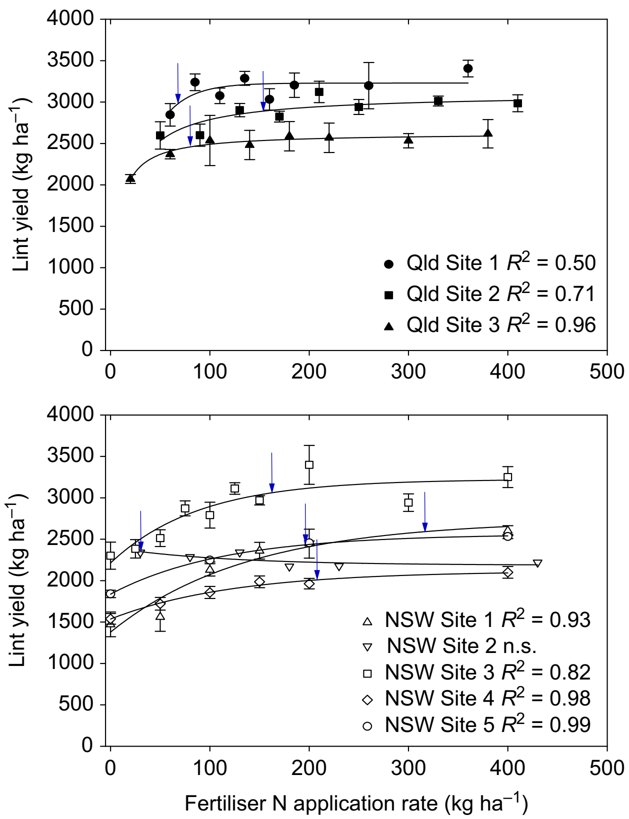

Fig. 3. The relationships between fertiliser nitrogen (N) application and lint yield across four sites in southern Qld (solid symbols) during the 2014/15 season and five sites in southern NSW (open symbols) during the 2016/17 and 2017/18 seasons. The blue arrows indicate the fertiliser N application rate required to achieve Y_{95} (95% maximum lint yield for each site), except at NSW Site 2 where the arrow represent maximum yield because of declining yield with additional fertiliser N application. The error bars represent the standard error for each fertiliser N application rate at each site.

Site N status (Table 2 – either profile mineral N measured before fertiliser N application, or the sum of initial profile mineral N and net *in situ* N mineralisation during the growing season – soil N) was not related to the fertiliser N requirement to achieve Y_{95} across the eight sites (Table 3).

While there did not appear to be any relationships between soil N availability and the rate of fertiliser N required to achieve Y_{95}, there was a positive correlation between the amount of available soil N at the various sites and the biomass N content (Fig. 1) without fertiliser N application.

Nitrogen performance indicators

Soil N

The recovery of soil N (NU$_P$E$_S$) was 0.7–0.9 kg crop N uptake kg of available soil N^{-1}, in all sites except NSW Site 1, where the crop accumulated only 0.5 kg N of available soil N^{-1} (Table 4). There was a significant difference in the mean NU$_P$E$_S$ between SQld and SNSW, with average NU$_P$E$_S$ for the two regions of 0.8 and 0.7, respectively. Similarly, there were significant differences in the ability of the crop to produce lint from available soil N (AE$_S$). The SQld sites produced an AE$_S$ of 15.6 kg of lint for each kg of soil N available, compared to 8.9 in SNSW: 76% greater efficiency. Notwithstanding the SQld data being from a single growing season, there was a strong indication that crops in that region were more able to capture soil N in the plant and convert the accumulated soil N to lint yield.

Fertiliser N

The calculated NU$_P$E for fertiliser N at rates delivering Y_{95} ranged from 0.1 to 0.6 kg N recovered kg N applied^{-1} (Table 4). The highest (0.6) and lowest (0.1) NU$_P$E values were both recorded in Qld sites under siphon-furrow irrigation management in the same growing season. At the site with NU$_P$E of 0.1, fertiliser N applied at a rate of 156 kg N ha^{-1} only resulted in an additional 23 kg N ha^{-1} in the crop. When NU$_P$E was plotted as a function of the relative crop N content (i.e. crop N content with no fertiliser applied at each site compared to the site with the highest crop N content where no fertiliser was applied) of the unfertilised treatments at each site (Fig. 4), it was shown that the stronger the crop N demand at a site, the more efficient the recovery of applied N fertiliser. Understanding site-specific drivers of crop N demand will be important to improve NU$_P$E, given there was no relationship between soil N and the fertiliser rate needed to optimise lint yield.

There was nearly a three-fold variation in AE (i.e. 2.3–6.0 kg lint kg applied N^{-1} – Table 4) of fertiliser N use across sites that required fertiliser N application to maximise production (i.e. excluding NSW Site 2). Once again, the SQld production environment showed greater capacity to produce lint from each kg of fertiliser N needed to reach Y_{95} when compared to SNSW (5.0 ± 1.0 and 2.9 ± 0.6, respectively). These values were only 20–50% of those recorded for soil-derived N in the unfertilised treatments, suggesting a much lower efficiency of use of fertiliser N.

Partial factor productivity of N

Despite the fertiliser application being optimised for Y_{95}, none of the eight sites fell within the target range of 13–18 kg lint kg N applied^{-1} (Table 4). While Qld Site 2 was near the upper boundary of the current benchmark, the other two Qld sites would be assessed as being significantly under fertilised. The NSW sites were closer to the target PFP$_N$, although three of the four sites would have been considered to have been over-fertilised for the yield achieved (i.e. PPF$_N$ < 13).

*i*NUE as a benchmark to compare efficiencies of use of soil vs fertiliser-derived N across regions

Given the confounding of NU$_P$E with site/crop N status, a more appropriate way of comparing the efficiency of use of

Table 4. Nitrogen (N) Uptake Efficiency (NU_PE) and Agronomic Efficiency (AE) for soil (S) and fertiliser response, Partial Factor Productivity of N (PFP_N) are at the point of 95% maximum yield (Y_{95}).

Site	Soil N		Fertiliser N			Crop	Reference
	NU_PE_S (kg uptake kg N^{-1})	AE_S (kg lint kg N^{-1})	NU_PE (kg uptake kg N^{-1})	AE (kg lint kg N^{-1})	PFP_N	*i*NUE (kg lint kg crop N uptake^{-1})	
Qld Site 1	0.8	14.8	0.3	6.0	47.6	19.4	
Qld Site 2	0.9	13.9	0.1	3.1	18.5	16.6	
Qld Site 3	0.8	18.2	0.6	6.0	31.3	19.0	
NSW Site 1	0.5	9.3	0.3	3.8	8.2	14.9	
NSW Site 2[A]	0.8	8.0	0.0	0.0	0.0	9.6	
NSW Site 3	0.7	10.9	0.4	5.2	18.8	14.7	
NSW Site 4	0.7	8.3	0.2	2.3	9.7	11.9	
NSW Site 5	0.7	7.8	0.4	3.0	12.4	10.5	
Mean	0.74 (±0.04)	11.4 (±1.3)	0.29 (±0.06)	3.7 (±0.6)	18.3 (±5.3)	14.6 (±1.3)	
SQld	0.80 (±0.04)	15.6 (±0.9)	0.33 (±0.1)	5.0 (±1.0)	32.5 (±8.4)	18.3 (±0.9)	
SNSW	0.70 (±0.05)	8.9 (±0.6)	0.26 (±0.05)	2.9 (±0.6)	9.8 (±2.3)	12.3 (±1.1)	
Industry N performance indicators						12.5 (±0.2)	Rochester (2011)
					13–18		Rochester (2014)
Published N performance indicators			0.3–0.5 (Qld) 0.5–0.6 (NSW)	11.0 (Qld) 17.1 (NSW)			Antille and Moody (2021)
			0.0–0.7		10.1–290.1	9.5–14.6	Rochester *et al.* (2001*a*)
					12.9–22.5		Rochester and Bange (2013)
			0.3–0.6		13.9–26.7		Rochester and Bange (2016)

The internal Nitrogen Use Efficiency (*i*NUE) for the crop was also determined at the same yield reference point. Standard error of the means across all sites and within the production regions are in parentheses. Current industry N performance indicators are included, and other published NUE indicators have been included where they were either directly described or could be determined from published data.

[A]The data for NSW Site 2 is for the point of maximum lint yield, not Y_{95}, due to the declining response following application of fertiliser N.

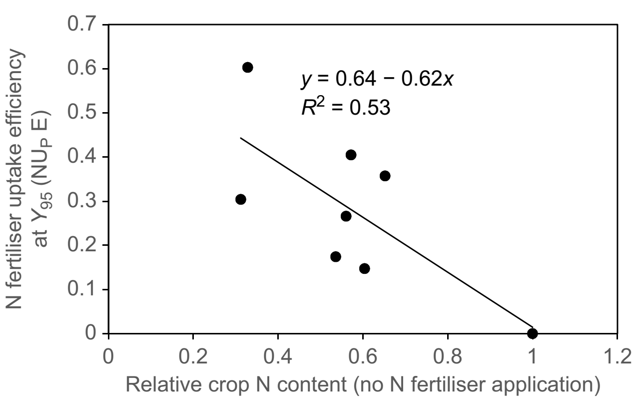

Fig. 4. The relationship between the relative crop N content of plants receiving no N fertiliser (i.e. crop N content with no fertiliser applied at each site compared to the site with the highest crop N content where no fertiliser was applied), and the efficiency of recovery of fertiliser N applied at the rate required to produce Y_{95}.

soil and fertiliser N is to compare the efficiency with which N accumulated in crop biomass was able to generate lint yield (*i*NUE). Using the crop N and lint yield data from Table 3 to calculate *i*NUE for N derived from soil, and Table 4 for that derived from soil + fertiliser, very similar average values were obtained (i.e. 15.6 ± 1.7 kg lint kg biomass N^{-1} derived from soil, compared with 14.6 ± 1.3 N kg lint kg biomass N^{-1} for N derived from soil + fertiliser).

Another interesting observation was the effect of production region, with the average *i*NUE in the SQld sites being 50% higher than those in SNSW for both N derived from soil (19.7 ± 2.4 vs 13.1 ± 1.5 kg lint kg biomass N^{-1}) and from the combination of soil + fertiliser at Y_{95} (i.e. 18.3 ± 0.9 vs 12.3 ± 1.1 kg lint kg biomass N^{-1}: Table 4). However, these average effects masked what was the significant variation between site-years, especially within the five SNSW trials. The range in *i*NUE at Y_{95} in the SQld sites (16.6–19.4 kg lint kg biomass N^{-1}) was relatively small, albeit from a single growing season, but was much greater across the five sites and two growing seasons from SNSW (9.6–14.9 kg lint kg biomass N^{-1}). The SNSW sites with the highest *i*NUE (NSW Site 1 and NSW Site 3, from different locations) had similar average yields to the Qld sites (2830 vs 2790 kg lint ha^{-1}) but accumulated a greater amount of biomass N (192 vs 153 kg N ha^{-1}). In comparison, the low *i*NUE sites from SNSW had similar, if not higher, biomass N (average of 217 kg N ha^{-1}) but a much lower lint yield (average of 2280 kg ha^{-1}), suggesting that factors affecting lint production were a larger driver for differences in *i*NUE.

Broadening the exploration of *i*NUE differences to include all fertiliser N rates sampled at each site (Fig. 5) reinforced the suggestion that these differences were more likely due to site management or soil related factors. This combined data set allowed a separation of data into an outer bound of high *i*NUE (sites with *i*NUE well above the current industry benchmark) that was achieved in the SQld sites (except with the highest fertiliser N application at Qld Site 3) and NSW Sites 1 and 3, while the other three NSW sites (and the highest fertiliser rate at Qld Site 3) showed lower *i*NUE due to low lint yields, rather than low crop N uptake. In both instances this relationship showed a decreasing lint yield response as crop N increased, which was consistent with the more pronounced plateau in lint yields than in crop N content as rates of fertiliser N application increased.

Whole-crop nitrogen performance indicators

Crop N balances (N applied in fertiliser – N removed in seed) were calculated for the unfertilised and fertilised treatments

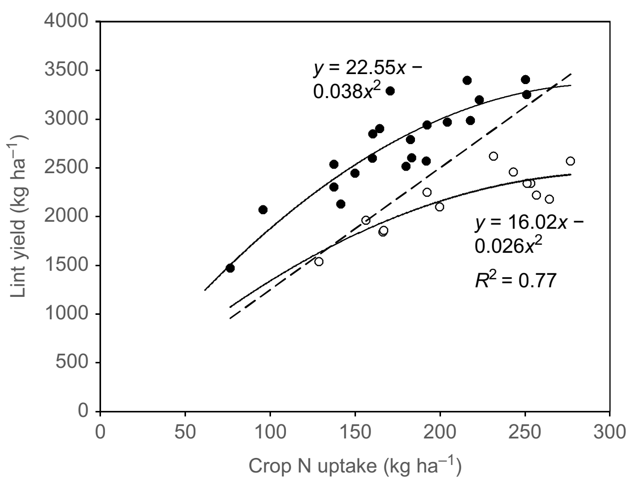

Fig. 5. The relationship between crop N uptake and lint yield at the SQld sites (excluding the highest fertiliser application at Qld Site 3) and NSW Site 1 and 3 with high *i*NUE (>12.5 kg lint kg crop N^{-1}; solid symbols), and the highest N rate at Qld Site 3 and NSW Site 2, 4 and 5 with low *i*NUE (<12.5 kg lint kg crop N^{-1}; open symbols). The dashed line represents the *i*NUE of 12.5 kg lint kg crop N $uptake^{-1}$ published by Rochester (2011).

(at rates achieving Y_{95}) at each site from data in Table 3. There was nearly a two-fold range in the rates of net N removal in cotton seed in the unfertilised treatments across the sites (from 85 to 160 kg N ha^{-1}), and while the application of fertiliser to achieve Y_{95} at each site reduced the variability in seed N removal between sites (110–160 kg N ha^{-1}), it was interesting to note that the N removed in seed increased by an average of only 28 kg N ha^{-1} in response to Y_{95} fertiliser N applications. This increase represented only 19% of the average rate of fertiliser N applied and suggests that little of the applied fertiliser N was recovered in the harvested product. There were greater proportional increases in seed N removal, relative to the fertiliser N application, at some individual sites (e.g. seed N removal at Qld Site 3 increased by 32%), but other sites showed very little impact of fertiliser N application on seed N removal (e.g. Qld Site 1). The efficiency with which fertiliser N was recovered in the harvested produce was therefore typically low.

The application of Y_{95} fertiliser N rates across all sites had a variable impact on the N balance of each crop (Fig. 6), with application rates of at least 140 kg N ha^{-1} required to balance N removal in cotton seed. This rate reflected that needed to reach Y_{95} at Qld Site 2 and NSW Site 3, but equivalent rates at other sites either generated moderate to large surpluses (NSW Sites 1, 4 and 5) or deficits (Qld Sites 1 and 3 and NSW Site 2).

The seemingly small proportion of applied fertiliser N removed in harvested produce raises the question of the fate of the applied N, and so apparent N budgets were calculated from the input and output data in Tables 2 and 3 for the fertiliser rate that produced Y_{95} at each location (Fig. 7*a*, *b*). This cross-site analysis showed a strong positive relationship between the rate of fertiliser N applied and the amount of N that could not be recovered in the plant or

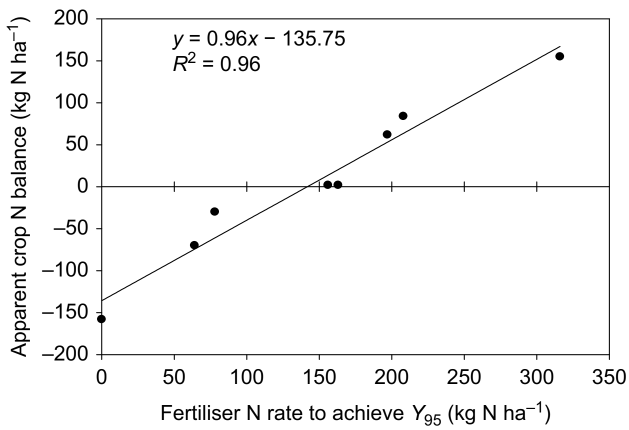

Fig. 6. The relationship between the fertiliser N rate needed to achieve Y_{95} at each site and the apparent N balance based on N removal in cotton seed.

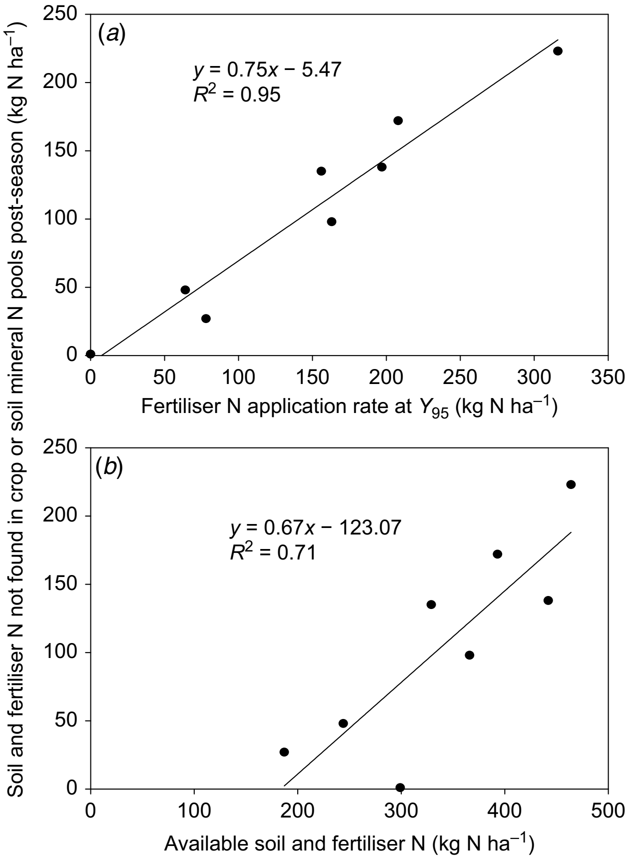

Fig. 7. Impact of (*a*) the rate of applied fertiliser N to achieve Y_{95} or (*b*) the sum of the applied fertiliser N for Y_{95} and the available soil mineral N pool on the amount of N that could not be accounted for in the mineral N and crop biomass pools at the end of the respective growing seasons. Data are shown for eight field sites across SQld and SNSW representing three growing seasons.

readily available soil mineral N pools at the end of the season (Fig. 7*a*). Interestingly, these strong linear relationships persisted when the soil available N was included in the analysis (Fig. 7*b*), with large differences in the intercept but quite similar slopes to those observed for the fertiliser N relationship (i.e. 0.67 vs 0.74). These analyses showed that even when fertiliser N application rates were optimised for individual sites and growing seasons, only 25% to 30% of the potentially available soil and fertiliser N could be accounted for in crop biomass or in labile mineral N pools in the soil profile at the end of the growing season.

Discussion

The results from these studies highlight two important issues that face the irrigated cotton industry in Australia: (1) the current benchmarks that are used by the industry are not good indicators of fertiliser NUE in the production areas of SQld and SNSW; and (2) N application rates required to achieve Y_{95} were lower than the average fertiliser N application of 275 kg N ha^{-1} (Roth Rural 2017) in all except NSW Site 1. Collectively, these findings suggest that there is considerable opportunity to improve NUE in both the southern and northern areas of the industry. However, without suitable financial or regulatory incentives and in the absence of regionally validated NUE benchmarks, change will be slow. The Australian cotton production system has been shown to be relatively insensitive to fertiliser N price (Welsh *et al.* 2015), with growers wanting to ensure yield is not limited by N availability (Rochester and Bange 2016). Significant changes in the value of the lint or cost of fertiliser are therefore required to drive changes in fertiliser application strategies in these systems (Antille and Moody 2021).

Relevance of current industry N performance indicators

The results presented in this paper have highlighted that the current partial factor productivity of N benchmark for fertiliser NUE, with an ideal 'fertiliser use efficiency' range of 13–18 kg lint kg fertiliser N applied^{-1} (Rochester and Bange 2013, 2016; Rochester 2014; Macdonald *et al.* 2018), and the *i*NUE productivity target of 12.5 (±0.2) kg lint kg crop N uptake^{-1} (Rochester 2011), are not suitable as 'one size fits all' goals across the industry.

Differences in the lint yield response to fertiliser N applications between sites and regions resulted in fertiliser N requirements to achieve Y_{95} differing substantially (Fig. 3), with the current PFP_N indicator underestimating N productivity responses in SQld and overestimating what can be achieved in SNSW (Table 4). A grower survey by Roth Rural (2017) and a review of N fertiliser use efficiency in the industry by Macdonald *et al.* (2018) using PFP_N suggest inefficient use of fertiliser because only a small percentage of industry and research data sits within the current ideal range. The data presented in this study suggests that the applicability of the current industry benchmarks is also questionable and may be confounding conclusions about N fertiliser use efficiency in different production regions.

The significant contribution of soil N to crop productivity in this study, and that soil N is not recognised in partial factor indices (Rochester and Bange 2016), represents a major limitation for the current N performance indicators. A large proportion of lint yield in many sites was achieved without any fertiliser N application (Table 2), so apparent net economic benefit from investing in N fertiliser application will be significantly overestimated. For example, in situations where the cost of N applied was AUD1.45 kg^{-1}, the net economic benefit of applying 200 kg N ha^{-1} to achieve a cotton crop producing 3141 kg lint ha^{-1} (Welsh *et al.* 2015) would be assessed as AUD5464 ha^{-1}. However, when lint yields are discounted by the yields obtained without any N fertiliser (i.e. obtained from soil N alone), the net economic benefit is reduced to only AUD1550 ha^{-1}. While the modified return on fertiliser investment is still clearly positive (AUD7.75 return for each kg of N applied), the marginal return from fertiliser N investment becomes less compelling.

Other metrics to quantify NUE are similarly distorted unless the soil N contribution is appropriately recognised. The AE resulting from optimising fertiliser N inputs in these experiments (Table 4) illustrated the significant overestimation that can occur with partial factor performance indices. The AE based on the additional lint yield produced from fertiliser application, rather than on total crop yield irrespective of N source, shows that the NUE of N fertiliser application in SQld and SNSW would be only 15–28%, respectively, of what would be reported using PFP_N. Importantly, crops receiving the fertiliser N rate that delivered Y_{95} in these trials were assessed as either being over or under-fertilised by the current PFP_N benchmark of 13–18 kg lint kg applied N^{-1}.

The relationship between crop N uptake and lint yield (*i*NUE) has been reported in a number of studies from northern NSW (Constable and Rochester 1988; Rochester *et al.* 2001*b*; Rochester 2011; Rochester and Bange 2016), with the simple target of 12.5 kg lint kg N $uptake^{-1}$ derived from these studies implying a linear relationship between crop N uptake and lint yield. However, our studies have clearly shown the relationships between crop N uptake and lint yield are curvilinear within and between sites (Fig. 5), with the rate of increase and the ceiling productivity differing between high and low *i*NUE experiments. The curvilinear component of the relationship illustrates the ability of cotton crops to incrementally accumulate N in biomass without producing concurrent increases in lint yield, highlighting limitation to simplistic indices like 12.5 kg lint kg N $uptake^{-1}$.

The importance of benchmarking indices such as *i*NUE for driving improvement in fertiliser use efficiency has been highlighted by Bronson (2021) for cotton grown in Texas and Arkansas, USA, with identification of the factors contributing to *i*NUE differences between sites and locations the key to improvement. A superficial analysis of *i*NUE data across sites in our study (Table 4) would suggest that the high and low *i*NUE response surfaces were associated with regional soil or climatic differences (i.e. SQld vs SNSW). However, a more detailed analysis across all N treatments (Fig. 5) shows that while 14 of the 15 data points in the low *i*NUE cluster were from SNSW sites, there was another set of data points from the same region (i.e. crops in NSW 1 and NSW 3) that were achieving similar *i*NUE to the crops in SQld. Yields in the low *i*NUE sites in SNSW were clearly not constrained by an ability to accumulate N in crop biomass, but rather by an inability to convert accumulated N into lint yield. The key drivers of increased yield are the fruiting branches per plant and the boll number m^{-2} (Constable and Bange 2015), so any combination of genetic/environment/management factors that limit these crop attributes will constrain yield potential and crop NUE. Identification of these constraints and adoption of an appropriate management response will make a significant impact on NUE at such locations.

Role of soil N

The importance of soil N in meeting crop demand and balancing N removal in harvested product has been recognised in irrigated rice production in southern NSW (Dunn *et al.* 2016); in high yielding wheat in southern Victoria (Harris *et al.* 2016); in sorghum and maize in northern NSW (Schwenke and Haigh 2016); and in cotton production in south-west USA (Bronson *et al.* 2017). It is therefore not surprising that soil N is also not the dominant source of crop N in the cotton production system, so establishing management strategies that sustain or build soil organic matter (SOM) stocks, and consequently the soil N pool, will be important to ensure N budget deficits do not lead to unsustainable decline of SOM (Scheer *et al.* 2022).

Crop N derived from background soil N was sufficient to produce an average of 77% (45–100%) of that accumulated with optimised fertiliser applications at Y_{95} (Table 3), which was similar to the 68–76% of accumulated crop N in irrigated cotton reported by Rochester and Bange (2016) and Macdonald *et al.* (2017). Similar contributions of soil N to crop N uptake have been derived using labelled ^{15}N fertiliser experiments, with Scheer *et al.* (2022) reporting 83% of the N taken up by cotton crops was derived from the soil N, while De Antoni Migliorati *et al.* (2014) found 48–74% of crop N was derived for soil N in wheat, sorghum and maize grown in sub-tropical cropping systems. Interestingly, the long term cotton experimental site described by Rochester and Bange (2016) showed that the fraction of crop N derived from the soil had not changed over a 20-year period, despite increasing annual crop N uptake and lint yields.

In addition to illustrating the importance of soil-derived N for irrigated cotton crops, our studies also showed that crop accumulation of soil N was highly efficient, with an average NU_PE_S of 74%, across all sites (Table 4). Brackin *et al.* (2019) hypothesised that the high level of soil N uptake efficiency may be related to the timing of the availability and rate of mineralisation of soil N, which better matched the physiological uptake limits of cotton while greatly reducing the potential for zones of high N concentration that increase the risk of N losses. However, it is likely that other factors will also affect crop accumulation of soil N, such as the amount of mineral N in the profile at the time of planting of the crop and the distribution of that N within the soil profile (Chen *et al.* 2008). These factors are often not considered by the industry, as 'upfront' applications are often made part-way through the winter fallow period when soils are depleted from the preceding crop, and typically dry and cool conditions ensure N mineralisation rates are low. These early upfront applications of fertiliser, although incorporated into other field preparation operations, have been shown to result in fertiliser recovery efficiencies as low as 17% (Rochester *et al.* 2001*a*).

Regional differences in AE_S were still significant, with much greater AE_S at the Qld sites the product of higher lint yield from lower crop N uptake. Given similarities in yield potential between the regions (Braunack 2013; Constable and Bange 2015), it is most likely that environmental conditions from the single Qld season enabled the retention of more harvestable bolls on the plant to contribute to higher lint yield. Lower quantities of post-season soil N at the Qld sites also suggest that those sites were better able to access the soil N possibly through greater exploration of the soil by the roots.

In-season mineralisation of N was an important contributor to soil N supply, although unlike the study of Brackin *et al.* (2019), there was no apparent correlations between soil organic carbon and the net amount of N mineralised. The highest rates of net mineralisation came from the sites that did not have cotton grown in the previous year (Table 2), while annual cotton cropping produced lower and fairly consistent mineralisation rates. While this observation is from limited data, the lower net mineralisation in continuous cotton sites is consistent with reports of immobilisation of N following incorporation of cotton residue noted by Rochester *et al.* (1992), Rochester *et al.* (1993) and Rochester *et al.* (1997) and attributed to the high C:N ratio of cotton residues.

Fertiliser response and efficiency

Background N fertility of soil is recognised as one of the key variables that determine fertiliser N responsiveness and use efficiency (Lemaire and Gastal 2019). A relationship between soil profile nitrate N content and optimum fertiliser N rate has been established for cotton production in northern NSW, with fertiliser N rate declining as soil profile nitrate content increased (Cotton Research and Development Corporation 2018). We report profile mineral N contents at our study sites (i.e. the sum of nitrate and ammonium-N), but this mineral N pool was also dominated by nitrate-N (data not shown). However, in our studies there was no relationship between fertiliser rate required to achieve Y_{95} and either soil mineral N measured at sowing (data not shown) or available soil N across the eight regional sites in this study, despite a significant positive relationship with crop N uptake. The variability of in-season N mineralisation due to rotation history (Table 2) and possible differences in timing of that mineralisation during the period of high crop N demand, when branching and fruiting structures are being established (Rochester *et al.* 2012), may contribute to this lack of correlation.

The variable lint yield response to N fertiliser application, and the differences in fertiliser N rates required to achieve Y_{95} (Fig. 3) are not unique. Indeed, research conducted by Constable and Rochester (1988), Rochester (2011) and Rochester and Bange (2016) noted similar findings and emphasised that greater understanding of the yield-limiting factors on a site-by-site basis was required. The lack of relationship between Y_{95} lint yield and fertiliser N application also highlights that the industry will not be able to simply advocate for lower fertiliser N input to improve NUE without risk of impacting on-farm productivity. We contend that site-specific factors that contribute to differences in fertiliser N requirements need to be factored into Best Management Practice programs (BMP) to improve localised applications (Johnston and Bruulsema 2014). A key factor in developing these recommendations will be understanding issues that influence the timing and intensity of crop N demand (e.g. region × sowing date interaction that determine crop growth and seasonal yield potential) and potential losses (e.g. water management, timing of N application), rather than just focussing on the pool of available N (Fig. 4).

In these studies, fertiliser N provided only marginal yield responses consistent with crops that are able to access enough N to occupy a position in the curvilinear segment of the crop N response surface (Antille and Moody 2021). Given the large contribution of soil N to seasonal crop N uptake and lint yield, it was not therefore unexpected that NU_PE of fertiliser would be lower than that of soil N. The incremental crop N uptake from fertiliser needed to achieve Y_{95} was quite modest (0–100 kg N ha^{-1}, with an average of 44 kg N ha^{-1}) with any additional fertiliser inputs providing increased crop N uptake but limited lint yield returns (Table 3). However, the fertiliser rates required to achieve these modest incremental increases in crop N uptake were in some cases quite high, and the range in NU_PE was large (0.1–0.6, with an average of 0.32; Table 4) with no difference between the two production regions. The NU_PE recorded in our studies were similar to the values of 0.46 and 0.30 reported for cotton in NSW and Qld, respectively, by Antille and Moody (2021).

Fertiliser N only provided an average of 19% of the lint yield at Y_{95} (Table 4), with the AE for fertiliser N only 35% of that derived from soil N (i.e. 4.2 kg lint kg N^{-1} compared to 11.9 for soil N; Table 4). However, while this relative inefficiency of fertiliser-derived N was evident in both regions, AE in SQld sites was 40% higher on average than that from the average of all sites in SNSW (i.e. 5.0 vs 3.6 kg lint kg N^{-1}). This comparison was distorted by the impact of the subset of lower yielding site in SNSW, with regional impact reduced if only the high *i*NUE sites in SNSW (NSW Site 1 and NSW Site 3; Fig. 5) were considered (average of 4.5 kg lint kg N^{-1}). Agronomic efficiency within the Australian cotton industry is not widely reported given the focus that has been placed on the PFP_N indicator. There have been recent reports of AE from sites in Qld and NSW by Antille and Moody (2021), of 11.0 and 17.1 kg lint kg applied N^{-1}, respectively, but these were based on seed-cotton rather than lint. Using the ratio of lint: raw cotton (turnout) from these experiments of 45% (data not shown), this would establish AE of 5.0 and 7.7 kg lint kg N applied^{-1}, which is consistent with our findings. Similar AE of fertiliser N were recorded in irrigated experiments conducted over a number of seasons in south-west USA (1.4–6.9 kg lint kg fertiliser N^{-1} (Bronson *et al.* 2017).

Despite the relatively small amounts of additional crop N uptake required to optimise lint yields, the rates of applied N fertiliser needed to achieve these yield responses can be quite large, due to fertiliser NUpE that averaged only 32% (Table 4). The cotton production system is a particularly challenging environment in which to achieve efficient recovery of fertiliser N. Fertiliser N is typically band-applied into the shallow topsoil layers, often in concentrated bands, which slow the transformations and subsequent redistribution of N within the soil profile (Janke *et al.* 2020), but the crop can have up to one-third of its roots below 60 cm soil depth during the peak period of N demand (Hulugalle *et al.* 2015). The Vertosol soils that dominate the Australian production regions (Bange *et al.* 2004) are characterised by slow internal drainage rates, especially when wet, and so leaching of nitrate N into deeper soil layers is slow. Combined with this, cotton crops require frequent irrigations, and particularly in flood irrigation systems these irrigations create conditions that promote N loss. Denitrification has been shown to be the dominant loss pathway with the magnitude of denitrification loss three and nine times the magnitude of loss that occurs in runoff and leaching, respectively (Macdonald *et al.* 2017). Denitrification can therefore result in reductions in plant N uptake (Milroy *et al.* 2009), with these effects shown to produce a reduction in dry matter, boll number and lint yield (Bange *et al.* 2004). Attempts to improve fertiliser N recovery will therefore rely on minimising the duration and intensity of soil conditions that favour denitrification loss, with irrigation system and site-specific water management likely to be important considerations.

Our studies were not able to compare the effects of differing irrigation management systems, as sites were predominantly surface irrigated (e.g. flood-furrow or bankless channel systems – Table 1). The site that employed an overhead irrigation system (Qld Site 1) did not show any real improvement in the NUE performance indicators that would suggest an advantage from use of alternative irrigation application systems (Table 4). Whilst inconclusive in itself, the apparent lack of NUE improvements in Qld Site 1 was consistent with findings of a review by Barakat *et al.* (2016) that concluded that both sprinkler and surface irrigation systems could still result in significant N loss through denitrification, particularly when compared to more controlled subsurface drip irrigation systems. More extensive investigations would be required before conclusions about the impact of irrigation application method could be made for the Australian cotton industry. In the interim, closer attention to management of surface irrigation systems may still offer opportunities to manipulate the timing and quantity of water applied during irrigation events, to lower the risk of denitrification loss. Varying irrigation practices to minimise the time when water is ponded on the surface and available to infiltrate the soil (North 2019), is one such approach. The ponding period is a key driver in determining the duration when soil Water Filled Pore Space (WFPS) is high and soil water logging and associated loss of oxygen (O_2) can occur. Such conditions promote the activity of denitrifying bacteria and fungi (Redding *et al.* 2016), and can vary between hours and/or days (R Hoogers pers. comm. 2017).

N Budget

The strong relationship between fertiliser rates needed to achieve Y_{95} and the apparent N balance achieved in that crop season (Fig. 6) indicated that rates above or below ~135 kg N ha^{-1} led to the net accumulation or depletion of soil N.

While this average seasonal N balance seems to indicate that the use of site-specific N rates will lead to marked improvements in NUE, it ignores changes in the stocks of soil N in the soil profile. Limitations in accuracy of quantification of the total mass of soil N using conventional soil test diagnostics have meant that it was impossible to quantify these small fractional changes in the large soil N pool. However, the analysis of the net changes in the soil mineral N pool that can be attributed to fertiliser N addition and/or crop N uptake suggest that there is considerable scope to improve NUE in the industry even where N supply is optimised for lint yield (Fig. 7).

Understanding the fate of available N is important given there is a misconception within the industry that large amounts of applied N (>50%) are taken up by the crop and relatively smaller amounts (<15%) are either immobilised or lost from the system (Roth Rural 2017). We were unable to account for up to 75% of the N that was available at the start of the season (i.e. available soil mineral N + applied N fertiliser) in either the soil mineral pool or the crop at the end of the season (Fig. 7*a*, *b*), although the allocation of that missing N to soil immobilisation or losses was not possible. These findings are larger than those reported in global estimates by Kant *et al.* (2011), that concluded that more than 60% of applied N can be either lost or immobilised from the system due to the volatile and mobile nature of mineral N (Crews and Peoples 2005). In a general N review, Kelley and Stevenson (1995) concluded that about one-third of fertiliser N can be immobilised in the year of application, which is consistent with more recent reports from northern NSW that suggested that 26% of the applied fertiliser N was immobilised during the growing season in NSW (Macdonald *et al.* 2017). While Australian cotton soils are often characterised by low soil organic matter, as was the case in most sites in this study (Table 2), incorporation of crop residue can significantly increase the immobilisation of NO_3^--N and limit the retention in the soil mineral N pool (Rochester and Constable 2000). If immobilisation rates consistent with published literature were applied to these studies, it suggests that 40–50% of the available N was lost in these studies, with the vast majority through denitrification (Rochester and Constable 2000; Macdonald *et al*. 2017).

Conclusions

There are clearly opportunities to rationalise the use of fertiliser N in irrigated cotton production systems, and to improve the efficiency of fertiliser N applied to increase lint production. While these opportunities are rarely explored due to the high value of the cotton crop and the (relatively) low cost of N fertiliser, our studies have illustrated that site-specific factors limiting potential yields and the propensity for inefficient conversion of accumulated crop N into lint yield will limit productivity responses to increasing N rates. Our studies have highlighted the limitations of current industry benchmarks such as PFP_N as indicators of fertiliser performance, as well as illustrated the variability that can occur in measured crop benchmarks such as *i*NUE in response to seasonal and site-specific yield constraints.

The industry needs to adopt more appropriate productivity benchmarks to assess fertiliser N recovery and use (e.g. kg additional N uptake kg fertiliser N applied^{-1}, and kg additional lint produced kg fertiliser N applied^{-1}), so that growers and advisors will be in a better position to optimise the return on fertiliser investment as well as benchmark performance of crops grown in individual fields. The inclusion of unfertilised reference strips at a scale that can allow easy yield measurement will improve understanding of the contribution of background soil N supply and allow the calculation more realistic agronomic responses to applied N. These strips, combined with approaches such as remotely sensed canopy N assessments calibrated against plant sampling to quantify crop N uptake, can allow NUE to be assessed at a scale of individual management units as well as assist in identifying where site-specific constraints may be limiting productivity.

Improving fertiliser NUE will be challenging, given the dominant role of soil N supply in meeting crop N demand in most irrigated cotton fields and the vulnerability of soil and/or fertiliser N to environmental losses. We have shown that understanding the availability of background soil N, in addition to understanding the efficiency of recovery of fertiliser N in individual fields, will be the keys to optimising the use of fertiliser N inputs.

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