Low fertiliser nitrogen use efficiency in irrigated cotton cropping systems

Clemens Scheer[1,2], David Rowlings[1], Diogenes Antille[3], Max De Antoni Migliorati[1], Kathrin Fuchs[2] and **Peter Grace**[1]

[1] Centre for Agriculture and the Bioeconomy, Queensland University of Technology, Brisbane, QLD 4000, Email: pr.grace@qut.edu.au
[2] Institute for Meteorology and Climate Research, Karlsruhe Institute of Technology, Garmisch-Partenkirchen, Germany
[3] CSIRO Agriculture and Food, Black Mountain Science and Innovation Precinct, Canberra, ACT 2601

Abstract

Irrigated cotton in Australia is mainly grown on heavy textured clay soils which are prone to waterlogging, resulting in significant losses of N via denitrification, deep drainage and surface run-off. This study investigated fertiliser nitrogen use efficiency (fNUE) over three seasons on five commercial cotton farms in sub-tropical Australia. Fertiliser NUE was consistently low (but highly variable) across all fertilised treatments, with on average 47% (25-75%) of the applied fertiliser lost over the season and only 17% of the N taken up by the crop derived from fertiliser. There was no significant effect of different N fertiliser products and rates on cotton lint yield. Using the nitrification inhibitor DMPP showed potential to reduce N fertiliser losses. The results demonstrate that under current on-farm management strategies, fNUE is low on irrigated cotton farms in Australia and highlight the need to account for soil N stocks and mineralisation rates when optimising N fertiliser rates.

Keywords

Cotton, nitrogen, ^{15}N, nitrogen use efficiency

Introduction

In Australia, cotton is mainly grown using gravity surface (furrow) irrigation systems on heavy textured clay soils, which are prone to waterlogging, resulting in significant losses of N via denitrification, deep drainage and surface run-off (Macdonald et al., 2017). The average N application rate in Australia is 285 kg N ha^{-1} with poor fNUE with only 17-50% of the applied fertiliser N taken up by the crop, and up to 70% completely lost over the season (Freney et al., 1993; Macdonald et al., 2017; Rochester et al., 1996). Only a few studies have reported fNUE in Australian cotton systems based on ^{15}N fertiliser experiments and these have mainly involved experimental research stations, however it is critical to have more realistic data from on-farm production.

The use of nitrification inhibitors (NI) has been proposed as a strategy to increase NUE and reduce environmental losses of reactive N (N_r) in cropping systems (Abalos et al., 2014). The agronomic efficacy of the NIs needs to be interpreted with caution, since most studies have only used one N rate while the potential benefits of NIs might be best achieved by reducing N application from the conventional rate (Rose et al., 2018). Moreover, current research on NIs has focused on cereal systems with only a limited number of recent studies conducted in cotton (Bronson et al. 2017; Schwenke and McPherson, 2018). Early research on NIs in cotton (Freney et al. 1993; Rochester et al. 1996) suggested that fNUE could be markedly improved by the use of NIs, but latest studies using novel NI formulations fail to show a significant effect on cotton yield, quality or fNUE (Li et al. 2020). This could be due to the higher rates of N now being applied in the cotton industry which potentially mask the impact of NIs.

Mode of irrigation is also a potential contributing factor to fNUE. There is increasing use of centre-pivot and lateral-move, up from 10% in 2008 to ~25% in 2019, to improve water use efficiency and give growers more flexibility over where and how to use their water allocations. However, little research has been conducted on the impact of different irrigation systems on fNUE in cotton production. In Australia, Antille (2018) found significantly higher N_2O emissions, and, in the USA, Bronson et al. (2017) increased recovery of N fertiliser in overhead irrigated systems compared to surface irrigation, however studies on the effect of irrigation system on fNUE based on ^{15}N fertiliser experiments are still lacking for irrigated cotton.

The goal of this study was to (i) develop N budgets and assess fNUE on commercial cotton farms in Australia and (ii) investigate if fNUE can be improved by fertiliser management.

Methods

Study area

Over three years (2015-2018) field trials were undertaken at five different commercial farms located in the eastern Darling Downs region about 150 km west of Brisbane, Australia (27.53° S, 150.58° E). The region is noted for its deep fertile clay soils, making it one of the most productive in Australia for grain and cotton production. The soils at the different experimental sites are classified as Black Vertosols (Isbell, 2002) and have clay contents between 45% and 72% in the top 1 m of the profile.

Experimental design

Field trials at all sites used a randomized complete block design with four replicates. The main treatment plots (macro-plots) measured 3 m (width) × 6 m (length) and to avoid edge effects each macro-plot was separated by a buffer of 1 m along the width and length. All sites were irrigated for each of the three cropping seasons. Each year, the trials were conducted on at least two furrow-irrigated, and two overhead-irrigated fields. The plant inter-row space was either 1 m or 1.5m depending on the site with a plant density of typically 10-12 plants m^{-1}. Fertiliser rates and application timings were guided by the local "farmer practice" rate and the experience of local agronomists for each farm. At the five commercial farms the farmer N practice was compared with up to two potential N best management practices (reduced N fertiliser rate, nitrification inhibitor).

The fertiliser treatments were: ZERO N: no added N fertiliser; UREA-FP (average 162 kg N ha^{-1}): urea fertiliser application following the standard farmer practice at each farm; UREA-RED (average 115 kg N ha^{-1}): urea fertiliser application following the standard farmer practice at a 30% reduced N rate. DMPP-RED: urea fertiliser coated with the NI 3,4-dimethyl-pyrazole phosphate (DMPP) (average 115 kg N ha^{-1}), following the standard farmer practice at a 30% reduced N rate.

15 N recovery plots

The recovery of N fertiliser in the soil and plant was assessed by applying ^{15}N-labelled fertiliser in 1 m (width) × 2 m (length) subplots (or micro-plots) located within the unfertilised macro-plots. At all sites, ^{15}N-labelled fertiliser was applied at planting by distributing 10% atom excess ^{15}N enriched urea dissolved in 1 L of deionised water either over the entire microplot (to mimic broadcasting) or 100 mm on either side of the crop row (to mimic banding). In the DMPP-RED treatments, the solution containing ^{15}N-enriched urea included DMPP at a ratio of 6 g DMPP kg^{-1} urea to replicate the same ratio of commercial DMPP urea (Incitec Pivot Fertilisers, personal communication).

15 N soil and plant sampling and analysis

Soil samples were collected at planting and harvest in all micro-plots. Soil sampling was conducted with a hydraulic core sampler (50 mm diameter) across a four core transect. The transect was perpendicular to the plant row and extended 50 cm on each side of the crop row. Soil samples were collected at three depth intervals (0-30, 30-60, 60-100 cm). For each plot, the soil samples belonging to the same depth and section of the transect (bed, furrow, fertiliser band and inter-row) were mixed together before being subsampled. Roots were removed from the soil prior to oven-drying a soil sub-sample at 60°C which was then finely ground. ^{15}N enrichment was determined using a 20-22 Isotope Ratio Mass Spectrometer (IRMS) (Sercon Limited).

Aboveground biomass and total N uptake were determined at harvest from representative samples collected in all macro-plots by cutting 1 m of crop row (eight plants) near the soil surface using hand clippers. Aboveground and belowground material including senesced leaves was collected in the ^{15}N micro-plots. Plant samples were oven-dried for 24 hours at 60°C after separating the lint and seed. The different components of plant biomass (lint, seeds, stems + leaves + pods, roots) were then weighed, finely ground and analysed separately. Plant samples were analysed for ^{15}N enrichment using an isotope ratio mass spectrometer (20-22 IRMS, Sercon Limited).

All ^{15}N fertiliser recovery calculations were conducted on an oven-dried basis. Total recovery of applied ^{15}N-labelled fertiliser was determined by mass balance. The percentage of N derived from the labelled fertiliser (Ndff) in each plant and soil pool was determined using equations outlined in IAEA (2001). Statistical analysis was performed with the R software (version 3.5.3) (R Core Team, 2019).

Results and discussion

Lint yield, total biomass and N crop uptake

Lint yields in the fertilised treatments varied significantly between the different seasons and were highest (2.7 ± 0.1 Mg ha^{-1}) in the 2015/2016 season and lowest (1.9 ± 0.2 Mg ha^{-1}) in the 2017/2018 season. The average cotton lint yield across UREA-FP treatments was 2.4 ± 0.2 Mg ha^{-1}. The reduced N fertiliser treatments (UREA-RED) were not significantly different in lint yields compared to UREA-FP, but there was a positive response in yield to N fertiliser ($p < 0.05$). Application of N fertiliser increased cotton yields by 20% compared to the ZERO N.

Total aboveground biomass ranged from 9.6 to 19.6 (average 13.1 Mg ha^{-1}) across the different sites and years. On average, the total aboveground biomass contained 60% leaves and stem material, 20% seed and 20% lint. Total crop N uptake ranged from 159 to 402 kg N ha^{-1} in the N fertilised treatments and increased significantly with increasing lint yield. The average N uptake in the UREA-FP treatment was 225 (±20) kg N ha^{-1}.

Reducing the N fertiliser application rate and the use of the NI had no effect on total N uptake in comparison to UREA-FP, but N uptake was significantly lower (average of 194 kg N ha^{-1}) in the ZERO N plots. Application of N fertiliser increased N uptake compared to the ZERO N treatment by 36 kg N ha^{-1}, 31 kg N ha^{-1}, and 33 kg N ha^{-1} in the DMPP-RED, UREA-RED, and UREA-FP treatments, respectively.

15 N fertiliser recovery and losses

On average, only 25% (11 - 53%) of the applied ^{15}N fertiliser was taken up by the crop across all fertilised treatments (Figure 1). The use of DMPP significantly increased fertiliser N recovery in the plant (32 ± 4 % of the applied N fertiliser), compared to the FP (25 ± 3%) and UREA-RED treatment (26 ± 3%). These relative recovery rates translate to an absolute amount of fertiliser taken up by the plant of 39.0 (±3.7) kg N ha^{-1} in the FP treatment, with similar uptake in the DMPP-RED treatment, and a significantly reduced uptake in the UREA-RED treatment. An average 28 ± 4% of the N fertiliser remained in the soil profile at harvest (ranging from 12 - 57%) with no significant effect of N management. Absolute amounts of fertiliser N found in the soil at harvest amounted to 42.5 (±4.0) kg N ha^{-1} in the UREA-FP and significantly lower in the DMPP-RED (by 9.3 ±4.1 kg N ha^{-1}) and UREA-RED (by 14.5 ±4.0 kg N ha^{-1}) treatments, respectively.

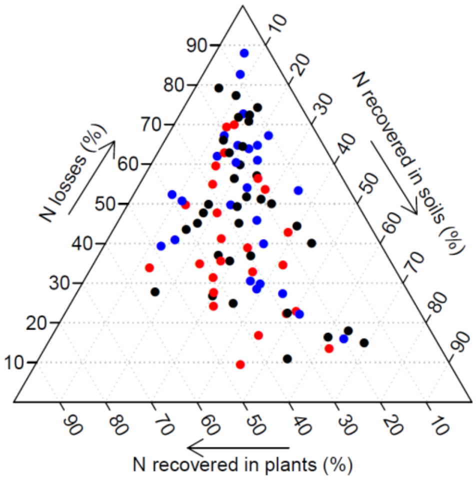

Figure 1: Fate of ^{15}N fertiliser applied as urea to 24 cotton production system treatments. Average recoveries of 28% and 25% in soil and plant respectively and 47% lost completely (black symbols: UREA-FP, blue symbols: UREA-RED, red symbols: DMPP-RED).

Across all trials, on average 47% (25 - 75%) of the applied N fertiliser was completely lost from the soil-plant system during the season (Figure 1). Nitrogen losses were significantly lower (38%) in the DMPP treatment. Overall N fertiliser losses were lower in the overhead-irrigated sites (35%) compared to the furrow-irrigated sites (51%), but this effect was not statistically significant due to the higher N rates used in the furrow irrigated systems.

Only 17% (35 kg N ha^{-1}) of the N taken up by the crop was derived from fertiliser (Ndff), i.e. 83% (182 kg N ha^{-1}) was soil derived N. The UREA-RED Ndff was 28% lower compared to UREA-FP, but Ndff was not significantly different in DMPP-RED. The use of the DMPP confirmed its potential to increase fNUE in irrigated cotton systems, in particular in combination with reduced N rates.

Conclusion

Fertiliser NUE in irrigated cotton production on heavy textured clay soils in Australia is low under current on-farm management strategies, with almost half of the applied fertiliser lost over the season and only 17% of the N taken up by the crop derived from fertiliser. High yields could be achieved even without the application of N fertiliser. This indicates that commercial cotton farms have highly elevated levels of available N in the soil at sowing, most likely due to excessive N fertiliser applications in previous years and rely on mineralisation of soil organic N and residual fertiliser as the primary N source. It is noteworthy that the average N application rate in our study (137 kg N ha^{-1}) was less than half the average application rate of 285 kg N ha^{-1} for irrigated cotton in Australia, indicating that average N losses across the industry might be significantly higher than reported in this study.

We conclude that there is substantial scope to reduce N fertiliser rates in irrigated cotton production systems on commercial holdings in Australia. The residual effect of N fertiliser applied in previous years needs to be considered when optimising N fertiliser rates. Despite the high N inputs at the commercial farms, more native soil N was removed with the harvest than fertiliser N was recovered in the soil, indicating an overall N budget deficit that could lead to long term, unsustainable declines of soil organic matter on the farms.

References

Freney JR, et al, (1993). Use of nitrification inhibitors to increase fertilizer nitrogen recovery and lint yield in irrigated cotton. Fertiliser Research, 34 37-44.

Abalos D, et al, (2014). Meta-analysis of the effect of urease and nitrification inhibitors on crop productivity and nitrogen use efficiency. Agriculture Ecosystems and Environment 189, 136-144.

Antille D (2018). Evaluation of fertigation applied to furrow and overhead irrigated cotton grown in a Black Vertosol in Southern Queensland, Australia. Applied Engineering in Agriculture 34, 197-211.

Bronson K, et al, (2017). Improving nitrogen fertilizer use efficiency in surface- and overhead sprinkler-irrigated cotton in the desert southwest Soil Science Society of America Journal 81, 1401-1412.

IAEA, (2001). Use of isotope and radiation methods in soil and water management and crop nutrition. Manual (No. IAEA-TCS-14). Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture.

Li Y, et al, (2020). Agronomic evaluation of polymer-coated urea and urease and nitrification inhibitors for cotton production under drip-fertigation in a dry climate. Scientific Reports 10, 1-8.

Macdonald B, et al, (2017). Tracking fertiliser and soil nitrogen in irrigated cotton: uptake, losses and the soil N stock. Soil Research 55, 264-272.

R Core Team (2019). A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing.

Rochester I, Constable G and Saffigna P (1996). Effective nitrification inhibitors may improve fertilizer recovery in irrigated cotton. Biology and Fertility of Soils 23, 1-6.

Rose TJ, et al, (2018). A re-evaluation of the agronomic effectiveness of the nitrification inhibitors DCD and DMPP and the urease inhibitor NBPT. Agriculture Ecosystems and Environment 252, 69-73.

Schwenke G and McPherson A (2018). Mitigation of nitrous oxide emissions from furrow-irrigated Vertosols by 3, 4-dimethyl pyrazole tetra-methylene sulfone, an alternative nitrification inhibitor to nitrapyrin for direct injection with anhydrous ammonia. Soil Research 56, 752-63.