EVALUATION OF FERTIGATION APPLIED TO FURROW AND OVERHEAD IRRIGATED COTTON GROWN IN A BLACK VERTOSOL IN SOUTHERN QUEENSLAND, AUSTRALIA

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ABSTRACT. *Field trials were conducted at gated pipe surface and overhead irrigation sites established to cotton (*Gossypium hirsutum *L.) to evaluate irrigation and fertigation management using a model-based control system. The control strategies determined the timing and volume of irrigation, and the rate of fertilizer-N to apply through fertigation. For this, nitrogen (N) was applied in-crop season using urea ammonium nitrate (UAN, 30% N solution) at a rate of 40 kg ha*$^{-1}$ *N. At the furrows site, the uniformity of distribution of fertilizer-N applied through fertigation was satisfactory, which was achieved both at distance (600 m) and depth (0-600 mm). Applying fertilizer-N through fertigation, at the rate used in this study, showed relatively small (≤8%) improvements in cotton yield, which was explained by relatively high N rates (180 kg ha*$^{-1}$ *N) applied before planting. Given current price ratios (fertilizer-to-cotton), application of N through fertigation appears to be economical in both systems, but relative agronomic efficiencies and economic return from the fertilizer applied were lower in furrow compared with overhead (*$P<0.05$*). Fertigation may be recommended when pre-season N application rates are low (e.g., <100 kg ha*$^{-1}$ *N), particularly in overhead irrigation as significantly higher efficiencies both in terms of water and N use can be achieved with this system. This would enable some of the operational constraints associated with application of N in-crop season to be overcome; thereby, reducing the need for high rates of N applied up-front. For the overhead system, there were also advantages compared with the furrow system in terms of reduced potential for* N_2O *emissions after irrigation or fertigation. Overall, short-term (30-day period) soil emissions of* N_2O *were approximately eight times higher in furrow compared with overhead. Emissions from non-fertigated crops were approximately two times higher in furrow compared with overhead. Emissions from the fertigated crop under the overhead system were comparable to the non-fertigated crop of the furrow system (*$P>0.05$*). In both systems, fluxes were highest within five days of irrigation or fertigation, but they decreased significantly after that time as soil moisture content (water-filled pore space) and soil nitrate levels decreased due to crop uptake. Nitrous oxide fluxes were similar in furrow and overhead 15 days after the irrigation or fertigation event. Areas that warrant further investigation are presented and discussed, including the need for improved timing of fertilizer delivery during the irrigation cycle to ensure that N losses through leaching or gaseous evolution (e.g.,* N_2O*,* N_2*) are not economically or environmentally significant.*

Keywords. *Greenhouse gas emissions, Irrigated cotton, Nitrogen use efficiency, Urea ammonium nitrate, Water-run urea.*

The majority (≈80%) of cotton (*Gossypium hirsutum* L.) grown in Australia is irrigated using furrow and overhead irrigation systems in approximately 90% and 10% of the area, respectively (Roth et al., 2013). The dominant soil types in the main cotton-producing region are Vertosols (Vertisol in the USDA Soil Taxonomy), which are characterized by their swelling and shrinking properties (Yule and Ritchie, 1980; Isbell, 2002). Between half and two-thirds of the nitrogen (N) fertilizer is applied to the crop before planting, typically between May and October (CRDC, 2016). Fertilizer may be injected as anhydrous ammonia (82% N) or incorporated into the soil as straight N in granular formulations (e.g., urea, 46% N) or NPK blends. The balance of N-fertilizer may be side-dressed or applied through fertigation in-crop season. In surface irrigation systems, fertigation is applied as 'water-run urea' by dissolving the fertilizer in the irrigation distribution channels or by injecting a N solution into a gated pipe. In overhead irrigation, the N solution is injected into the pressurized system. The fertilizer solution is subsequently delivered to the crop with the irrigation water (Wallace and Rochester, 2013). The irrigation performance influences the efficiency of fertigation by affecting the uniformity of distribution of water both spatially and at depth, and consequently the rate of fertilizer applied to the crop (Bar-Yosef, 1999). Recent research (e.g., Scheer et al., 2013; Macdonald et al., 2015, 2017) has shown that losses of N (leaching, runoff, and gaseous emissions) from intensively-managed irrigated cotton systems are significant, both from the environmental and economic perspectives, which cost the Australian cotton industry more than AUD30 M each

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year (AUD 1 ≈ USD 0.75). Nitrous oxide (N_2O) is largely produced under conditions of high (>60-80%) water-filled porosity (Li et al., 2005) when nitrate (mainly from fertilizer-N) and soil organic carbon (mainly from crop residues) are available (Antille et al., 2015; Dang et al., 2017). Hence, N_2O emissions can be exacerbated by addition of synthetic N fertilizers via fertigation. Other research (e.g., Chantigny, 2003) has also shown that application of urea-based fertilizers can stimulate desorption of soil organic carbon (SOC). Such mechanism may increase the amount of dissolved organic C (DOC) in the irrigation water, which therefore provides a readily available source of C used for microbial denitrification (Weier et al., 1993; Pittaway et al., 2017). This process, coupled with dissolved (inorganic) N from applied fertilizer, sets the conditions for increased N_2O and N_2 emissions thereby affecting the overall efficiency of N applied via fertigation. These considerations are of importance in practice because the heavy-textured soils in which cotton is grown are prone to sustained waterlogged or near-saturated conditions after irrigation is applied, particularly, in surface irrigation systems (Rochester and Constable, 2000; Bange et al., 2004). Despite this, fertigation offers cost advantages compared with other methods of fertilizer application (e.g., side-dressing), and it also allows the timing of application to be better synchronized with crop demand for water. This, in turn, can lead to increased fertilizer-use efficiency because of the positive nitrogen × soil water effect on crop uptake, once field capacity is restored (Scarsbrook et al., 1959; Wang et al., 2017). Soil incorporation of granular fertilizers can also cause mechanical damage (root pruning) to established crops, which is avoided with the use of fertigation (Ennis, 1955; Snipes and Mueller, 1992). Whilst fertigation provides flexibility to manage nutrients, efficient irrigation management is also required to ensure that the duration of waterlogged conditions post-irrigation is minimized, and that fertilizer-N recovery and crop yield are not compromised (Hodgson and MacLeod, 1988; Hou et al., 2007; Wei et al., 2012).

The considerations for N management addressed in this work are relevant in the current scenario (e.g., Angus and Grace, 2017) because the Australian cotton industry is committed to a 20% reduction in greenhouse gas emissions from (direct) energy use on-farm and applied N fertilizers by 2019. Such emission reduction target is relative to the 2014's on-farm carbon footprint levels associated with cotton production, which were estimated at ≈400 kg CO_2 per (metric) ton of lint (Hedayati et al., 2015). At present, there is little information available for the Australian cotton industry discussing the overall efficiency of N applied via fertigation, despite that this practice is widely used and that it is recommended under current cotton nutrition guidelines (e.g., NUTRIpak, Australian Cotton CRC, 2001). Therefore, field-scale experimental work was undertaken to acquire background dataset to quantify the agronomic efficiency of fertilizer-N applied via fertigation, including quantification of short-term soil emissions of N_2O following irrigation. This dataset may be used to inform fertilizer management guidelines for in-crop season application of N through fertigation, which may enable future experimental and modeling work to be undertaken.

OBJECTIVES AND SCOPE

The objectives of this study were to: (1) investigate the uniformity of distribution of fertilizer-N applied through fertigation both in the soil profile and along the furrows, (2) estimate use efficiency of fertilizer-N applied through fertigation to overhead- and furrow-irrigated cotton crops, (3) measure short-term nitrous oxide (N_2O) emissions after fertigation of furrow- and overhead-irrigated cotton crops, and (4) provide recommendations for improved N management in fertigated cotton, and highlight areas that require further research.

Whilst acknowledging the need to conduct longer-term field experimentation and with high frequency sampling that accounts for seasonal and inter-annual effects on N_2O emissions and soil N dynamics, this work informs about the likely use-efficiency of N fertilizer applied through fertigation. The dataset reported here is also relevant to alternative fertigation methods such as 'water-run urea', which are widely employed within the Australian cotton industry and overall whose efficiency is not well documented. As such, this work is central to a broader scope of research funded by the Australian Government under the 'More Profit from Nitrogen Program' (http://www.crdc.com.au/more-profit-nitrogen). This program aims to achieve increased farm profitability and reduced environmental impact by increasing N use efficiency of intensive cropping and pasture systems, including cotton, dairy, sugar and horticulture.

MATERIALS AND METHODS

EXPERIMENTAL SITES

The study was conducted in a commercial cotton farm (27°28'07.48" S, 151°34'43.74" E, elevation: 388-m above-sea-level) located in Yargullen (SE Queensland, Australia) at two adjacent experimental sites referred to as furrow and overhead irrigated fields, respectively. Long-term and seasonal (farm) rainfall and temperature records for Yargullen are shown in figure 1. The soil at the sites is described in Isbell (2002) as a Black Vertosol, which has shrinking-swelling behavior and is representative of the soils that occur within the main cotton-producing region in Australia. The overhead site is relatively flat (slope <0.10%) while the furrows site had been graded to a uniform slope of 0.20%. A general characterization of the soils at both sites was conducted prior to the experiments as shown in table 1. Surface water infiltration was measured using the double-ring infiltrometer method (Parr and Bertrand, 1960). Infiltration rates were subsequently obtained by differentiating Kostiakov's equation ($F_t = a \times t^n$) with respect to time to describe the relationship between the rate of infiltration and time ($I_t = a \times n \times t^{n-1}$). Infiltration measurements were replicated three times (n=3).

Experiments were conducted over three cotton growing seasons (2013/2014, 2014/2015, and 2015/2016) at the

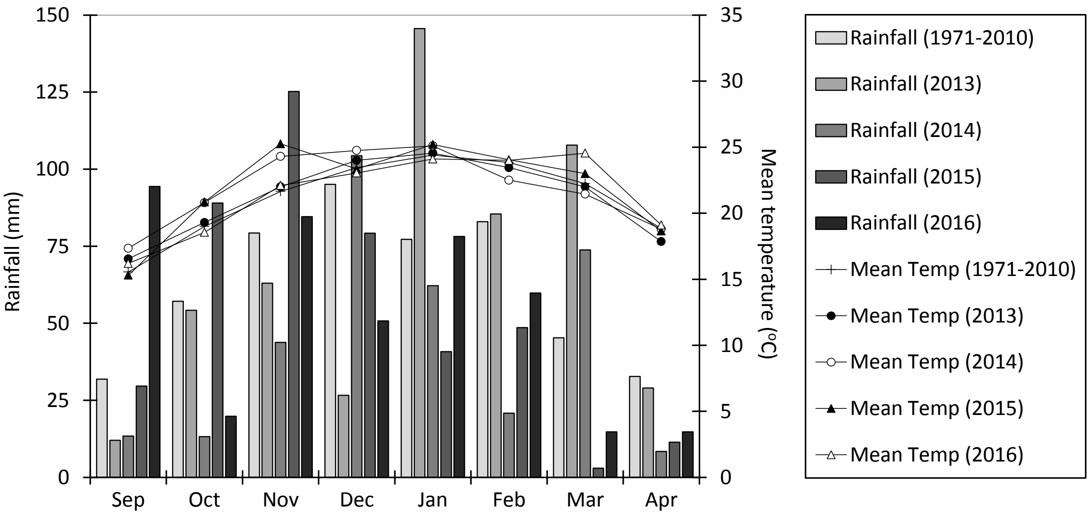

Figure 1. Long-term (1971-2010) and in-crop season (2013-2016) rainfall and temperature records. Historical data for Yargullen (QLD, Australia, 27°43' S, 151°72' E, elevation: 406-m above-sea-level, BOM Station No.: 041359) (after BOM, 2016). In-crop season data was recorded on-site (27°28'07.48" S, 151°34'43.74" E, elevation: 388-m above-sea-level).

furrows site and over one season (2014/2015) at the overhead site, respectively. Both sites had similar cropping sequences [e.g., corn (irrigated)-winter cereal (non-irrigated)-long fallow-first cotton-winter fallow-second cotton], which are common across the Australian cotton regions (e.g., Hulugalle et al., 2016). In Australia, cotton is grown between September and April, but optimum timing of planting and harvest vary depending upon the growing region, the year-specific climatic conditions, and irrigation water availability (Bange and Long, 2011; Braunack et al., 2012). Cotton was planted each year between the 20 and 30 October at 40-in. (≈1-m) row-spacing at a density of 14 plants per m, which given the configuration of this system equates to 14 plants per m^2. The cotton varieties grown at the sites were Sicot 74BRF (furrow) and 75RRF (overhead), which are indeterminate and commonly used in irrigated systems in southern Queensland (Bange et al., 2008). Seedbed preparation involved non-inversion shallow tillage (≈150 mm) at both sites; except for forming the furrows at this site prior to establishment of the first cotton crop.

At the furrows site, measurements were conducted from two field strips (width: 54-m, furrow length: 600-m), which were established to compare fertigated and non-fertigated crops, respectively. These strips were separated by a buffer strip of equal dimensions that prevented cross-contamination of the non-fertigated crop used as a control. The buffer strip was also established to cotton and managed as per standard farm practice, but had no N applied in-crop season. The width of the strips was chosen to match that of the irrigation shift of a 6-inch diameter gated pipe used in the furrow irrigation system, and water delivered from outlets placed at every other furrow using a skip row strategy (Subramani and Martin, 2012). At the overhead site, fertigation was applied to one-fifth (≈10 ha) of the total irrigated area (52 ha) and measurements conducted on a 9-m wide strip under the fifth span of a 7-span center pivot equipment. The width of this strip was chosen to match that of a 9-row cotton planter and compatible with an 18-m boom sprayer, both available at the farm. Blanket fertilizer applications were performed each year prior to planting (early to middle of September) based on standard agronomic practice (Rochester and Bange, 2016) at a rate of 180 kg ha^{-1} N (≈390 kg ha^{-1} urea) in a granular blend containing 45 kg ha^{-1} P_2O_5, 20 kg ha^{-1} K_2O, 60 kg ha^{-1} SO_3, and 1.85 kg ha^{-1} ZnO, and incorporated to a depth of 150 mm. The fertilizer used for fertigation was urea ammonium nitrate

Table 1. Characterization of the Black Vertosols at the furrow and overhead sites located in Yargullen (QLD, Australia) as recorded prior to the experiment (baseline levels).[a]

Determination, Unit	Furrow Site	Overhead Site	Method
Sand (>20 μm), % (w/w)	9.6 ± 0.58	11 ± 0.70	Bouyoucos (1962)
Silt (2-20 μm), % (w/w)	18.7 ± 1.15	22 ± 2.00	
Clay (<2 μm), % (w/w)	71.7 ± 1.53	67 ± 2.08	
Field capacity,% (w/w) at ⅓ bar	40.4 ± 3.11	38.7 ± 1.53	Cassel and Nielsen (1986)
Soil bulk density, kg m^{-3}	1040 ± 85	1020 ± 8.0	Blake and Hartge (1986)
Total porosity of soil, %	60.8 ± 4.96	61.5 ± 0.48	From density properties (ρ_p =2650 kg m^{-3})
Soil $pH_{1:5}$ (soil/water suspension)	8.4 ± 0.01	8.2 ± 0.07	Rayment and Lyons (2011)
$EC_{1:5}$ (soil/water extract), dS m^{-1}	0.22 ± 0.001	0.34 ± 0.008	Rayment and Lyons (2011)
Soil organic C, % (w/w)	1.57 ± 0.020	2.07 ± 0.08	Walkley and Black (1934)
Total N in soil, % (w/w)	0.11 ± 0.040	0.18 ± 0.010	Bremner (1960); MAFF (1986, Method 49)
Soil mineral N, mg kg^{-1}	18.2 ± 4.57	15.5 ± 5.01	MAFF (1986, Method 53)
Soil extractable P, mg kg^{-1}	61.5 ± 19.09	21 ± 8.79	Colwell (1963)
Infiltration rate, mm h^{-1}	$I_t = 30.45t^{-0.67}$, R^2=0.75	$I_t = 37.94t^{-0.74}$, R^2=0.96	Parr and Bertrand (1960)

[a] Mean values (n=3) ± standard deviation (SD). Depth range: 0-200 mm, except for soil mineral nitrogen (N): 0-600 mm.

(UAN, 30% N, solution) applied in-crop season at a standard farm rate of 135 L ha^{-1} (≈40 kg ha^{-1} N) with a Venturi injector (orifice's *d* =0.5 mm). Liquid fertilizer was injected at an average (±SD) rate of 0.05 ± 0.02 L s^{-1} for an average (±SD) irrigation water flow of 2 ± 0.28 L s^{-1}. The application of fertilizer was conducted during the first-third to first-half of the irrigation event. The reader is referred to McCarthy et al. (2016) where full specifications and graphical information about the solar-powered fertilizer injection system, and hydraulic characteristics of the irrigation systems are provided. Fertigation was applied on 6 February 2014 (first season), 25 January (second season), and 18 February (third season), respectively, based on external agronomic advice given to the grower. Supplementary irrigation was applied to the crop with underground water (pH =8.3, EC =1.62 dS m^{-1}) using the VARIwise model-based control system (McCarthy et al., 2010). The control strategies specified within VARIwise determined the day to irrigate and volume of irrigation, and the application of this model to the work reported here is discussed in McCarthy et al. (2016). The rate of irrigation typically varied between 80-100 mm (or 0.8-1.0 ML ha^{-1}) and between 25-35 mm per irrigation event at the furrows and overhead sites, respectively. These rates were consistent with irrigation practices reported for the Australian cotton region (e.g., Tennakoon and Milroy, 2003) although McCarthy et al. (2016) have reported improved timing of irrigation using the VARIwise model-based adaptive control strategy.

MEASUREMENTS AND ANALYSES

Cotton yield (lint + seed) was measured in all three cropping seasons (2013/2014-2015/2016) to determine the effect of fertilizer-N applied via fertigation. Lint and seed yield was determined within a week before defoliation by collecting three 1-m whole-plant samples from the fertigated and non-fertigated crops from each of the sampling points located at 150, 300, and 450 m along the furrows, respectively (n=18). Cotton balls were oven-dried at 40°C for 48 h to achieve uniform moisture content in all samples. The lint and seed were manually separated from carpels, weighted, converted to kg per ha equivalent, and reported. Yield is also reported as bales per ha, which is the standard unit used in Australia (1 bale = 227 kg of lint). The agronomic efficiency was derived by dividing cotton yield by the rate of N applied as fertilizer. In the second crop season, additional measurements were conducted to quantify fertilizer-N recovery in cottonseeds at harvest. Total seed-N for both fertigated and non-fertigated crop was conducted based on MAFF (1986, Method No.: 48), which involves conversion of N in the sample to ammonium-N (NH_4^+-N) by Kjeldahl digestion with sulfuric acid (H_2SO_4) and sodium sulfate (Na_2SO_4) with a copper-selenium catalyst. The ammonia released with sodium hydroxide (NaOH) is removed by steam distillation and determined titrimetrically. Conditioning of samples for total seed-N analyses was based on the technique used by Rochester (2012). Total seed-N data for true controls (zero-N) was obtained from Antille (2017), which enabled apparent N use efficiency (NUE) to be estimated for the 2014/2015 season. These relationships are shown in equations 1 and 2, respectively (Baligar et al., 2001).

$$AE = \frac{Y_F}{N_{RATE}} \tag{1}$$

$$NUE = \frac{U_F - U_{F=0}}{N_{RATE}} \times 100 \tag{2}$$

where AE is agronomic efficiency (kg kg^{-1}), and Y_F is cotton yield (lint + seed, kg ha^{-1}) corresponding to fertilized crops. NUE is N use efficiency (%) based on apparent N recovery in cottonseed, U_F and $U_{F=0}$ are N recoveries in cottonseed (kg ha^{-1} N) from fertilized- and non-fertilized (zero-N) crops, respectively, and N_{RATE} is total N rate applied as fertilizer (kg ha^{-1}).

Uniformity of distribution of fertilizer-N applied through fertigation (furrows site) was determined in water running on furrows during the fertigation event and compared with water samples taken from non-fertigated furrows where only irrigation had been applied. At the furrows site, soil samples were also collected from the corresponding strip before and after application of irrigation or fertigation. For both soil and running water, sampling was conducted at the three locations down-furrow (150, 300, and 450-m, respectively) where yield measurements were performed, and samples subject to determination of mineral N (MAFF, 1986, Method No.: 53). Additional water samples were collected directly from the irrigation systems to determine background mineral N levels in irrigation water. Soil mineral N (SMN) was extracted with a 2 mol L^{-1} solution of potassium chloride (KCl), and reported as the sum of nitrate-N (NO_3^--N) and ammonium-N (NH_4^+-N). Measurements of SMN were conducted between 48 and 72 h after the irrigation or fertigation event to a depth of 600 mm at regular increments of 200 mm in the furrow system and from the top 200 mm in the overhead system. Differences in the sampling depths selected for the furrow and overhead sites were consistent with the amount of water applied through irrigation. Soil samples were collected from the centerline of the interrow in both irrigation systems.

NITROUS OXIDE EMISSIONS

Short-term soil emissions of nitrous oxide (N_2O) from fertigated and non-fertigated crops were measured and compared for both irrigation systems (season: 2014/2015) using the static chamber technique (Chadwick et al., 2014) and quality criteria as outlined by De Klein and Harvey (2015). Four cylindrical chambers (dimensions: 250 mm diameter, 0.01 m^3 headspace volume) were inserted into the soil surface to a depth of 100 mm, and placed at the centerline of the interrow (fig. 2). At the furrows site, chambers were placed on irrigated furrows (every other furrow) whereas at the overhead site, chambers were placed on adjacent interrows, and wheel lanes were avoided (Tullberg et al., 2018). Gas samples were taken the day before (day -1), the day of irrigation or fertigation (day 0),

Figure 2. Overview of fertigated cotton crops at the experimental sites in Yargullen (QLD, Australia). Top left: overhead irrigation system; top right: furrow irrigation system; and bottom center: close-up of a cylindrical gas chamber placed in the crop interrow.

at days 1 through to 5, and subsequently at 7, 10, 15, 20, 25, and 30 days after the treatments were applied. This enabled fluxes to be measured over a wetting and drying phase, respectively. Gas samples were extracted with a 25-mL syringe from the headspace into pre-evacuated 12-mL glass vials at 0, 20, 40 and 60 minutes after enclosure, respectively (Melland et al., 2017). Sampling was conducted between 9 A.M. and 12 P.M. to reduce the expected variability in experimental observations caused by diurnal patterns of soil emissions (Christensen, 1983); except at day 0 at which samples were taken in early afternoon because of the timing of irrigation. Nitrous oxide concentrations were measured using gas chromatography (Shimadzu GC-2014, Kyoto, Japan). Flux rate calculations were estimated from the slope of the linear increase in N_2O concentration within the closed chambers over the 60-min closure time (van der Weerden et al., 2012). Flux rates estimates were discarded when R^2 was <0.75. The flux rate was then calculated with equation 3. All flux rate estimates were corrected for air temperature during measurements and site pressure (eq. 4), expressed on an elemental weight basis (µg N_2O-N m^{-2} h^{-1}), converted to g N_2O-N ha^{-1} day^{-1}, and reported.

$$F = \frac{\beta \times V_{CH} \times MW \times 60 \times 10^{-6}}{A_{CH} \times MV_c \times 10^{-9}} \tag{3}$$

where F is flux rate, β is increase in headspace concentration (ppb min^{-1}), V_{CH} is chamber volume (m^3), MW is molecular weight of the gas (28 g mol^{-1} N-N_2O), A_{CH} is chamber area (m^2), and MV_c is temperature-corrected molecular volume (m^3 mol^{-1}). Factors 60, 10^{-6} and 10^{-9} convert from min to h, g to µg, and ppb to µL m^{-3}, respectively. And,

$$MV_c = 0.02241 \times \left(\frac{273.15 + T}{273.15} \times \frac{P_0}{P_1} \right) \tag{4}$$

where MV_c is temperature-corrected molecular volume (m^3 mol^{-1}), 0.02241 mol L^{-1} equates to 22.41 mol m^{-3} volume, 273.15 converts Kelvin to Celsius, T is air temperature during the measurements (°C), and P_0 and P_1 are the air pressure at sea level and at the experimental site, respectively. Emissions are reported as daily and cumulative N_2O fluxes over the 30-day period.

Volumetric soil moisture content was measured at each sampling event (depth range: 0-100 mm) using a capacitance probe, previously calibrated for the same soil type (Antille, 2017), and used to estimate the water-filled pore space (eq. 5). All measurements from fertigated and non-fertigated soils were setup in triplicate (n=3) under both irrigation systems.

$$WFPS = \frac{\left(\theta_g \times \rho_b \right)}{\eta} \tag{5}$$

where WFPS is water-filled pore space (%), θ_g is gravimetric water content (g g^{-1}), ρ_b is soil bulk density (g cm^{-3}), and η is total porosity (cm^3 cm^{-3}) (Linn and Doran, 1984).

STATISTICAL ANALYSES

Statistical analyses used GenStat Release 16th Edition (VSN International Ltd., 2013), and involved ANOVA. The least significant differences (LSD) were used to compare means with a probability level of 5% or 10% as indicated in the text depending upon the measurement.

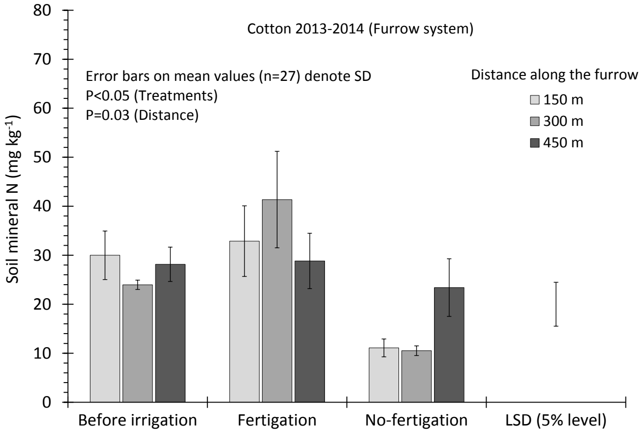

Figure 3. Soil mineral nitrogen (N) distribution at three locations along the furrows (150, 300, 450-m, respectively) as recorded before and after irrigation or fertigation during the 2013/2014 cotton season. Mean values (n=27) for the measured 0-600 mm depth interval.

Statistical analyses were graphically assessed by means of residual plots and normalization of data was not required. Analytical values are reported as the mean ± standard deviation (SD).

RESULTS AND DISCUSSION

MINERAL NITROGEN IN SOIL AND WATER

Figures 3 and 4 show soil mineral nitrogen (SMN) distribution along the furrows and within the soil profile (depth range: 0-600 mm), respectively, before and after irrigation as recorded in the 2013/2014 cotton season. Differences in SMN distribution along the furrows were mainly due to lower nitrate-N levels recorded after irrigation within the non-fertigated crop ($P<0.05$). Overall, SMN levels after application of fertilizer via fertigation were higher (range: ≈30-40 mg kg^{-1}), than those recorded prior to irrigation (range: ≈20-30 mg kg^{-1}), which was observed at the three locations along the furrows. Data in figures 3 and 4 shows that distribution of fertilizer-N applied through fertigation was relatively uniform both along the furrow and at depth. Slightly higher SMN concentrations in the 0-200 mm depth interval may be explained by the time at which fertigation was initiated relative to the start of the irrigation. Given that these soils exhibit a significant decrease in infiltration rates with respect to time (table 1), deep percolation of N applied as fertilizer is concurrently reduced when the start of fertigation is delayed relative to the start of the irrigation cycle. Soil cracks seal-off as irrigation is applied thereby reducing the risk of fertilizer-N losses through leaching. Where fertigation had not been applied, differences in SMN before and after irrigation suggested that native SMN leached below 600 mm deep, particularly within the first half along the furrow. Losses of nitrate in deep drainage in furrow-irrigated cotton systems in Australia are mentioned by Silburn et al. (2013) to be related to total rainfall and irrigation applied over the crop season. System's optimization and improved management (flow rate, field length, and cut-off time) can significantly reduce deep losses of both water and nitrate (Silburn et al., 2013), particularly when effective rooting depth is not restricted by soil mechanical constraints (Dodd et al., 2013; Kodur et al., 2014). Granular fertilizer applied before planting needs to be placed at shallow depth (e.g., 50-100 mm) at the centerline of the hill or on the side, but near the ridgetop, to minimize the risk of N moving out of the root zone when irrigation is applied (Siyal et al., 2012). These observations are consistent with soil wetting patterns typically observed in furrow irrigation systems (Horst et al., 2007; Zhang et al., 2015), and suggested that the use of surge flow systems may allow for improved system's performance for joint application of water and fertilizer-N (e.g., Izuno et al., 1985; Boldt et al., 1994). By reducing infiltration rates, surge irrigation allows for smaller applications of water thereby reducing deep percolation (Yonts et al., 1996). Experimental work conducted for the sugar industry in Australia (e.g., Robertson et al., 2000) showed promising results derived from surge irrigation, but work on heavier soils (e.g., Wood et al., 2017) such as those used for cotton production is warranted.

Measurements conducted at the furrows site in the 2014/2015 season were fairly consistent with those

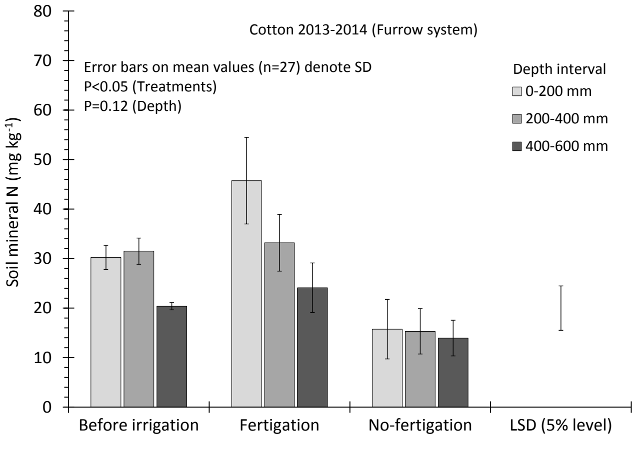

Figure 4. Mineral nitrogen (N) distribution within the soil profile (depth interval: 0-600 mm) as recorded before and after irrigation or fertigation during the 2013/2014 cotton season. Mean values (n=27) for the three locations (150, 300, 450-m, respectively) along the furrows.

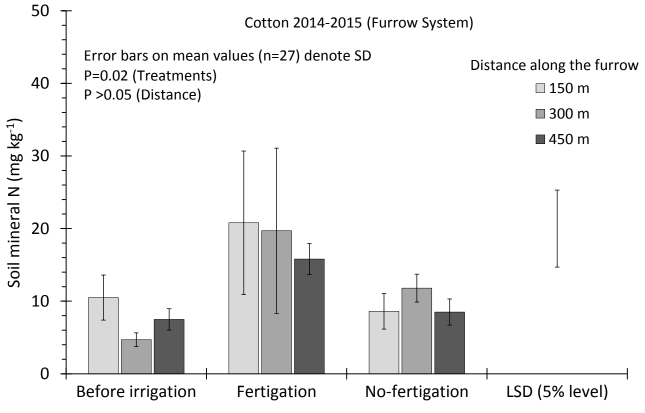

Figure 5. Soil mineral nitrogen (N) distribution at three locations along the furrows (150, 300, 450-m, respectively) as recorded before and after irrigation or fertigation during the 2014/2015 cotton season. Mean values (n=27) for the 0-600 mm soil depth interval.

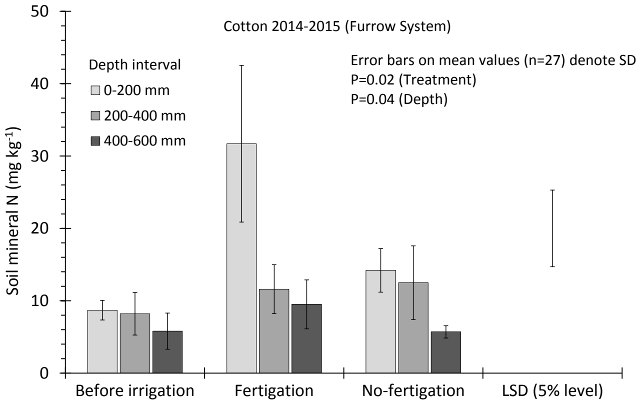

Figure 6. Mineral nitrogen (N) distribution within the soil profile (depth interval: 0-600 mm) as recorded before and after irrigation or fertigation during the 2014/2015 cotton season. Mean values (n=27) for the three locations (150, 300, 450-m, respectively) along the furrows.

observed the previous year (figs. 5 and 6). Overall differences in SMN at the three locations along the furrows were not significant, which was observed in both the fertigated and non-fertigated strips (P-values >0.05), respectively. Differences in SMN before and after irrigation where fertigation had not been applied were not significant, which suggested improved cut-off time and therefore a relatively smaller leaching fraction allowed compared with 2013-2014 (McCarthy et al., 2016). Differences in SMN at the three depth intervals ($P<0.05$) were attributed to relatively higher values observed in fertigated furrows within the top 200 mm of the profile (fig. 6). A relatively high variability in SMN data for the 0-200 mm depth interval (SD =23.03 mg kg^{-1} SMN) was observed, which also explained a significant effect at such depth. For the fertigation treatment, the statistical analysis showed that two data points corresponding to the sampling locations at 150 m and 300 m down-furrow had large residuals. When these values were removed from the dataset, the statistical analysis showed no differences in SMN distribution within the soil profile (0-600 mm). However, the dataset is reported in full as this reflects the spatial variability in soil infiltration that is typical of Vertisols (Kishné et al., 2010).

Figure 7 shows mineral N concentration in water during irrigation or fertigation from samples collected in the 2013/2014 and 2014/2015 crop seasons. Differences in mineral N in water observed at the three locations down-furrow were within <10 mg L^{-1} ($P>0.05$). This confirmed that N applied via fertigation was uniformly distributed along the furrows, which was therefore consistent with SMN data. Overall, no significant differences ($P>0.05$) in (mean) mineral N concentrations in water were found between underground water and water samples collected from non-fertigated furrows. However, there was relatively greater variability in the data derived from water collected from furrows during the irrigation events. The delivery of liquid fertilizer from the fertilizer tank to the irrigation system is not a continuous flow (McCarthy et al., 2016), which may explain relatively wider range of mineral N values observed in samples collected directly from the outlet of the irrigation system and from fertigated furrows after injection of fertilizer. Application of fertilizer through fertigation during the first-third to first-half of the irrigation event, but after irrigation had been initiated, proved satisfactory in terms of uniformity of distribution both down-furrow and within the measured soil depth interval (0-600 mm). This observation is in close agreement with an earlier study by Abbasi et al. (2012), which showed that fertilizer applied in the first half of the irrigation cycle significantly reduced losses through runoff and suggested that percolation below a depth of 500 mm would not be of concern in well-designed systems. By contrast, work conducted by Jaynes et al. (1988, 1992) showed significant solute losses by leaching because of long fertilizer injection time and continuous flood irrigation. Hence, it appears that the inflow rate, as specified in McCarthy et al. (2016), was correctly selected and therefore distribution uniformity of fertilizer applied via fertigation was relatively less sensitive to injection timing. Improved root solute uptake can also be achieved when fertigation is applied in the middle, instead of the beginning, of the irrigation event (Šimůnek et al., 2016).

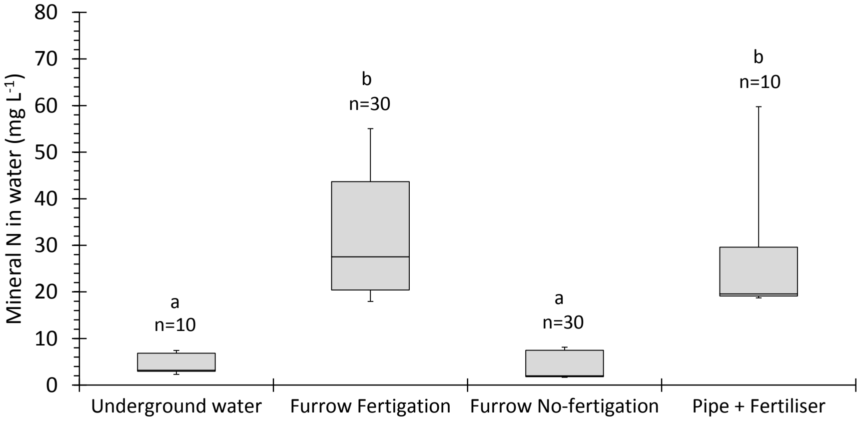

Figure 7. Mineral nitrogen (N) in water recorded during irrigation or fertigation. Box plots show: Min, Q_1, Med, Q_3, and Max, respectively, for samples collected in the 2013/2014 and 2014/2015 crop seasons. 'Pipe + Fertilizer' denotes mineral N in water after injection of UAN (30% N, solution) to the gated pipe of the furrow system. Different letters indicate that mean values are significantly different at a 5% probability level, 'n' is number of observations.

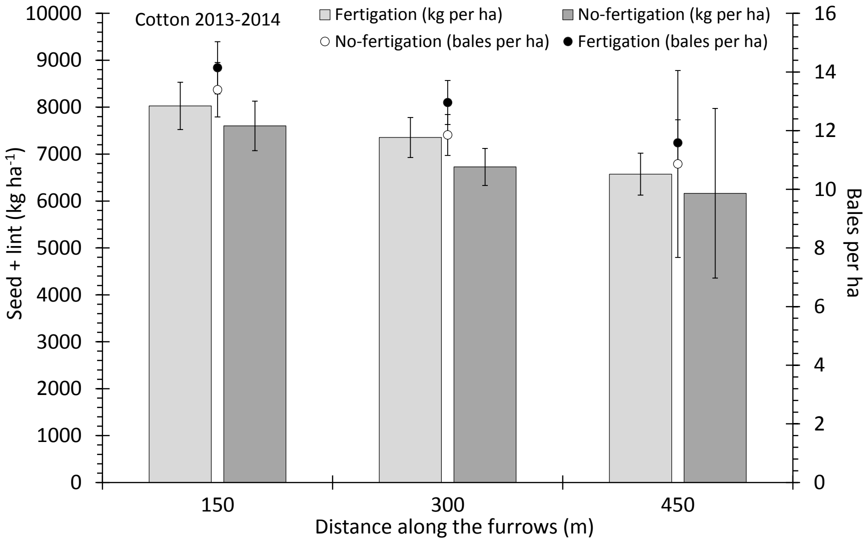

Figure 8. The effect of fertigation on yield of cotton under furrow irrigation as recorded in the 2013/2014 crop season. Error bars on mean values (n=6) denote the standard deviation (SD). Use P>0.10 (Treatment, LSD 10% level: 634.6), P=0.01 (Distance, LSD 10% level: 732.8), and 1 bale =227 kg of lint.

EFFECT OF FERTIGATION ON CROP

Yield measurements conducted at the experimental sites are shown in figures 8 to 10 for all crop seasons. Overall, no statistical differences in yield (seed + lint) were observed between fertigated and non-fertigated crops (P-values > 0.05). Despite this, N applied through fertigation, at the rate and timing used in this study, increased yield by an average of approximately 0.91 ± 1.24 bales per ha over the three crop seasons. In the 2014/2015 season, overall differences in yield between furrow and overhead irrigated crops (fig. 9) were significant at a 10% probability level (P=0.08). Nitrogen applied through fertigation increased yield by ≈0.6 and 0.9 bales per ha in the furrow and overhead systems, respectively, but differences between fertigated and non-fertigated crops were not significant (LSD 10% level: 1.93 bales per ha). Overall differences in yield observed at the three locations along the furrows (figs. 8 and 10) were only significant in the 2013/2014 season (P<0.1), which was consistent with the SMN dataset. Yields observed in these experiments were comparable to the five-year (2012-2016) average (11.24 bales per ha) reported for the Australian cotton industry (Boyce Chartered Accountants, 2016), and compares to ≈16 bales per ha (3500 kg ha^{-1} of lint) potentially attainable under irrigated conditions in southern Queensland and northern New South Wales (Constable and Bange, 2015).

Given the current price ratio N-fertilizer-to-lint (AUD 0.77 per kg N, AUD 450 per bale), application of N through fertigation appears to be economical. This price ratio is equivalent to the breakeven ratio and indicates the extra return of lint that just covers the extra unit of N added. At this point, the economic return from the N applied as fertilizer is maximized (Kachanoski, 2009). At low price ratios, growers tend to apply N at rates that are higher than the optimum rate, even though the economic return from the fertilizer applied diminishes. This approach is often perceived by Australian cotton growers as an ‘insurance policy’ as yield penalties from sub-optimum fertilization of the crop will have a significant impact on gross margin, particularly when yield is likely not to be affected by seasonal effects of weather. Generally, this additional fertilizer cost does not translate into an equally significant economic loss to the grower that may result from loss of yield. In cotton, the cost N fertilizer is relatively small (about 10%-12% of total operating costs) compared with other components (e.g., energy, tillage, water) of the overall cost structure for the crop, particularly in irrigated systems (Boyce Chartered Accountants, 2016). Whilst the case-study reported here represents a low input N scenario compared with the median (>250 kg ha^{-1} N) and the top 30% (300-400 kg ha^{-1} N) of cotton growers (Boyce Chartered Accountants, 2016), from the environmental perspective, this has significant implications for N use efficiency and increased risk of N losses to the environment (Grace et al., 2016).

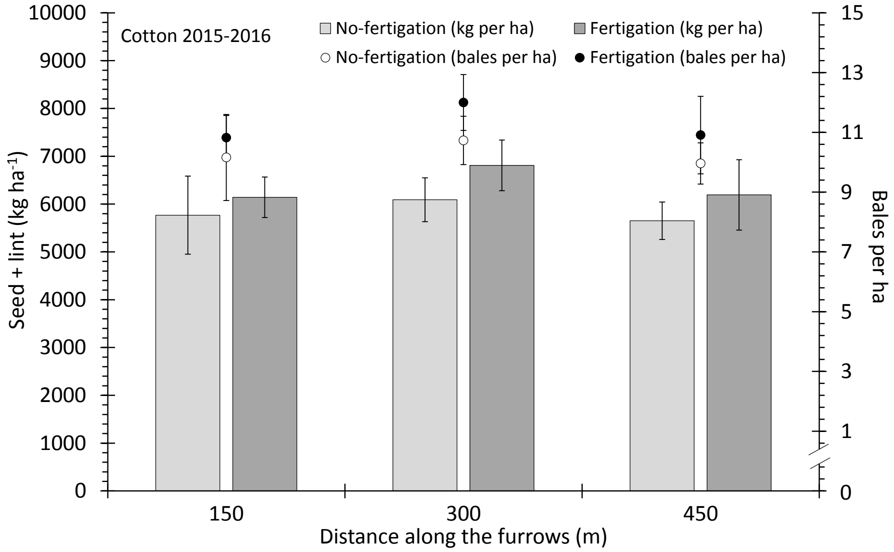

Figure 10. The effect of fertigation on yield of cotton under furrow irrigation as recorded in the 2015/2016 crop season. Error bars on mean values (n=6) denote the standard deviation (SD). Use P>0.10 (Treatment, LSD 10% level: 658.6), P>0.10 (Distance, LSD 10% level: 806.7), and 1 bale =227 kg of lint.

Agronomic efficiency calculations reported values between 21 and 46 kg kg^{-1} (fig. 11a). On average, agronomic efficiency in fertigated crop was approximately 2 kg kg^{-1} higher in overhead compared to furrow (P=0.05), consistent with yield differences observed in both treatments. Nitrogen recoveries in seed for the 2013/2014 and 2014/2015 cotton crops are shown in figure 11b from which N use efficiency (NUE) calculations were derived. Mean (±SD) values of NUE (kg kg^{-1}) were: 0.50 ± 0.018 (furrow, no fertigation), 0.46 ± 0.031 (furrow fertigation), 0.44 ± 0.029 (overhead, no fertigation), and 0.39 ± 0.012 (overhead fertigation), respectively.

Previous studies by Rochester (2011, 2012) showed that cottonseed N can be used to assess whether the crop has been under or over-supplied with N-fertilizer. Based on the assumptions made in Rochester's analyses, it was shown that a cottonseed N content of 3.5 ± 0.2% corresponded with the optimum N application rate. Seed-N concentrations lower or higher than Rochester's critical value would reflect suboptimal or excess supply of N-fertilizer, respectively. For both fertigated and non-fertigated crops, mean N concentrations in seed were within Rochester's range in 2013/2014, but were higher in 2014/2015. The zero-N cotton crop (control) had significantly lower (P<0.05) seed-N concentrations (Antille, 2017). An increment of approximately 0.1% N concentration in seed above the optimum suggested by Rochester (2012) denotes an excess of fertilizer-N applied of ≈20 kg ha^{-1} N. These results also suggested that the N applied as fertilizer prior to planting, at the rates used to establish the commercial crop, plus soil N mineralized throughout the cropping season was sufficient to meet crop's demand for N.

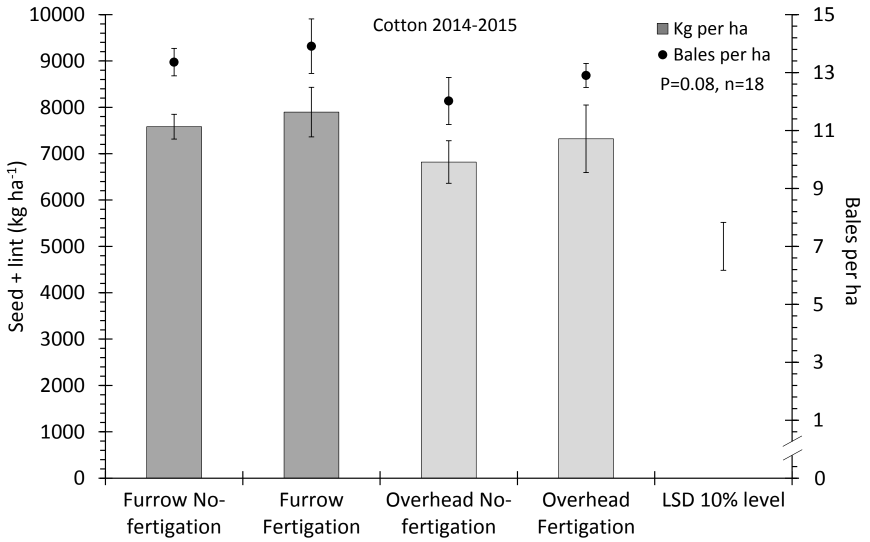

Figure 9. The effect of fertigation on yield of cotton under furrow and overhead irrigation as recorded in the 2014/2015 crop season. Error bars on mean values (n=18) denote the standard deviation (SD). Use 1 bale=227 kg of lint. Data from the furrows site includes measurements at the three (150, 300, and 450-m) locations down-furrow.

Nitrogen recoveries may be significantly increased by reducing the N rate applied before planting to approximately one-third to half the total N applied as fertilizer, with the balance applied in-crop season in two or three splits depending on the rate.

EFFECT OF FERTIGATION ON SHORT-TERM SOIL EMISSIONS

Mean (daily) and cumulative nitrous oxide (N_2O) fluxes are shown in figure 12. Overall differences in N_2O emissions in the furrow system were approximately eight times higher than the overhead ($P<0.05$). Emissions from non-fertigated crops were approximately two times higher in furrow compared with overhead ($P<0.05$). Emissions from the fertigated crop under the overhead system were comparable to the non-fertigated crop in the furrow system ($P>0.05$). In both systems, fluxes were largest within the first three days of irrigation or fertigation, but decreased significantly after and were statistically similar after 15 days ($P>0.05$). This observation was consistent with earlier work (e.g., Macdonald et al., 2017), which showed that gaseous losses of N occurred directly after fertilizer was applied. Cumulative emissions from fertigated crops over the 30-day period accounted for ≈0.8 kg ha^{-1} N_2O-N and ≈0.1 kg ha^{-1} N_2O-N in furrow and overhead, respectively, which therefore represented 2% or less relative to the total N applied (40 kg ha^{-1} N) as fertilizer during the fertigation event. These losses compare with cumulative, year-round, emissions of approximately 1.10 to 1.90 kg ha^{-1} N_2O-N measured by Scheer et al. (2016) from a Black Vertosol in a cotton-fallow sequence with N application rates between 180 and 270 kg ha^{-1}. Soil emissions of N_2O often represent a small proportion of total N loss due to complete denitrification, however, recent research in irrigated cotton in southern Queensland has shown that the N_2:N_2O ratio may be as high as 70:1 (e.g., Grace et al., 2016). Mass N balance calculations for irrigated cotton in northern New South Wales (e.g., Macdonald et al., 2016) agree well with these observations. This consideration is more important for furrow compared with overhead systems because of higher irrigation rates normally applied with that system, which in these experiments were approximately 3 to 4 times higher. Consequently, soil moisture conditions in furrow systems are higher and can be sustained for longer after irrigation has been applied. This influences the frequency and extent of wetting and drying cycles, and sets the conditions for increased N losses through denitrification. Water-filled porosity data (WFPS, fig. 13) collected at the sites supports the above statements and agrees with earlier studies (e.g., Bremner and Shaw, 1958; Linn and Doran, 1984). Anaerobic soil conditions are known to enhance N_2O production when labile forms of C and N are available (Mosier et al., 2004). In most soils, N_2O emissions increase significantly when the water-filled pore space (WFPS) is >60% (Li et al., 2005), while above ≈80% WFPS the ratio N_2:N_2O also increases due to complete denitrification (Ruser et al., 2006). Soil oxygen (O_2) concentrations and relative diffusivity of O_2 decrease as WFPS increases, which encourages production of N_2O and N_2 under such conditions (Hmielowski, 2017). Nitrous oxide emissions are also dependent on N rate and tend to increase in a non-linear fashion above ≈250 kg ha^{-1} N (e.g., Hoben et al., 2011; Scheer et al., 2016), which may raise environmental concerns in furrow irrigated systems that have higher water and N inputs than those reported in these experiments. However, by reducing the rate of N applied prior to planting and allowing for N applications in-crop, the risk of significant N losses through gaseous evolution early on in the season will also reduce proportionally. At industry-level, this is an important consideration for N management since approximately 20% of growers applied all N-fertilizer before planting, and about 30% of growers applied 300 to 400 kg ha^{-1} N.

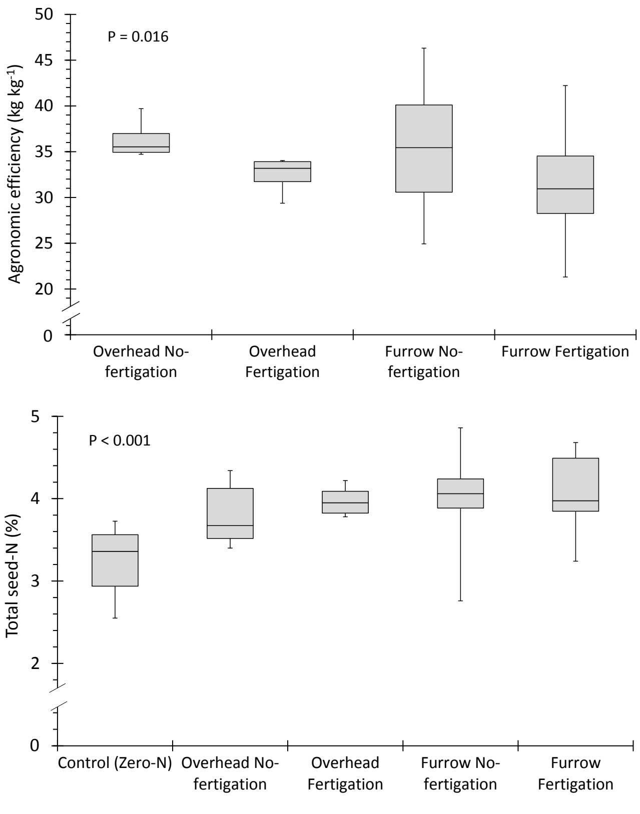

Figure 11. The effect of fertigation on: (top) agronomic efficiency recorded for overhead (2014/2015) and furrow (from 2013/2014 to 2015/2016) irrigated cotton crops, respectively, and (bottom) total seed-N. Box plots show: Min, Q_1, Med, Q_3, and Max, respectively. In (a), data for control (zero-N) was retrieved from Antille (2017).

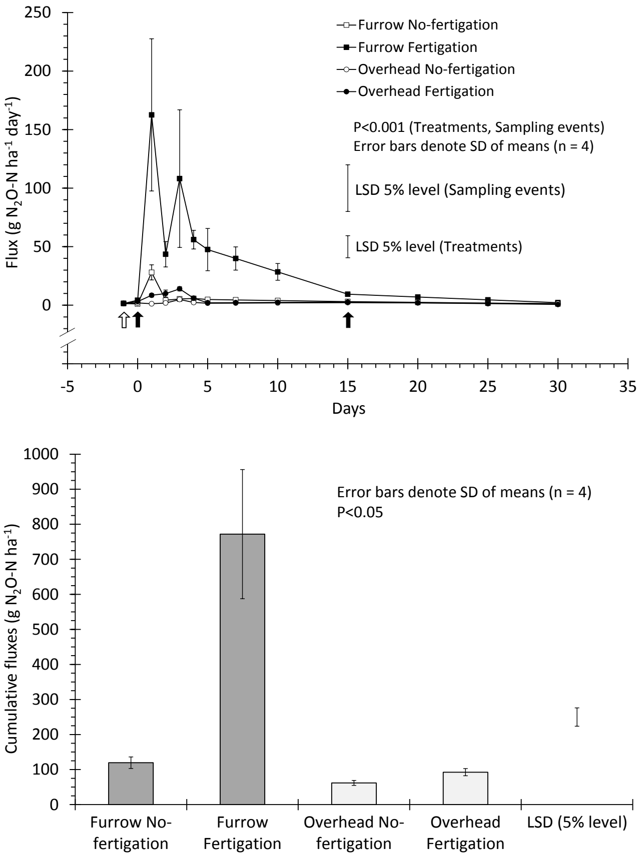

Figure 12. Short-term nitrous oxide (N_2O) emissions recorded in fertigated and non-fertigated cotton under furrow and overhead irrigation (season: 2014/2015); (top): mean daily fluxes and (bottom) cumulative fluxes over the 30-day measuring period. Arrows (top image) denote the day before irrigation (-1) and the day irrigation (0, 15) was applied, respectively.

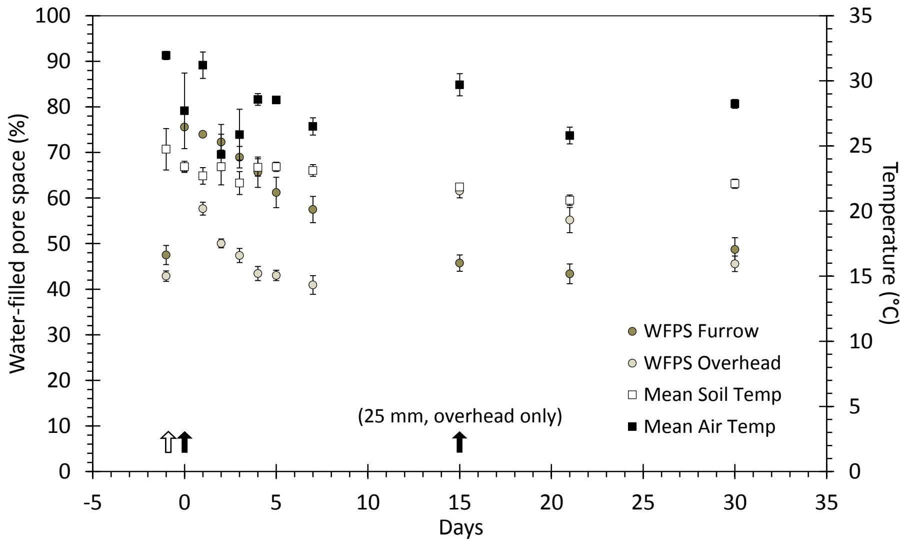

Figure 13. Water-filled pore space (WFPS) measured at the furrow and overhead sites, and mean soil (depth range: 0-100 mm) and air temperatures. The arrow on day 15 denotes the timing of a second irrigation event (25 mm) conducted at the overhead site. Error bars denote the standard deviation (SD) of the mean. Use n=4 for WFPS, and n=3 for temperature. Arrows denote the day before irrigation (-1) and the day irrigation (0, 15) was applied, respectively.

Figure 13 shows that the irrigation event at day 0 increased WFPS in the top 200 mm of the profile from approximately 45% (before irrigation) to 65% in the overhead and 75% in the furrows system, respectively. Wetter soil conditions persisted for longer in the furrows system compared with the overhead system in which WFPS decreased to less than 45% within five days of irrigation. Hence, N_2O fluxes over the drying phase were also lower despite that soil nitrate levels recorded in this system were still high (31 ± 14.7 mg kg^{-1} NO_3-N) seven days after fertigation was applied. A subsequent irrigation event (25 mm) conducted at the overhead site 15 days after fertigation had no significant effects on N_2O emissions because nitrate concentrations in soil dropped to less than 15 mg kg^{-1} NO_3-N, coupled with high rates of N uptake by the crop around peak flowering (Mullins and Burmester, 1990).

CONCLUSIONS

The main conclusions derived from this work are:

1. Differences in yield between fertigated and non-fertigated crops were not significant and therefore fertigation may not be justified when pre-season N rates are already high (e.g., >100 kg ha^{-1} N). However, fertigation may be used when pre-season N application rates are low, particularly in overhead irrigation as significantly higher efficiencies both in terms of water and N use can be achieved. Fertigation enables some of the operational constraints associated with application of fertilizer in-crop season to be overcome, such as those commonly encountered with granular materials or anhydrous ammonia, which require soil incorporation. Given current price ratios (fertilizer-to-cotton), fertigation appears to be economical, but care must be exercised in furrow irrigation systems because of inherently higher risk of environmental losses,
2. For the furrow irrigation system, the uniformity of distribution of N fertilizer applied through fertigation

was satisfactory, which was achieved both at distance and depth. Greater control over the water applied to furrows, and improved placement of granular fertilizer before planting, will likely reduce the risk of deep percolation (>600 mm) of native soil mineral N. For the overhead system, there were advantages compared with the furrow system in terms of reduced N_2O emissions following irrigation or fertigation, which were approximately eight times lower. Such results were attributed to differences in water-filled porosity and the extent of soil moisture drawdown observed within five days after fertigation was applied. Cumulative N_2O losses over the 30-day period accounted for ≈0.8 and 0.1 kg ha^{-1} N_2O-N in furrow and overhead fertigated crops, respectively, and were consistent with the N rate applied as fertigation in both systems. These losses had little impact on agronomic efficiency calculations,

3. One important possibility that could increase N use efficiency in the Australian cotton industry would be for a proportionally higher amount of fertilizer-N to be applied in-crop season and one way of doing this would be to improve the efficiency of fertigation methods available. Where possible, low-efficiency fertigation techniques such as ‘water-run’ urea need to be replaced. This may be possible as growers progressively convert from furrow (and flood) irrigation to overhead (and drip) irrigation systems allowing for greater degree of automation, and potentially joint optimization of water and N use (spatially-controlled inputs). Improved diagnostics of real-time crop requirements (stresses) may be also possible through a combination of simulation-optimization approaches informed by crop and soil sensing technology (e.g., sensor fusion).

FUTURE RESEARCH REQUIREMENTS

The following research priorities were identified:

1. Optimization of timing of fertigation relative to the irrigation cycle in furrow systems. Determine the feasibility and potential benefits of pre-irrigating the soil prior to fertigation to reduce infiltration rates and therefore deep percolation of fertilizer-N. Fertigation may be subsequently applied on pre-irrigated soil so as to minimize such losses. There is a need to ensure that potential reductions in losses of N by leaching do not lead to increased gaseous emissions (N_2O, N_2) both from soil and irrigation water containing fertilizer (pollution swap). Co-optimization of inflow rate with start and cut-off times, and duration of fertilizer injection is required to minimize N losses and improve recovery in crop. Future field-scale experimentation should be undertaken to determine emission factors for furrow and overhead irrigation,
2. Improved diagnostic of N requirements for in-crop season fertilizer application. This requirement is being addressed by current CRDC-funded research into N use efficiency, including the need to quantify the contribution of mineral N derived from mineralization of soil organic matter. There is also a need to consider in more detail the N dynamics within furrow irrigated cotton systems that rely on low-cost fertigation techniques (e.g., water-run urea) for in-crop season fertilizer application. This is important because N_2O emissions are affected by fertilizer-N source (e.g., dissolved urea *vs*. UAN), and depend on site- and weather-specific conditions (Snyder et al., 2009). Therefore, the evaluation of N lost through excess irrigation water leaving the field needs to be considered to assist furrow systems’ design, re-utilization of tail water and recovery of dissolved nutrients in such water,
3. For overhead systems, there is a need to investigate the feasibility of adopting variable rate technology (VRT) for both water and N, and identifying effective adoption pathways. In Australia, uptake of VRT for water and N management in cotton is low despite that benefits have been widely demonstrated for other cropping systems at commercial-scale farming. There is sufficient evidence to state that significant improvements in N use efficiency, with the associated reduction in greenhouse gas emissions, can be achieved with VRT compared to uniform application.

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