



**Application ID: AOTGR2-0008**

**FINAL REPORT – COTTON RDC – DETERMINING OPTIMUM NITROGEN STRATEGIES FOR  
ABATEMENT OF EMISSIONS FOR DIFFERENT IRRIGATED COTTON SYSTEMS**

Principal Investigator: Dr Graeme Schwenke (Senior Research Scientist, NSW DPI)

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**FINAL REPORT****PROJECT TITLE:**

**Determining optimum nitrogen strategies for abatement of emissions for different irrigated cotton systems.**

Principal Investigator: Dr Graeme Schwenke (Senior Research Scientist, NSW DPI)

**1.0 PROJECT DESCRIPTION**

This project evaluated and demonstrated nitrogen fertiliser and irrigation management strategies aiming to reduce nitrous oxide emissions from commercial irrigated cotton systems in three climatic zones – Central Queensland (Emerald), the Gwydir Valley (Moree) and the Liverpool Plains (Gunnedah) in Northwest NSW.

**2.0 EXECUTIVE SUMMARY**

*Use this section to summarise the findings of this project.*

- In 2014–15, farmers' N rates were at least 25% higher than necessary to achieve the same lint yield, i.e. 50–100 kg N/ha less N fertiliser could have grown the same amount of cotton.
- Increasing N rates increased total nitrous oxide emissions, especially in prolonged wet soils
- A split N application strategy showed no cotton yield benefit compared to all N fertiliser applied pre-plant. The all pre-plant strategy concentrated nitrous oxide emissions into the first several weeks at the start of the season, with little afterwards.
- Soil nitrate from pre-plant and water-run N applications was shown to be mobile both vertically within the soil profile and horizontally within the plant bed.
- Nitrous oxide emissions at Moree in 2015-16 were lower when fertiliser N was applied into the non-irrigated side of the plant bed, compared to when N was applied to the irrigated side
- Nitrous oxide emissions were generally low from the irrigated furrow position, and potentially high from the non-irrigated furrows that collected soil nitrate leaching out of the plant beds during irrigation.
- Head ditch soils and tail drain sediments can have high concentrations of mineral N with subsequently high emissions of nitrous oxide after irrigation.
- Nitrification inhibitors (N-Sure™ and N-serve™) directly injected into anhydrous ammonia during pre-plant N application were effective in delaying conversion of ammonium to nitrate for 2–3 months, and as a result reduced nitrous oxide emissions during pre-plant and early crop growth.

This project aimed to research and demonstrate a range of potential management practices to reduce the emission of nitrous oxide, a greenhouse gas, from furrow-irrigated cotton in northwest NSW and central Qld. Over three cotton-growing seasons, we conducted 8 on-farm trials of abatement technologies, strategies and management practices to measure and demonstrate how these may reduce agricultural nitrous oxide emissions while maintaining or enhancing productivity. We also conducted a laboratory incubation study that compared nitrous oxide emissions from the non-cropped head ditch and tail drain soils/sediments of 10 commercial paddocks from across the region.

In 2014–15 we compared nitrous oxide emissions from 3 fertiliser N rate treatments at each of 3 commercial farms located near Emerald (Qld), Moree (NSW), and Gunnedah (NSW). At each farm, the three N rates included the farmer's chosen rate for that paddock, a 25% lower rate and a 25% higher rate. Despite receiving 8–9 irrigations as well as several intense rainfall events in a season, there were typically only 3–4 significant nitrous oxide flux periods during the season, with most occurring early in the season, i.e. irrigations 1 and 2. Further significant emissions events occurred mostly in response to the addition of in-crop N fertiliser followed by irrigation and/or intense rainfall. Previous research has concluded that N fertiliser applied at rates in excess of crop requirements may lead to exponential increases in nitrous oxide emitted (and therefore an increase in EF). However, this only occurred at the Moree trial when the in-crop N was followed by a long period of wet soil conditions. N rates were clearly in excess of crop requirements at all sites as there was no yield response to increasing N rate. Therefore, the farmers' chosen N rate at all sites was at least 25% higher than necessary to achieve the same lint yield in that year of cropping at those sites, i.e. between 50 and 100 kg N/ha less N fertiliser could have been used to grow the same amount of cotton. At the Moree and Gunnedah sites, use of the lower rate would have also reduced the farm's nitrous oxide emissions by 24–26%.

In 2015–16, treatments were developed in consultation with the co-operating farmers using suggested management options from previous research. At Emerald, we compared N application either 100% pre-plant or split between pre-plant and in-crop. The duration of irrigation was also compared within the split N application treatment. The long-duration irrigations, an older practice in the region, led to reduced crop productivity and initially increased nitrous oxide emissions. The split N application strategy showed no agronomic benefit compared to all N fertiliser applied pre-plant. Nitrous oxide peaked within a few days of the first irrigation in each treatment, especially in the non-irrigated hill position of each treatment. The initial "burst" of higher emissions activity after the first irrigation continued for several weeks. In terms of best practice for N<sub>2</sub>O emissions reduction, these treatments significantly affected emissions intensity at different measurement times, but the overall losses were too variable to statistically separate treatments when considered across the whole season.

The Moree trial in 2015–16 compared irrigating next to the fertiliser band versus the opposite side of the hill, plus irrigating every furrow rather than every second furrow. Crop production was not affected by these treatments, but nitrous oxide emissions were less when the opposite side of the hill was irrigated. Emissions from watering every furrow were no different to watering the opposite side of the hill. Soil nitrate from pre-plant and water-run N applications was shown to be mobile, both vertically within the soil profile and horizontally within the plant bed.

At Gunnedah, the 2015–16 trial compared 100% pre-plant versus split N application, as well as irrigating either next to the fertiliser band or on the opposite side of the hill, as in Moree. The current practice of split N application produced N<sub>2</sub>O emissions lasting up to a week in response to each N application/irrigation event. The older practice of applying 100% pre-plant N concentrated almost all of the seasons N<sub>2</sub>O

emissions after the first irrigation event, with little additional N<sub>2</sub>O lost after subsequent irrigations. However, due to the high variability in results there was no cumulative treatment difference across the season. Irrigating the furrows close to the fertiliser band rather than those on the other side of the hill from the fertiliser band increased the initial intensity of N<sub>2</sub>O released after the first irrigation, but again there was no cumulative seasonal difference. The 100% pre-plant treatment produced larger biomass plants with a lower %N content and lower seed N offtake, but did not affect cotton lint yield.

The 2016–17 trials at Emerald and Gunnedah investigated the potential for nitrification inhibitors injected in-line with anhydrous ammonia during pre-plant N application to mitigate nitrous oxide emissions and potentially reduce wholesale N loss from the paddock. At Emerald, generally dry conditions and a short (week-long) pre-plant period meant that nitrous oxide losses were low, but both inhibitors still reduced emissions compared to the control. At Gunnedah, very wet soil conditions followed by 280 mm of rainfall during the 3 month pre-plant period meant high nitrous oxide emissions from the control but very little was emitted from the inhibitor treatments. While the effects of the inhibitors on soil processes were clear, the high variability associated with soil sampling on a fertiliser band meant that we were unable to establish significant differences in total mineral N remaining at sowing. The effectiveness of both inhibitors dissipated after 2–3 months. At Emerald, subsequent application of an inhibitor during urea side-dressing proved to further extend the mitigation of nitrous oxide during following irrigation events. No impacts of the inhibitors on cotton lint yield from pre-harvest biomass cuts were observed at Emerald. The raw picked cotton yields at Gunnedah did not show any treatment differences. Ginned lint yields are not yet available.

The laboratory incubation experiment with 10 head ditch soils and 10 tail drain sediments from farms across the study region showed that the magnitude of nitrous oxide emissions was largely driven by the initial mineral N concentration, which ranged widely across the sample set. Nitrate and, in one case, ammonium were extremely high, particularly in tail drain samples. Samples with high mineral N concentrations produced nitrous oxide losses up to 100 times greater than those from some of the low mineral N samples. A simulated application of water-run urea increased nitrous oxide losses from head ditch samples with low initial mineral N, particularly after the second irrigation cycle. These non-cropped areas of cotton paddocks are of concern because they will continue to retain high soil mineral N concentrations throughout the season unlike the remainder of the paddock where the growing plants deplete the available N.

*Explain how the outcomes and outputs of this research will benefit Australian agriculture.*

The Australian cotton industry aims to present an image of responsible environmental stewardship to national and global markets and consumers. The outcomes of this research will firstly help quantify the greenhouse gas emissions (nitrous oxide) associated with commercial cotton production by adding to the existing data more “real-world” measurements from commercial crops that may be considered when revising national emission factors used in national greenhouse gas inventory accounting. Our data mostly sit below the current Australian emissions factor of 0.55% for irrigated cotton. We have documented emissions resulting from both new and old fertiliser N application and irrigation strategies used by farmers in the regions studied. Outcomes of this research help answer questions about the potential environmental effects of variations in practices. Our most recent trial results demonstrate the significant reduction in nitrous oxide emissions from using nitrification inhibitors during the pre-plant application of anhydrous ammonia. In conditions of waterlogging, these inhibitors can also potentially retain more of the N in soil from applied fertiliser that may otherwise be lost through denitrification before the crop is established. These inhibitors have not previously been tested in Australian agricultural conditions.

*Include the significance of these findings for policy makers and the Australian agricultural industry.*

These results represent a significant addition to the existing knowledge of nitrous oxide emissions from irrigated cotton production in northern Australia, covering some regions where such work has not been previously done. We have also researched several strategies for potential nitrous oxide mitigation that have not previously been examined. Several of these strategies could potentially be developed for inclusion in methodologies for reducing greenhouse gas emissions in irrigated cotton.

*Identify any questions that remain unanswered or arose as a result of the project.*

In our final trial year we tested two nitrification inhibitor products injected with anhydrous ammonia at pre-plant N application. To our knowledge this is the first time one of these products have been applied this way. The Dow Agrosiences product “N-Serve” has been used with anhydrous ammonia before in the USA, but is not currently available in Australia. The Incitec Pivot product “N-sure” is currently being developed, and our project was the first to use it, and the first to evaluate its effects on nitrous oxide mitigation. Since the trial area was inadvertently top-dressed by the grower late in the growing season, we were unlikely to measure any treatment effects on crop production. Further research is needed to quantify whether these inhibitors can actually benefit cotton yields and are thus economically viable. More detailed experiments are needed to quantify whether the use of the inhibitors impacts on the N fertiliser response curve for cotton, thus potentially reducing the N fertiliser requirement, i.e. achieving equivalent yields using less N fertiliser.

Another question arising from the use of the inhibitors concerns the potential effects of different species of available N on cotton plant N uptake. Using inhibitors keeps the mineral N available in the ammonium form. Does this form affect plant function and development of the cotton? Also, what is the impact on plant productivity of potentially having more mineral N available later in the season?

In 2015–16 we briefly looked at the diversity of nitrous oxide responses according to measurement position. Chambers positioned in furrows, plant rows, hill sides on fertiliser bands, hill sides away from fertiliser bands, etc. all recorded different nitrous oxide flux patterns according to the time after irrigation and thus soil water content. This heterogeneity of emission makes chamber location and indeed gas sample timing crucial to understanding how and when nitrous oxide losses occur. Further research is necessary to describe how the different zones contribute to nitrous oxide losses at different stages.

In our laboratory incubation study, we found that head ditch and tail drain areas of an irrigated cotton paddock are often high in soil mineral N and, once irrigated, can release potentially large emissions of nitrous oxide. Since these areas are not cropped, there is no uptake of mineral N during the season so these areas may continue to produce nitrous oxide throughout the season even though the cropped areas do not continue emissions after the first 1–2 irrigations (unless additional N is added). Field monitoring of these areas is needed to confirm whether they do indeed continue these high fluxes in a field situation.

## 3.0 METHODOLOGY

### 3.1 Project background and 2013-14 project initiation

Nitrous oxide emissions from irrigated cotton systems may be substantially reduced by management practices to improve nitrogen use efficiency (NUE). Previous research has shown that up to 3.15% of applied N in these systems can be lost as nitrous oxide emissions, primarily through denitrification (Grace *et al.* 2016). Cotton grower and consultant surveys show potential for N fertiliser use efficiency to be improved on many cotton farms. Nitrogen use efficiency trials have been run every decade or so at the Australian Cotton Research Institute (ACRI), Narrabri. In spite of this, there is uncertainty in the industry as to whether these recommendations apply in their specific location. Practice often does not reflect research recommendations and thus there is need validate the research trial results on-farm in different climatic regions. This project aimed to provide detailed information on the potential to reduce N<sub>2</sub>O emissions in a range of climatic conditions, which may then be used in industry extension campaigns to improve N use efficiency. For example, nitrification inhibitors have been shown to conserve N fertiliser in cotton cropping, but have not been shown to reduce N<sub>2</sub>O emissions under commercial irrigated cotton systems.

Grace P, Shcherbak I, Macdonald B, Scheer C, Rowlings D (2016) Emission factors for estimating fertiliser-induced nitrous oxide emissions from clay soils in Australia's irrigated cotton industry. *Soil Research* **54**, 598-603.

Due to contracting delays preventing hiring of technical staff and purchase of equipment, no field work was carried out in the 2013-14 summer cotton-growing season. Also, the project start date of 1<sup>st</sup> October was too late in the year to begin summer field trials as farmers typically apply nitrogen (N) fertiliser several months earlier than this. In the central Qld region, the cotton crop had already been planted by this time. Therefore, funds allocated to the first year were carried forward and distributed across subsequent years.

### 3.2 2014-15 N fertiliser rates: on farm trials

In the 2014-15 summer season, 3 trials were conducted in commercial farms located near Emerald (Qld), Moree (NSW), and Gunnedah (NSW). At each farm, the trial treatments focused on the total rates of N fertiliser applied during the season, with three N rates, including the farmer's chosen rate, a 25% lower rate and a 25% higher rate (Table 1). The fertiliser products used, application method and application timing varied according to each co-operating farmer's practice. There were 3 replicate plots (randomized in the trial plan) of each treatment that were 8–12 rows wide x paddock length.

**Table 1.** *Table 1. N rate treatments used at the three on-farm trial sites in 2014-15 (i-u = incorporated urea, aa = anhydrous ammonia, s-uan = sprayed urea ammonium nitrate, w-u = water-run urea, b-u = broadcast urea)*

Site	N applied pre-sowing (kg N/ha)	N applied in-crop (kg N/ha)	Total N applied (kg N/ha)
Emerald	160(i-u)	0	160
	160(i-u)	60(s-uan)	220
	160(i-u)	120(s-uan)	280
Moree	150(aa)	58(w-u) + 62(w-u) + 60(w-u)	330
	150(aa)	58(w-u) + 62(w-u) + 100(s-uan) + 60(w-u)	430
	150(aa)	58(w-u) + 62(w-u) + 200(s-uan) + 60(w-u)	530
Gunnedah	80(aa)	40(b-u) + 40(w-u)	160
	130(aa)	40(b-u) + 40(w-u)	210
	180(aa)	40(b-u) + 40(w-u)	260

From sowing until harvest, we used manual chambers located in the irrigated furrow, the non-irrigated furrow and on the crop bed to monitor emissions of nitrous oxide (N<sub>2</sub>O), methane (CH<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>) from the soil in each plot. The sampling protocol used fertiliser application, rainfall and irrigation events as triggers for field sampling. Other measurements included: surface soil mineral N and water content (0-10 cm) (monthly), post-harvest soil mineral N to 90 cm depth, plant biomass and biomass N content, cotton lint yield and turnout.

Baseline soil sampling to 30 cm depth was conducted using SCaRP protocols at the start of the 2014-15 trial season at all 3 sites. However, since most trial sites were located in new paddocks each year, there was little perceived value in continued soil carbon monitoring for possible changes due to one season of trial treatments. There is much previous agricultural research that demonstrates that at least 5 years of continuous changed management are needed to raise soil organic carbon concentrations high enough above the natural variability to be statistically significant. Therefore regular soil carbon monitoring was discontinued. Instead, we planned and carried out a soil/sediment incubation study with soils from a range of commercial farms which aimed to increase our understanding of the interaction of soil carbon and nitrous oxide emissions under simulated irrigation conditions.

### **3.3 2015-16 N fertiliser timing and irrigation strategy: on farm trials**

The on-farm trials conducted during 2015-16 investigated the impact of alternative management methods suggested by local growers for mitigating nitrous oxide production while still achieving optimum cotton yields. In each case, the treatments were developed in consultation with the co-operating farmers using suggested management options from previous research.

At each farm trial we included the farmer's current practice as one of the three replicated treatments in the current year's trial. The other two treatments featured alternative management options.

Treatments were:

Emerald (Wills Road, Cam Geddes).

- (1) Current farm practice: 180 kg N/ha pre-plant N application as urea drilled into both sides of every plant bed. First irrigation was 1.5 ML/ha pre-plant. Second irrigation was 1.0 ML/ha post-plant. In-crop irrigations run for 12 hours maximum. In-crop N applications of 20 kg N/ha as UAN were applied in the 4<sup>th</sup>, 5<sup>th</sup> and 6<sup>th</sup> irrigations.
- (2) N applications were identical to treatment 1. Irrigations were longer (around 24 hours) than in treatment 1, and there was no pre-plant irrigation. The second irrigation was 2.5 ML/ha.
- (3) All crop N was applied as urea pre-plant at a rate of 240 kg N/ha, which equals the total amount of N applied in the other two treatments. No in-crop N applications of UAN were made, instead these plots were irrigated with water immediately before the others. The irrigation schedule and watering duration for this treatment was the same as in treatment 1.

There were 3 replicate plots of each of these treatments randomised within the overall trial area, giving a total of 9 plots. Each plot was 12 rows (1 m) wide X 1500 m long (full paddock length).

Moree (Redbank, Ray Fox).

- (1) Current farm practice: Pre-plant application of 180 kg N/ha of anhydrous ammonia injected into the plant bed on the non-irrigated side. In-crop N applications totalling 160 kg N/ha were applied as water-run urea in irrigations 4, 6 and 8. Irrigation was with siphons watering every second furrow.
- (2) As per treatment 1 except that all furrows were watered by siphon irrigation.
- (3) As per treatment 1 except the pre-plant N fertiliser was applied on the irrigated side of the plant bed, not the non-irrigated side.

There were 3 replicate plots of each of these treatments randomised within the overall trial area, giving a total of 9 plots. Each plot was 12 rows (1 m) wide X 380 m long (full paddock length).

Gunnedah (Ruvigne, Rod Smith).

- (1) Current farm practice: Pre-plant application of 100 kg N/ha of anhydrous ammonia injected into the plant bed on the non-irrigated side. In-crop N applications of 30 kg N/ha applied as water-run urea in 2 irrigations.
- (2) As per treatment 1, except that the pre-plant N application was injected into the irrigated side of the plant bed. In-crop N applications were as per treatment 1.
- (3) All N fertiliser applied pre-plant (160 kg N/ha) as anhydrous ammonia injected into the plant bed on the non-irrigated side. No in-crop N applications, instead these plots were irrigated with water immediately before the other plots receiving water run N.

There were 3 replicate plots of each of these treatments randomised within the overall trial area, giving a total of 9 plots. Each plot was 8 rows (1 m) wide X 580 m long (full paddock length).

Nitrous oxide measurement chambers were installed at all three sites immediately after the application of the pre-plant N fertiliser. This season we used a dual sampling strategy, with 36 manual chambers (= 9 plots X 4 positions in each plot), and 4 semi-automatic chambers (= 2 treatments X 2 replicate plots X 1 chamber per plot).

Manual chamber sampling was restricted to 5–6 key irrigation events across the season and consisted of samples collected 1, 2, 4 and 7 days after a chosen irrigation event. The events chosen included the first two irrigation events after the pre-plant N application, plus 3–4 later irrigation events that had water-run N applied. Later irrigations with no N applied were not monitored with manual chambers as results from the 2014-15 season indicated that these typically generated negligible nitrous oxide emissions.

The semi-auto chambers were programmed to sample twice a week throughout the whole season; from immediately after the pre-plant N application through until harvest. This was planned to provide a continuous trace of nitrous oxide emissions throughout the season to complement the targeted intensive manual sampling. Unfortunately, there were recurring technical reliability issues with the semi-auto sampling equipment at all three sites. Nevertheless, the semi-auto sample data still covered the majority of the pre-season and growing season periods.

At the Gunnedah site we also conducted 3 one-off additional gas emissions campaigns. These were designed to examine in greater detail, (a) the variation in nitrous oxide emissions over a full 24 hour period—as our regular measurements were all made between 9–10 am, (b) the variation in nitrous oxide emissions across a full 2 metre transect using 12 chambers—we use 4 chambers per plot in regular

sampling, and (c) the variation in nitrous oxide emissions in relation to chamber closure time—our regular sampling goes for 60 minutes, so we tested other durations from 15 minutes to 90 minutes.

We carried out limited sampling and analysis of N in the irrigation water during the first 3 irrigation events at the 2015-16 Gunnedah trial. At a point mid-way through the irrigation, samples were collected from the head ditch channel and from the tail drain furrows, both irrigated and non-irrigated. Samples were frozen on the day of sampling, then later thawed and analysed for concentrations of urea, ammonium, and nitrate (including nitrite) N forms.

Before any N fertiliser was applied, all three sites were soil sampled to depth (down to 90-150 cm depending on the sampling equipment available at each site). Samples were collected from each plot at 3 positions in the field, i.e. 50–70 m from the head ditch end (where the gas sampling took place), across the middle of the field, and 50–70 m from the tail drain end of the paddock. All samples were analysed for mineral N (nitrate and ammonium N), and soil water content. Pre-trial sampling at Moree found extremely high mineral N in the soil of the initially selected paddock, so we moved to another paddock before the trial commenced. The mineral N at this second paddock was more suitable to N fertiliser trials.

Surface soil (0-10 cm) samples were collected approximately monthly from each of the 36 manual chamber positions in each trial for analysis of mineral N concentration and water content. Soil water content in the topsoil was also recorded using a Theta-probe at each manual gas sampling occasion. Probe recordings were compared with gravimetric soil water contents at 4 different water contents during the season to ensure that the probe readings were calibrated with the local farm soil.

All three trial sites were planted according to the normal planting schedule at each farm. Weather conditions at each site were logged using automated weather stations located near to each gas, soil and plant sampling area.

Plant biomass was sampled at the point of maximum biomass. All plants within a metre of row at 3 positions in each of the 9 plots (head ditch end, middle, tail drain end) were removed, weighed and a subsample collected for later total N analysis. We also collected lint samples from the same 27 positions across the trial site immediately prior to harvester picking. Total plot lint yields were calculated from ginning results from the cotton picked from each individual plot.

### **3.4 2015-16 Sediment collection: on-farm survey**

Soil samples for the sediment incubation study were collected from head ditch (0-10 cm) and tail drain (0-5 cm) locations at 10 irrigated cotton farms in the northwest NSW and central Qld cotton growing areas (including three sites used for the on-farm trials). All samples were air-dried, crushed to <5 mm size, and thoroughly mixed before analysis of soil organic carbon (6B2\*), total nitrogen (7A5\*), ammonium and nitrate nitrogen (7C2b\*), particle size analysis (pipette method\*\*), water holding capacity (WHC, water content of soil allowed to drain for 24 hrs after wetting by slow dripping from above) and dissolved organic carbon (total organic carbon analysis of water centrifuged from soil at 100% WHC). This sample set represented a good cross section of the northwest NSW (and Emerald, CQ) soils used for irrigated cotton production.

\* Rayment GE, Lyons DJ (2010) 'Soil Chemical Methods - Australasia.' (CSIRO Publishing: Melbourne)

### 3.5 2016-17 Nitrification inhibitors: on-farm trials

The final year's trials were restricted to two locations owing to budget constraints. Both trials, at Emerald and Gunnedah, featured a comparison of N fertiliser applied with or without two different nitrification inhibitor products. Previous research into the potential for nitrification inhibitors to reduce nitrous oxide emissions has focused on coated urea products. In the present study, we applied the concentrated inhibitor compounds directly into the anhydrous ammonia stream as it was applied into the soil.

Treatments were:

Emerald (Barwin, Ross Burnett).

- (1) Current farm practice: 150 kg N/ha pre-plant N application as anhydrous ammonia applied into the soil on both sides of every hill. A further 150 kg N/ha was applied as urea in a side-dress operation to the irrigated side of the hill only, immediately before the 2<sup>nd</sup> irrigation.
- (2) As for T1, except "N-Sure" (nitrification inhibitor liquid containing DMPP) was applied at a rate of 2.5 L/ha during the application of the anhydrous ammonia. Also, ENTEC-Urea was applied during the side-dress N application instead of ordinary urea.
- (3) As for T1, except "N-Serve" (nitrification inhibitor liquid containing nitrapyrin) was applied at a rate of 2.5 L/ha during the application of the anhydrous ammonia. Ordinary urea was used for the side-dress N application as nitrapyrin-coated urea could not be sourced for the trial.

There were 3 replicate plots of each of these treatments randomised within the overall trial area, giving a total of 9 plots. Each plot was 8 rows (1 m) wide X 1060 m long (full paddock length).

Gunnedah (Ruvigne, Rod Smith).

- (1) Current farm practice: 300 kg N/ha pre-plant N application as anhydrous ammonia applied into the soil in the non-irrigated furrow.
- (2) As for T1, except "N-Sure" (nitrification inhibitor liquid containing DMPP) was applied at a rate of 2.5 L/ha during the application of the anhydrous ammonia.
- (3) As for T1, except "N-Serve" (nitrification inhibitor liquid containing nitrapyrin) was applied at a rate of 2.5 L/ha during the application of the anhydrous ammonia.

There were 3 replicate plots of each of these treatments randomised within the overall trial area, giving a total of 9 plots. Each plot was 8 rows (8 x 1 m) wide x 580 m long (full paddock length).

Manual chamber measurements of gaseous emissions were restricted to 4–5 major rainfall, fertiliser application, or irrigation events at each site. At the Emerald site, most sampling events were triggered by irrigation, whereas at the Gunnedah site most events were rainfall-related. The semi-automated chambers were installed at both sites (4 chambers at Emerald, 8 chambers at Gunnedah) but technical issues with these systems meant many of the targeted sampling events were missed. All manual and auto-chamber gas and soil sampling was concluded at both sites by the end of November 2016. Plant biomass was collected at peak biomass as in previous seasons, but cotton hand-picking at harvest was not done due to insufficient

project funds. Instead, the lint and seed were separated from the biomass collected at maximum biomass sampling and were ginned and analysed for N concentration. Crop yield data from Gunnedah was not available at the time of reporting.

### **3.6 2016-17 Sediment incubation experiment**

Incubation chambers (150 x 150 mm) were filled with 2 kg of dried, ground soil/sediment, allowing enough space for the application of water. There were 10 farms x 2 locations (head ditch, tail drain) x 2 irrigation water treatments (water only, water-run urea) x 4 reps = 160 chambers. For the simulated water-run urea treatments, 5 kg N/ha N was added to the tail drain samples and 30 kg N/ha added to the head ditch samples. This simulated a typical water-run urea application in the field. Both water only and water-run urea treatments included 10 mg/L of dissolved organic carbon (DOC), applied as glucose, to simulate the DOC typically found in irrigation water (G. Nachimuthu pers. comm.). All chambers were set up in an air-conditioned room set to 25°C. An amount of water calculated to adjust the air-dried soil to saturation was pre-weighed for each chamber, suspended above the open chamber in a plastic bag, then slowly dripped onto the soil surface through a glass-fibre filter paper. After completion of the water addition, chambers were periodically (1, 2, 4, 7, 14 days after water added) capped with lids for 1 hour and fluxes of nitrous oxide, methane and carbon dioxide measured by manual gas sampling through a rubber septum in the lid. Lids were removed after sampling, allowing the soils to slowly dry during the incubation period. On day 14, all chambers were soil sampled using a mini core sampler. After the core was removed from the soil, it was immediately replaced with another core of the same soil/sediment from another set of similarly incubated cores that had been treated identically. Core-samples were analysed for ammonium, nitrate and, for those treated with urea solution, urea-N. Next, all soils were again wet up, this time to 100% water holding capacity. For the next 10 days chambers were sampled for gaseous fluxes at the same time intervals as before (i.e. days 1, 2, 4 and 7 dafter water application). All soils were again soil cored at the conclusion of the trial on day 25 and analysed for mineral N and water content as before.

### **3.7 Unanticipated events and technical/resourcing difficulties**

Our initial gas sampling protocol was based on that used in previous research programs, e.g. NANORP, where likely N<sub>2</sub>O emissions events were to be captured by a period of manual chamber sampling over the following week. These events included significant rainfall events (> 20 mm), irrigation, and N fertiliser application. In 2014-15, using all these triggers throughout the entire season (in a year with frequent rainfall events) led to a high frequency of gas sampling and consequently high costs of labour, transport and sample analysis.

To avoid excessive costs in following years, the sampling protocol was restricted to a maximum of 6 sampling events at each site, with 4 sampling days after each event. We concentrated on irrigation events at the start of the season and those where in-crop N application occurred, as the results from 2014-15 showed that emissions activity outside these events was minimal. However, to ensure we still covered the whole season we also installed semi-auto chamber sampling units at each site and programmed them to collect samples 2–3 times a week every week. This proved invaluable for capturing emissions caused by heavy rainfall events that occurred after our manual sampling quota was exhausted. Unfortunately, these semi-auto chamber systems were technically unreliable, and we struggled to keep them operating continuously with frequent breakdowns occurring and many sampling times missed. While the supplier of these systems (QUT) did their best to provide assistance to us and our contractors (and farmers), the

frequent faulting caused many hours of unanticipated labour to be spent in their maintenance. Despite back-to-base system maintenance, testing, updating and training by QUT before the 2016-17 season commenced, the reliability issues continued to plague their operation in the field. The systems were withdrawn from use in late November 2016 to save funds.

There were resourcing difficulties with regards the high turnover of CottonInfo staff in the regions where our trials were, especially Gunnedah. The original proposal aimed to have CottonInfo staff helping to run these trials and collect samples. This only worked at Moree and only in the year that we focused on N rate treatments, as the CottonInfo trial focus differed from ours in other years. We also had difficulty finding suitable contractors available to collect samples and monitor the trials at Moree, as the work was infrequent and often coincided with either weekends, holidays or other part-time jobs the contractors already had. A shortage of irrigation water allocation leading into the 2016-17 cotton season at Moree meant that we were unable to consider trials at Moree in that season.

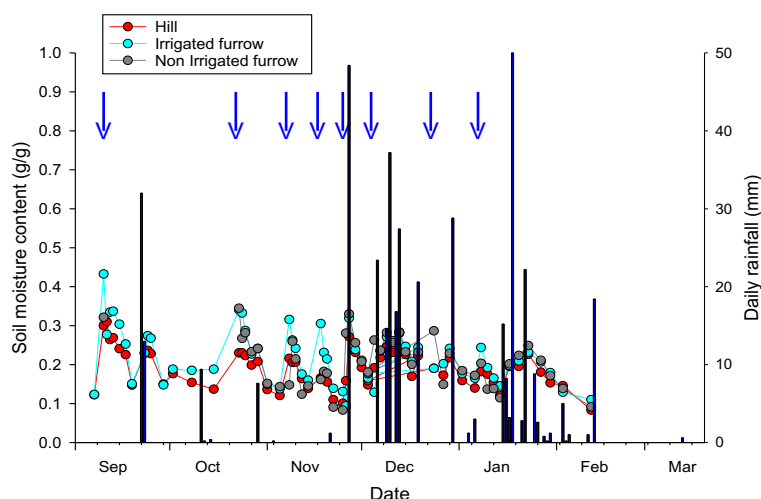
We are extremely grateful for the assistance of Incitec Pivot Fertilisers Ltd for supplying the necessary equipment, knowledge and time required to apply nitrification inhibitors with anhydrous ammonia application – no easy task. They also supplied the N-Sure inhibitor product and ENTEC-urea for the side-dressing at Emerald free of charge. Without their help these treatments would not have been possible. Dow Agrosiences provided the N-serve product free of charge. We are also grateful for patience of the farmers involved for the additional time of them and their staff spent in helping to get this applicator system operational.

## 4.0 RESULTS AND DISCUSSION

### 4.1 2014–15 N fertiliser rate trials

#### 4.1.1 Emerald 2014–15

Results from the monitoring of soil moisture and rainfall during the growing season at the Emerald trial site are shown in Figure 1, along with arrows showing the dates of irrigation. This soil had a clay-loam texture (35–42% clay and 53–44% sand; from surface 0–30 cm down to subsoil 60–90 cm,) compared to the medium clay textured soils at the other sites. As a result, soil water contents were generally much lower in the surface soil at Emerald than at either Moree or Gunnedah.



**Figure 1.** Soil moisture in the surface 0–10 cm (circles) and daily rainfall (bars) at the Emerald trial site (2014-15). Arrows show the dates of irrigation.

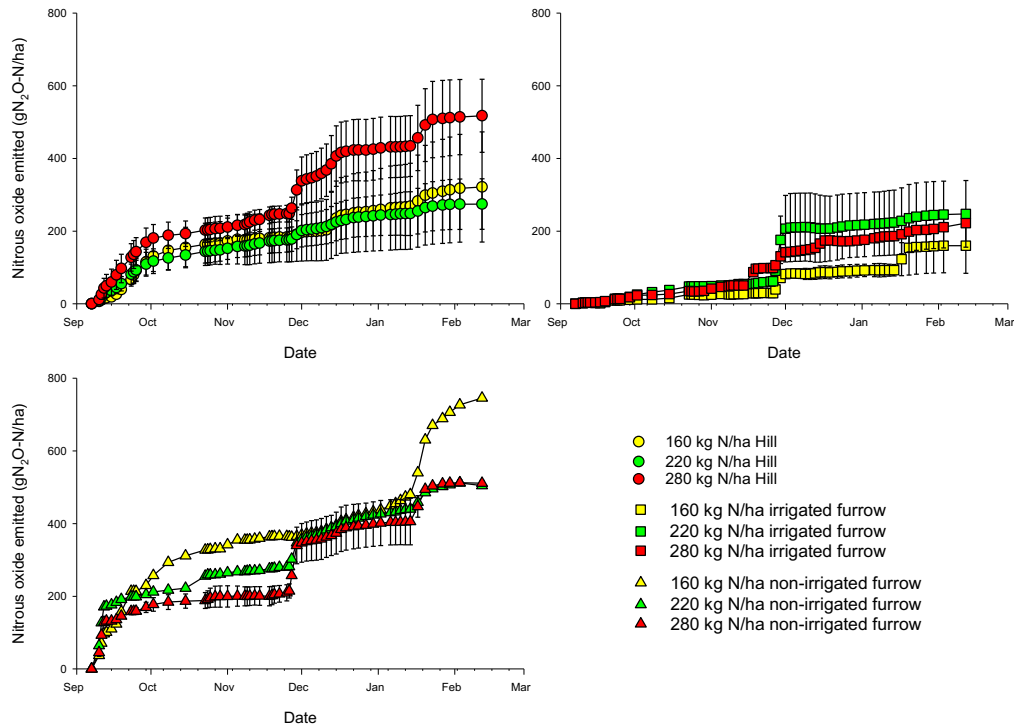
Figure 2 shows the cumulative nitrous oxide gas emitted from each of the 3 sampling positions within each of the three N-rate treatments. Gas sampling started after sowing, with the first irrigation leading to a rapid initial loss of nitrous oxide from the hill position and non-irrigated furrow positions, but not from the irrigated furrows. Rainfall later in September did not increase emissions much, suggesting that it was not sufficient to induce denitrification. There were two further distinct N loss events (late November and mid-January) coinciding with high rainfall events (>40 mm) occurring soon after irrigation events. The in-crop N had been added to the soil in early November to the 220 and 280 kg N/ha treatments, which explains why the increase in emissions in late November did not occur in the non-irrigated furrows of this treatment. Losses from the non-irrigated furrow appeared to be greatest from the lowest N rate treatment, but the error margins surrounding these treatment means were large (not shown). Overall, nitrous oxide losses during the measurement period were relatively small for the amount of N applied.

Using the proportional N losses from the different positions within each plot, we estimated the total nitrous oxide N lost from across whole plot area. This is only an estimate as the chambers used did not cover every possible position across the unit soil area, and no background emissions from unfertilised soil were measured. Losses were 407, 372, and 487 g N<sub>2</sub>O-N/ha which equated to 0.25%, 0.17%, and 0.17% of the 160, 220 and 280 kg N/ha applied treatments, respectively. These EFs are well below the current Australian EF for irrigated cotton of 0.55%.

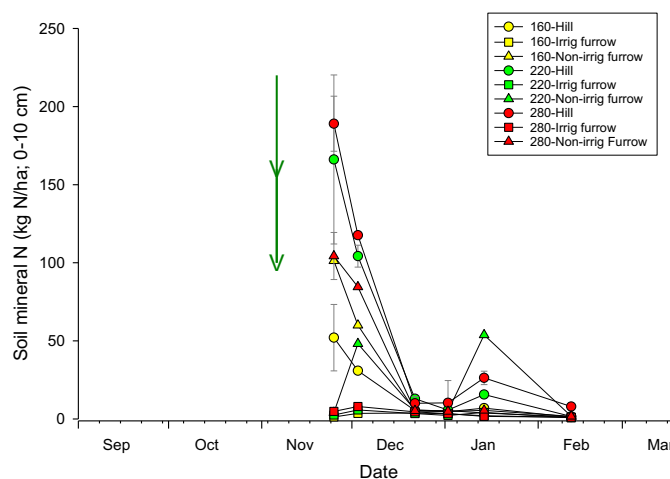
Figure 3 shows that the lowest mineral N was found in the irrigated furrow position, which helps explain why the nitrous oxide losses from this position were lower than in the other positions. The mineral N in the

hill position was initially higher than in the furrow positions and generally increasing in proportion to the rate of N applied. Mineral N declined in all treatments and positions over the season, although the rain in January appears to have temporarily increased the mineral N measured in the 0-10 cm depth. By the end of the season there was little mineral N remaining in the surface soil in any treatment. Mineral N in the soil profile to a depth of 90 cm after harvest averaged 40 kg N/ha, with no significant differences according to treatment or location (i.e. hill, irrigated or non-irrigated furrow).

Cotton lint yield averaged 10.7 bales/ha across the trial and was not significantly affected by N rate treatment.



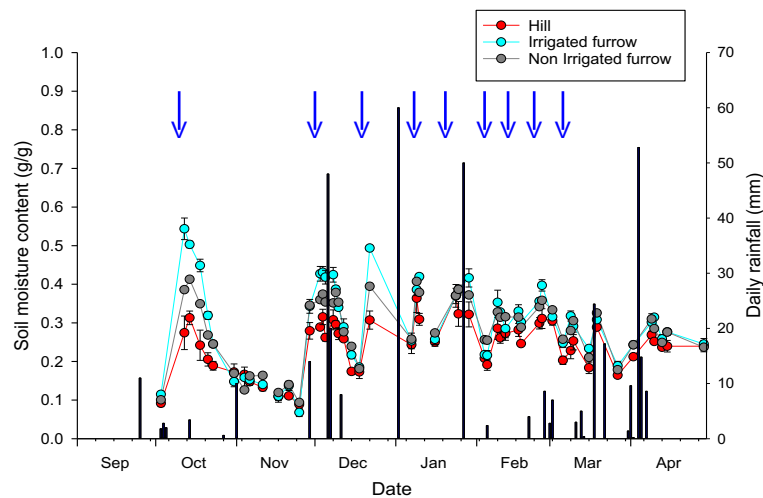
**Figure 2.** Cumulative nitrous oxide emissions from three sampling positions within the three N rate treatments at the Emerald trial site. Most data are means of 3 replicates  $\pm$  standard error, except the 160 and 220 non-irrigated furrow treatments which were not-replicated.



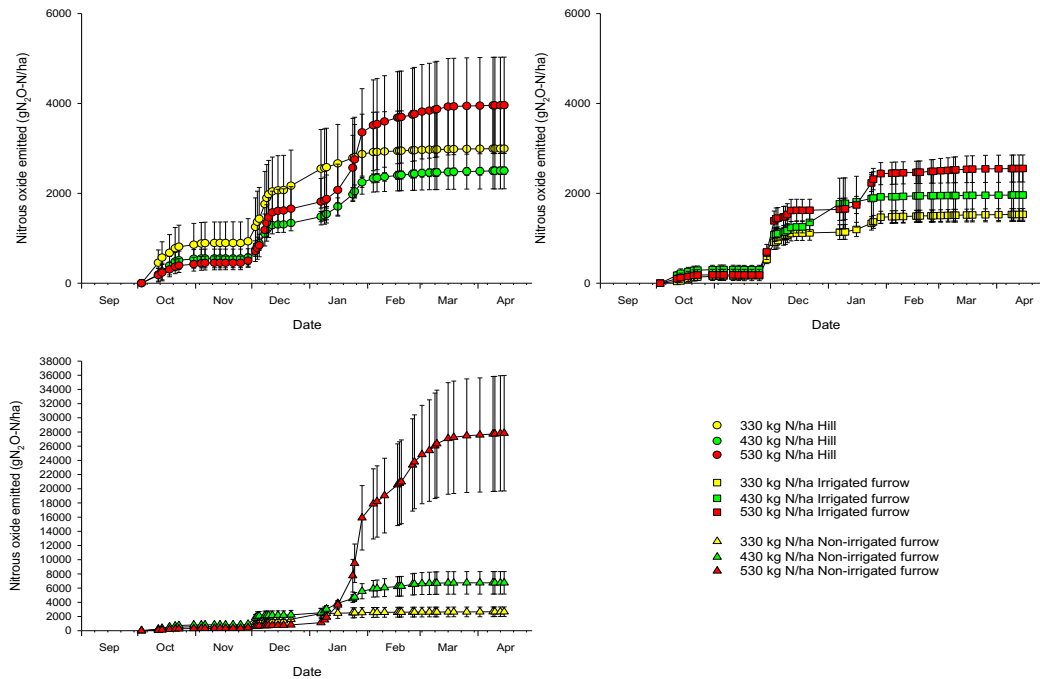
**Figure 3.** Mineral N in the surface soil (0-10 cm) at the Emerald trial. Arrows indicate in-crop N fertiliser application date. Data are means of 3 replicates  $\pm$  standard error.

#### 4.1.2 Moree 2014–15

At the Moree site, the soil had a heavy texture (50–52% clay, 27–23% sand) and showed a large range in soil moisture results (Figure 4), particularly in the period from mid-October to late November when it was very dry. Figure 5 shows that nitrous oxide emissions were moderate until late November (although equal to whole season losses from Emerald), after which irrigation and intense rainfall triggered an increased rate of loss. However, the application of in-season N fertiliser (see Figure 6), combined with irrigation and followed by a >50 mm rainfall event in early January, combined to greatly increase the rate of nitrous oxide emissions, especially from the non-irrigated furrow where UAN was applied in the 430 and 530 kg N/ha treatments. Emissions from the non-irrigated furrow of the 530 kg N/ha treatment continued at a high rate until February, resulting in very high nitrous oxide loss from this position of this treatment.



**Figure 4.** Soil moisture (circles) and daily rainfall (bars) at the Moree trial site (2014-15). Arrows show the dates of irrigation.

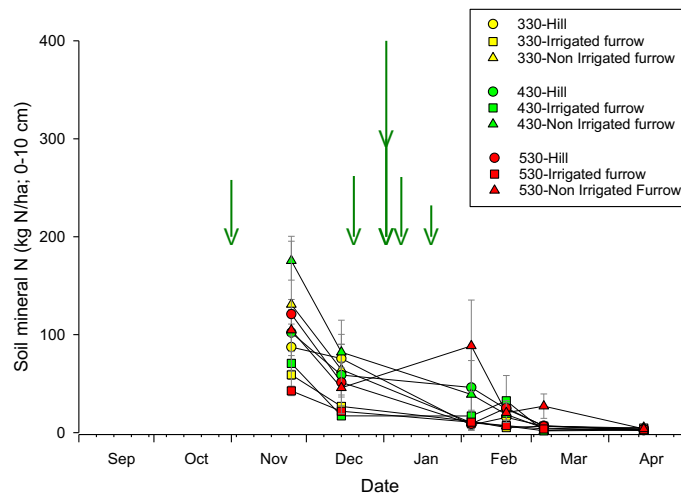


**Figure 5.** Cumulative nitrous oxide emissions from three sampling positions within the three N rate treatments at the Moree trial site. Data are means of 3 replicates  $\pm$  standard error.

Using the proportional N losses from the different positions within each plot, I estimated the total nitrous oxide N lost from across each plot area. Again, this is only an estimate as the chambers used did not cover every possible position across the unit soil area. Losses were 2.67, 3.47 and 9.28 kg N<sub>2</sub>O-N/ha, which gave EF's of 0.81%, 0.81%, and 1.75% for the 330, 403 and 530 kg N/ha treatments, respectively. These estimated EF's for the Moree site exceeded the Australian default EF for irrigated cotton in all three N rate treatments, with the top N rate showing that when N applied is greatly in excess of that required, emission losses increase exponentially.

As with Emerald, the lowest soil mineral N at the Moree site was found in the irrigated furrow position, which again explains why the nitrous oxide losses from this position were lower than in the other positions (Figure 6). However, at the Moree site, the mineral N in the irrigated furrows was quite high compared to that seen at the other trial sites. Mineral N declined in all treatments and positions over the season, although the in-season N applications did lead to more N in the soil later in the season. By the end of the season there was only 23 kg N/ha remaining in the soil to 90 cm depth with no effect of either N fertiliser rate or location.

All three N rate treatments gave essentially the same cotton yield results, 13.2 bales/ha. Therefore, applying an additional 200 kg N/ha above the lowest N rate did not benefit productivity.



**Figure 6.** Mineral N in the surface soil (0-10 cm) at the Moree trial. Arrows indicate in-crop N fertiliser application dates. Data are means of 3 replicates  $\pm$  standard error.

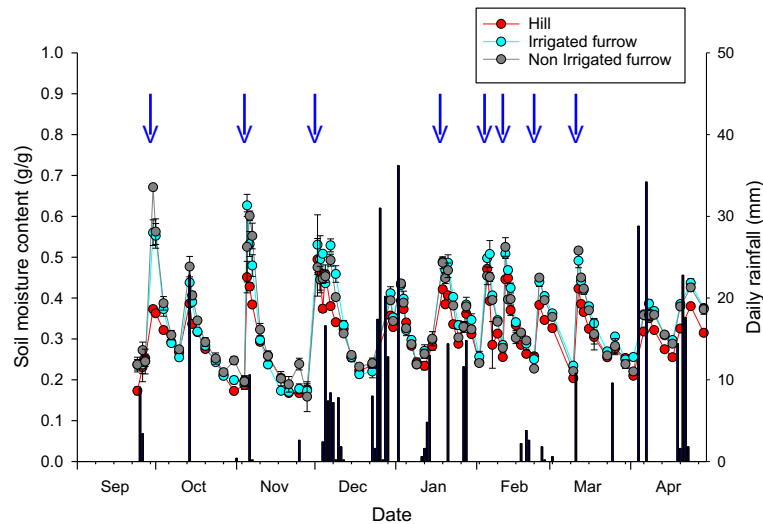
#### 4.1.3 Gunnedah 2014–15

The soil at the Gunnedah trial site (54–64% clay, 10–8% sand) had a higher clay content than Emerald, hence the range in soil moistures (Figure 7) was greater than at the Emerald site (Figure 1). Figure 7 clearly shows the impact of rainfall and irrigation on the surface soil moisture content, with samples from the furrows saturated for several days after watering.

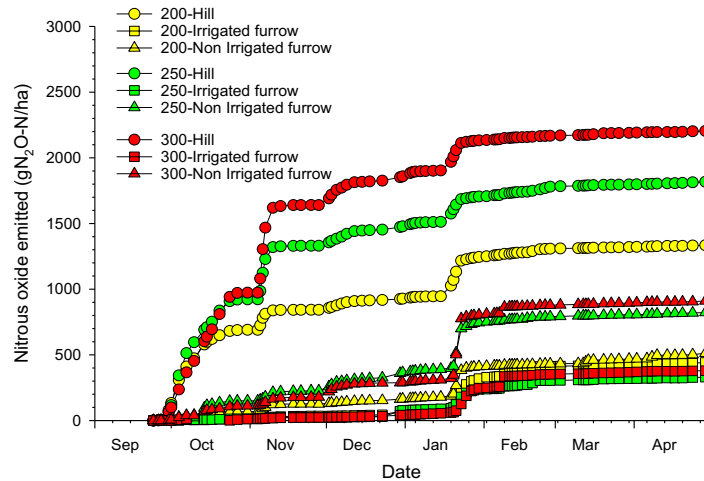
The scale of nitrous oxide losses was greater at Gunnedah (Figure 8) compared to Emerald, but less than at Moree. At the Gunnedah site, the nitrous oxide losses tended to be in proportion to the differences in N rates as the N-rate differences were established in the pre-plant N application, rather than through differences in in-crop application as was the case at the other two sites. The greatest rate of nitrous oxide loss occurred from the hill position – where the fertiliser had been pre-applied. The next highest flux

occurred after irrigation in early November. Despite heavy December rainfall, the nitrous oxide losses were small until after the in-crop N application in mid-January. There were few losses after January 2015, despite further watering and rainfall events. More nitrous oxide was emitted from the non-irrigated furrows than the irrigated furrows.

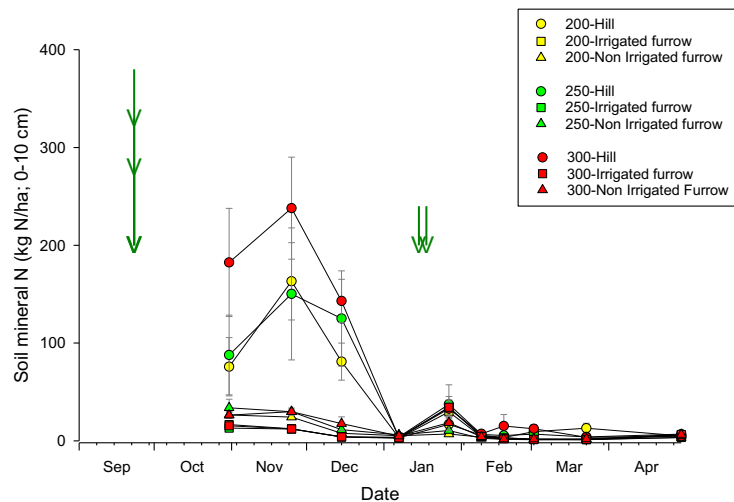
The estimated paddock-scale nitrous oxide losses from the Gunnedah site were 0.74, 0.97, and 1.13 kg N<sub>2</sub>O-N/ha, which, as a proportion of the amount of N fertiliser applied (Emission Factor = EF) was 0.37%, 0.39% and 0.38% for the 160, 210, and 260 kg N/ha treatments, respectively. These EFs were essentially the below the Australian EF figure for irrigated cotton (0.55%) and showed no variation with N-rate.



**Figure 7.** Soil moisture (circles) and daily rainfall (bars) at the Gunnedah trial site (2014-15). Arrows show the dates of irrigation.



**Figure 8.** Cumulative nitrous oxide emissions from three sampling positions within the three N rate treatments at the Gunnedah trial site.



**Figure 9.** Mineral N in the surface soil (0-10 cm) at the Gunnedah trial. Arrows indicate N fertiliser application dates.

Lint yield across the trial averaged 13.0 bales/ha with no significant treatment effect of N fertiliser rate.

Soil mineral N, measured approximately monthly in the surface soil of each trial, showed large concentrations of mineral N in the fertilised hill position until January when little remained in the surface soil (Figure 9). After in-crop N applications in mid-January mineral N increased slightly but was back to baseline by February. As with the other sites, the lowest mineral N was typically found in the irrigated furrow position. By the end of the season there was little mineral N remaining in the surface soil at any of the chamber locations, and just 30 kg N/ha to 90 cm depth, averaged across the site.

#### 4.1.4 Conclusions from the 2014–15 N-rate trials

The intensive sampling of gas emissions from the three N-rate trials showed that, despite receiving 8–9 irrigations as well as several intense rainfall events in a season, there were typically only 3–4 significant nitrous oxide flux periods during the season – a finding we used to better target sampling in the following trial years.

In the 2014-15 trials, gas sampling began just after sowing with the first noticeable fluxes occurring in conjunction with the irrigation applied soon after planting (in later years gas sampling began after the pre-plant N application in order to capture any losses occurring in response to rainfall events before sowing).

At Moree and Gunnedah, the second irrigation also led to increased nitrous oxide emissions, which had effectively ceased as the soil dried down after the initial irrigation. Further significant emissions events occurred mostly in response to the addition of in-crop N fertiliser followed by irrigation and/or intense rainfall. This was especially the case at Moree, where the spray application of UAN onto the soil surface of the non-irrigated furrows followed by irrigation and 60 mm rain led to spectacularly high nitrous oxide losses in the 430 and 530 kg N/ha treatments. These losses continued at a high rate for nearly 2 months and resulted in a proportional nitrous oxide loss well above the Australian default of 0.55%.

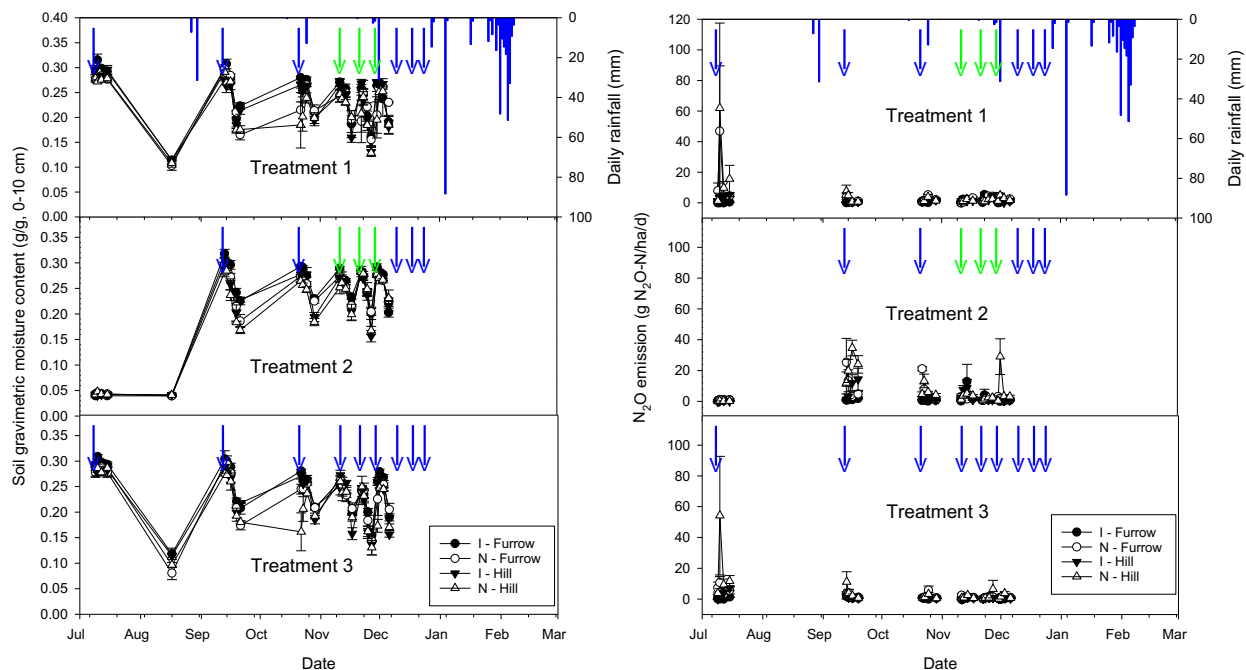
Previous research elsewhere has concluded that N fertiliser applied at rates in excess of crop requirements will lead to exponential increases in nitrous oxide emitted (and therefore an increase in EF). However, we only saw this occurring at Moree when the in-crop N was followed by a long period of wet soil conditions. N rates were clearly in excess of crop requirements at all three trial sites as there was no yield response to

increasing N rate at any of the three trials. Therefore, the farmer’s chosen N rate at all sites was at least 25% higher than necessary to achieve the same lint yield in that year of cropping at those sites, i.e. between 50 and 100 kg N/ha less N fertiliser could have been used to grow the same amount of cotton at those farms. At Moree and Gunnedah sites, use of the lower rate would have reduced the farm’s nitrous oxide emissions by 24–26%.

## 4.2 2015-16 N fertiliser timing and irrigation strategy trials

### 4.2.1 Emerald 2015–16

Figure 10 [left] shows the gravimetric soil water content measurements of the three treatments as recorded during manual gas sampling and soil mineral N sampling. The most obvious difference was in July when treatments 1 and 3 were irrigated pre-plant while treatment 2 remained dry. By mid-August, the topsoil in treatments 1 and 3 had dried down again but not quite as dry as the un-watered soil in treatment 2. Following rainfall in September and the post-plant irrigation, soils in all treatments were wet, with the soil in treatment 2 (after the 24 hour irrigation time) found to be wetter after each irrigation than treatments 1 and 3 with the 12 hour irrigation time. This difference in soil moisture was seen in all measurement positions and in most cases lasted for the week-long duration of post-irrigation measurements. Interestingly, at the third irrigation, there was a clear difference in soil water contents in the non-irrigated hill position of treatments 1 and 3 versus treatment 2, with the 12-hour watered treatments (1, 3) initially much drier than in treatment 2 for the first two days after irrigation.

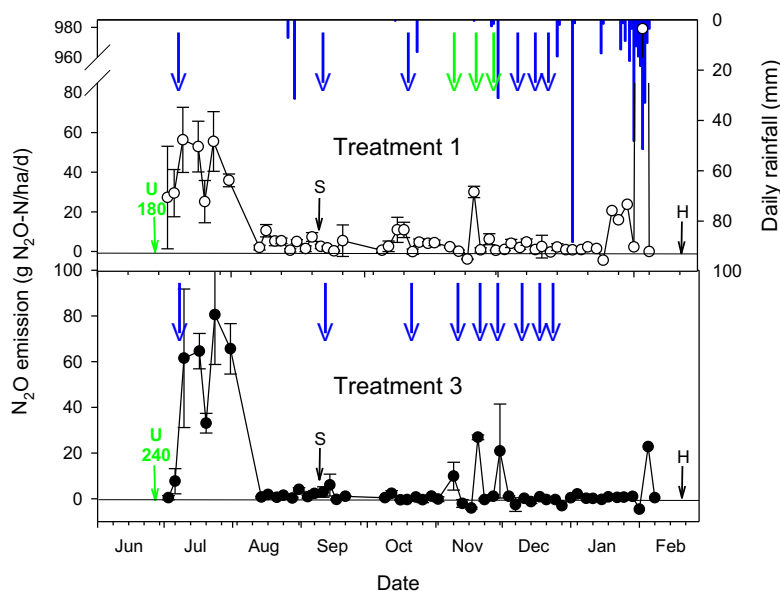


**Figure 10.** Soil gravimetric water content (0-10 cm) [left] and daily nitrous oxide emission rate [right] at four positions within each of the three treatments at the 2015-16 Emerald trial. Daily rainfall is indicated in the top graphs, and the dates of irrigation are indicated for each treatment by the downward arrows. Blue arrows are water-only irrigations, while green arrows indicate water-run UAN in the irrigation. Data are means of 3 replicates  $\pm$  standard error.

Figure 10 [right] shows the daily nitrous oxide emissions measured using manual chambers throughout 6 post-irrigation sampling events. The influence of the initial pre-crop irrigation in July is clearly noticeable

with the largest daily emissions of the whole season measured 2 days after the initial irrigation in treatments 1 and 3. These high emissions were measured in the non-irrigated hill position (treatments 1 and 3), and in the non-irrigated furrow position for treatment 1 only. In contrast, there were negligible emissions measured from treatment 2 which was not irrigated after N application like the other two treatments were. However, treatment 2 did show high nitrous oxide emissions after the 1<sup>st</sup> post-sowing irrigation, with maximum loss rates occurring from the non-irrigated hill position, followed by the non-irrigated furrow and the irrigated hill positions. The emissions from treatments 1 and 3 at this time were smaller and only noticeable in the non-irrigated hill and furrow positions. Emissions after later irrigations were mostly small across all treatments although treatment 2 did show some impact of the first water-run UAN in irrigation #4, but little after this except for a spike in emissions from the non-irrigated hill position on day 2 after irrigation #6 in response to 31 mm rainfall. Emissions from the irrigated furrows in all treatments were low across the whole season.

Results from the semi-automated chambers are shown in Figure 11. The system was set to sample twice a week from 4 chambers – two in T1 plots and two in T3 plots. Technical issues with the equipment meant that not all planned samples were collected, as is seen in the data gaps during August and September. For the last month of measurements there was only one replicate from each treatment measured.



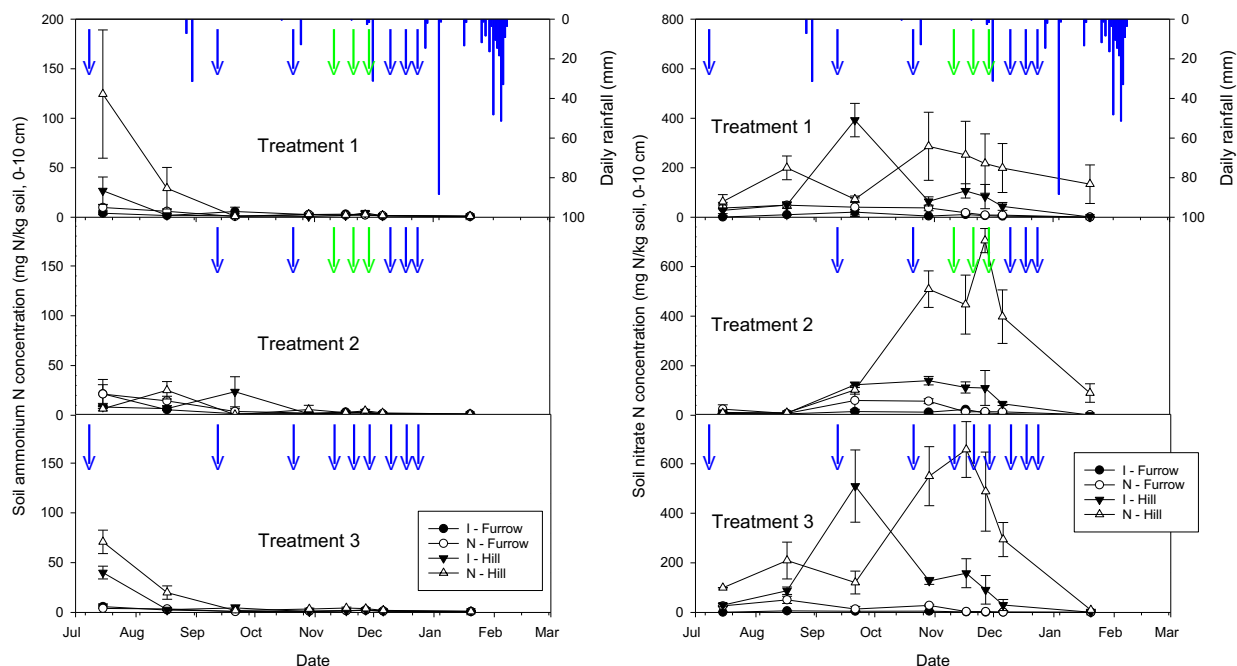
**Figure 11.** Nitrous oxide emissions measured at Emerald 2015-16 using the semi-automated chambers in T1 and T3 only. Data are means of two replicates  $\pm$  standard error. Blue arrows indicate irrigation dates. Green arrows indicate N application dates. Sowing (S) and harvest (H) are indicated with black arrows. Daily rainfall is indicated by the blue bars in the top graph only.

The data show an initial period of high  $N_2O$  emissions during July in response to the first (pre-plant) irrigation. The magnitude of the  $N_2O$  flux is similar to that measured in the non-irrigated hill position with the manual chambers in the week after the first irrigation. The automated chambers were larger than the manual chambers and covered the whole hill width. The manual chamber data indicated that the  $N_2O$  emission event had subsided significantly by the end of the week after the irrigation, whereas the auto chamber data suggests that the event continued and even increased after an initial decline in flux. The large variation in the data from the two replicates means that there were no statistically significant treatment differences in daily  $N_2O$  flux on any sampling date.

After the initial irrigation, there were only small responses in N<sub>2</sub>O flux resulting from most irrigation events, with the exception being irrigation 5, which was the second irrigation event where UAN was applied in the water in T1 (no UAN applied in T3). The response here may indicate temporary waterlogging not seen after other irrigations. The heavy rainfall event near the end of the season produced an extremely high N<sub>2</sub>O flux in T1 (979 g N<sub>2</sub>O-N/ha/d), but only a small response in T3. Without the end-of-season spike in emissions, all chambers recorded a total cumulative N<sub>2</sub>O-N emission of 2.4 kg/ha, with no significant treatment difference owing to the large variation typical of N<sub>2</sub>O measurements. This suggests an emission factor (EF) of 1%, although the actual EF requires subtraction of N<sub>2</sub>O emitted from an unfertilised background soil, which we did not have.

Mineral N concentration in the surface soil (0-10 cm) at the Emerald site is shown in Figure 12 with ammonium on the left and nitrate on the right. The results presented are concentrations in specific sampling locations, so the very high results are indicative of samples collected directly on top of fertiliser application bands. It should be remembered that these bands represent only a small area of the overall paddock, but these small areas are likely the “hot-spot” for nitrous oxide emissions from the paddock. Note the difference in scaling of concentrations between the ammonium and nitrate graphs. Mineral N sampling was conducted at the end of each 7-day post-irrigation gas emissions period.

Ammonium N was high after the initial pre-plant irrigation in treatments 1 and 3. This is because the pre-applied urea was rapidly hydrolysed in the soil, more so in the non-irrigated hill position than the irrigated hill position. Very little ammonium was detected in either furrow type at any time during the season. Since treatment 2 was not irrigated pre-plant, the conversion of urea to ammonium was inhibited by the dry, cool conditions.



**Figure 12.** Soil ammonium N concentration [left] and soil nitrate N concentration [right] (0-10 cm) at four positions within each treatment at the Emerald AOTG-Cotton trial 2015-16. Daily rainfall is indicated in the top graph, and the timing of irrigation events is indicated for each treatment by the downward arrows. Blue arrows are water-only irrigations, while green arrows indicate irrigation water-run UAN.

Soil nitrate [Figure 2, right] concentrations were much more dynamic, showing distinct treatment-induced patterns of nitrate accumulation in the topsoil, mostly in the two hill positions. Treatments 1 and 3, with

pre-plant irrigation, had an early build-up of soil nitrate, particularly in the non-irrigated hill position. Treatment 2, which remained largely dry between N application until just before planting, showed minimal accumulation of nitrate until after the 2<sup>nd</sup> post-plant irrigation when the nitrate continued to accumulate to high levels in the non-irrigated hill position, especially after the water-run UAN was applied. Interestingly, treatment 1 did not show any nitrate accumulation in response to the water-run N irrigations. Both treatments 1 and 3 showed a large initial accumulation of nitrate N in the irrigated hill position after the first post-plant irrigation, but after this time nitrate was generally low, possibly due to lateral movement from the irrigated hill position across to the non-irrigated hill position during subsequent irrigations. There were still significant concentrations of nitrate N in the non-irrigated hill positions of treatments 1 and 2 at the latest soil sampling in January, but none left in the soil under treatment 3.

Results of the hand cut biomass assessment (Table 2) showed no treatment differences in plant population, boll numbers, dry matter or dry matter N content. However, there was a significant effect of sampling location on the N content with lower %N in samples collected from the middle section of the long plots. Likewise, there was no treatment difference on the hand-pick lint yield, lint N content, or seed N content. Similar to biomass N concentration, seed N from samples of all treatments was found to be significantly lower in the samples collected from the central part of the long plots.

**Table 2.** Results of the biomass hand-cuts (at 20% open bolls) and lint hand-pick (immediately prior to commercial picking) sampling of the Emerald trial plots

Measure	Treatment			Significant difference?	Least significant Difference
	T1	T2	T3		
<i>Biomass hand-cut results</i>					
Population (plants/ha)	73,300	72,200	77,800	no	n/a
Boll number (bolls/m <sup>2</sup> )	136	124	144	no	n/a
Plant dry matter (t/ha)	17.7	15.1	18.0	no	n/a
Dry matter N (kg N/ha)	242	200	248	no*	n/a
<i>Hand-pick results</i>					
Lint yield (kg/ha)	2820	2610	2470	no	n/a
Lint N (kg N/ha)	5.2	5.0	4.5	no	n/a
Seed N (kg N/ha)	163	151	135	no**	n/a

\* there was a significant effect of sample location on the N concentration in the biomass, with samples from the mid-field location significantly lower in N (1.32%) than either head-ditch-end (1.43%) or tail-drain end (1.48%) samples in all three treatments. This difference in %N translated to a difference in dry matter N according to location in the field. There was no significant effect of sample location on dry matter yield.

\*\* seed N showed a significant effect of sample location with the lowest seed N found in the mid-field position compared to the samples collected near to either end.

However, the Emerald trial did produce some clear treatment differences in commercially harvested lint yield and quality (Table 3). While the lint yield was down on expectations due to the heavy rainfall prior to picking, over 10 bales/ha was still achieved across the trial site. The yield from T2 was significantly less than either T1 or T3 which were statistically similar. Lint colour, strength and length were not affected by treatment, but uniformity and micronaire were, with T2 scoring lower than T1 for both measures and lower than T3 for micronaire.

**Table 3.** Yield and quality results of the commercial picking and ginning of the Emerald trial plots

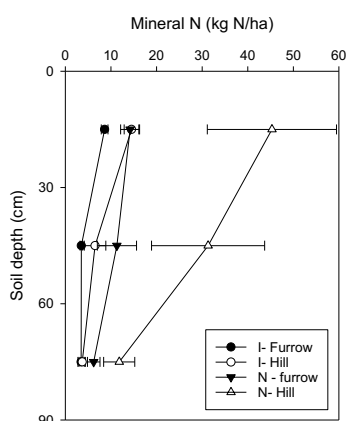
Measure	Treatment			Significant difference?	Least significant Difference
	T1	T2	T3		
Bales/ha	11.0	10.1	11.0	Yes	0.5
Colour	41.0	40.6	41.0	No	n/a
Strength	27.7	27.7	27.9	No	n/a
Length	1.2	1.2	1.2	No	n/a
Uniformity	81.76	81.46	81.55	Yes	0.25
Micronaire	4.70	4.57	4.70	Yes	0.03

The influence of treatment on crop growth can be seen in the Google-Earth satellite image (Figure 13) where T2 plots showed up as a paler shade of green compared to the T1 and T3 plots either side of them.



**Figure 13.** A satellite photo of the cotton trial at Emerald (27/11/2015). The three lighter coloured horizontal strips are the three replicated plots of T2. The vertical line near the left-hand edge of the paddock is the manual gas sampling transect with boards allowing access across the rows.

The soil at each of the 36 manual chamber locations (4 locations per plot x 3 treatments x 3 replicates) was sampled to 90 cm soon after picking to assess whether there was any residual effects of the N fertiliser or water application practices on soil mineral N. There was no treatment effect on soil mineral N results. However, there was a significant effect of location within the plot on soil mineral N (Figure 14) with more mineral N found at all depths in the non-irrigated hill position, regardless of treatment. The variation seen in sample results from this location is high because all three plots in the third replicate (i.e. plots 7,8 and 9) had very high nitrate results, regardless of N treatment. There was no difference in soil water content due to N treatment or sampling position.



**Figure 14.** Mineral N (nitrate + ammonium) in the soil to 90 cm depth from all locations used for manual chamber sampling. Data are averaged across all 3 treatments as there was no significant treatment difference at any depth.

### *Conclusions from the Emerald results:*

It is likely that the larger post-plant irrigation in T2 compared to T1 and T3, as well as the longer irrigation times for subsequent irrigations, may have led to greater waterlogging in T2 with possible damage to plant roots and subsequently reduced plant root growth. Previous research at ACRI has shown that waterlogging early in crop growth has a greater influence on yield than later in the season, and that the effect on yield was associated with reductions in final boll number. In our trial there was no significant treatment effect on boll number in the assessment made at maximum biomass, despite an apparent trend in the treatment averages (Table 2).

The light-green colouring of the T2 plots seen in the satellite image (Figure 13) tends to suggest that the plants in these plots were N deficient, presumably as a result of greater N losses, since all three treatments received the same rate of N applied in total. Losses of N in T2 via nitrate denitrification were likely greater after the first post-plant irrigation as shown by the greater N<sub>2</sub>O emissions and lower soil nitrate in T2. The fact that the first two of the three in-crop N applications were not able to “green up” the cotton in T2 either suggests that the deficiency may have been established earlier on in the season (i.e. after the first irrigation) or that the longer watering times used in each irrigation of T2 were leading to greater waterlogging at each irrigation, as indicated by greater N<sub>2</sub>O emissions after these irrigations in T2 compared with T3 (manual chamber data).

Waterlogging or not, all plots in the trial showed higher concentrations of mineral N (as nitrate) in the non-irrigated hill position (Figure 14), and not just at the surface. All three sample depths to 90 cm were significantly higher in nitrate compared to the irrigated side of the hill or either furrow position, indicating downward leaching of the nitrate N during the season. This data agrees with the 0-10 cm mineral N results (Figure 12), which showed high nitrate N concentrations in the non-irrigated hill position even at the last sampling in T1 and T2, while in T3 the nitrate was minimal. In all three treatments the nitrate in the non-irrigated hill position was initially low then increased mid-season, indicating nitrate had moved out from the irrigated hill position. The end-of-season soil sampling to 90 cm depth showed that this movement was not only sideways but also down the soil profile. Ultimately this nitrate N was excess to the cotton crop’s requirements and will remain in the soil until it is either taken up by a following crop, leached further down as the profile refills with moisture, or denitrified in later waterlogging events.

In a productivity comparison between T1 (current farm practice) and T2 (previous farm practice), the current practice has clearly led to an improvement over the previous, at least in terms of water management. In terms of N management, T1, with the split N application regime, showed no agronomic benefit over T3 where all N fertiliser was applied pre-plant.

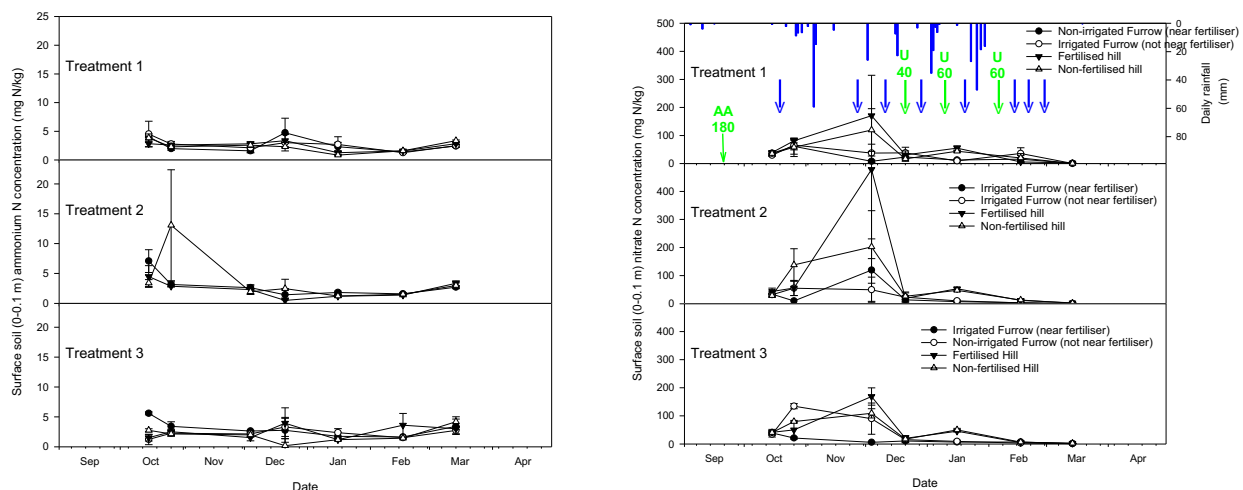
Detailed N<sub>2</sub>O emissions patterns showed a peak within a few days of the first irrigation in each treatment, which was typically higher in the non-irrigated hill position of each treatment and non-irrigated furrows of T2. The semi-auto chamber data indicated that the initial “burst” of higher emissions activity after the first irrigation continued for several weeks after the 1 week measuring period used for the manual chamber measurements. In terms of best practice for N<sub>2</sub>O emissions reduction, T1 and T3 were equivalent as the high variability meant we were unable to statistically differentiate between emissions from these treatments. We have no auto chamber data for T2, but the manual chamber data indicated that it was probably similar to the other treatments when considered in terms of the season as a whole.

#### 4.2.2 Moree 2015–16

Prior to the commencement of the trial, we found a total of 172 kg N/ha in the hill positions and 139 kg N/ha in the furrows, averaged across samples taken in from the head-ditch, tail-drain and across the middle of the paddock. Two thirds of this mineral N was found below 60 cm depth, with 38% of the N in the profile found below 90 cm. The site therefore was not ideal for N-fertiliser responses but it still had potential for irrigation management treatments to impact on nitrous oxide losses. So, the trial treatments at the Moree site were focussed on variations in the method of applying the irrigation water, as all plots had the same rate of N fertiliser applied at the same time throughout the season.

Surface soil (0-10 cm) sampling during the season showed little impact of treatment or sampling position on the concentration of ammonium N (Figure 15-left). However, there were very large and highly variable concentrations of nitrate N found in the hill positions until mid-December (Figure 15-right). During January, soil nitrate increased in the hill positions before declining again in February down to low levels by March. The increasing concentrations in the hills through the season indicates upward movement of nitrate during irrigation events from the pre-plant N fertiliser bands. Nitrate in the irrigated furrow position remained comparatively low in T3 despite this furrow having the pre-plant N bands along its sides and the in-crop N applied. In this treatment, nitrate was much more concentrated in the non-irrigated furrow after the initial irrigation, indicating significant through-hill movement of nitrate away from the irrigated furrow. In T2, every furrow was irrigated, but there was more nitrate found in the furrow nearest the pre-plant fertiliser in December. Therefore, irrigating every furrow led to less sideways movement of nitrate across the hill, with more concentrating in the hill itself and also a large amount accumulating during December in the furrow nearest the pre-plant N fertiliser.

At the conclusion of the season, deep soil core sampling to 90 cm found a total of 30 kg N/ha across all treatments, with slightly more found under the irrigated furrow position than the non-irrigated furrow or the hill positions. Treatment 3 had more nitrate N in the 30-60 cm zone than the other two treatments, with most found in the fertilised hill and irrigated furrow positions.



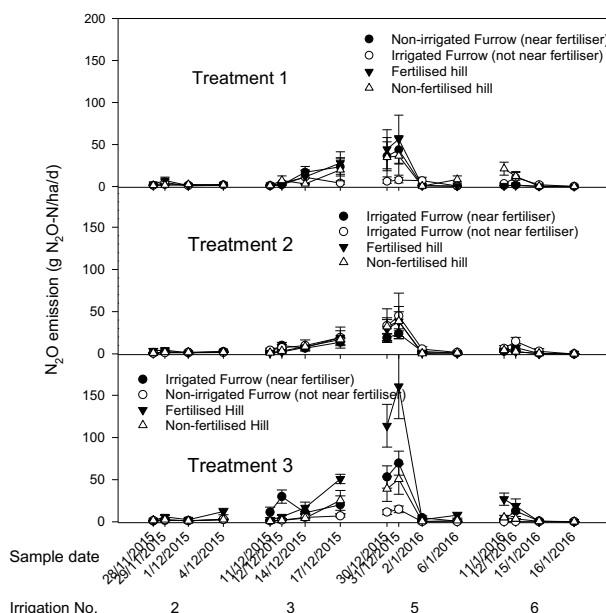
**Figure 15.** Soil ammonium N concentration [left] and soil nitrate N concentration [right] (0-10 cm) at four positions within each of the three treatments at the Moree AOTG-Cotton trial 2015-16. Rainfall and the timing of irrigations and water-run N application events is indicated by the downward arrows on the top graph. The total N application rate was the same for all 3 treatments.

Daily N<sub>2</sub>O fluxes were measured using manual chambers on five occasions—after irrigations 1, 2, 3, 5 and 6 (out of a total of 11 irrigations). Unfortunately, the gas samples collected in the week following the first irrigation event were somehow lost between the Moree post office and the laboratory. The results from the other four sampling events showed a variety of responses to different irrigation events and different treatments (Figure 16). There was very little emission response to the 2<sup>nd</sup> irrigation event in late November, despite there being large concentrations of nitrate in the soil at that time (Figure 15-right).

The 3<sup>rd</sup> sampling event (irrigation 3) showed initially low emissions after the irrigation ceased, but then an increase after 30 mm of rainfall during the latter part of the week of post-irrigation measurement.

The 4<sup>th</sup> sampling event (after irrigation 5) produced very high N<sub>2</sub>O fluxes for the first few days after the irrigation ceased, particularly in the fertilised hill position of T3. This irrigation event was water-only but closely followed irrigation 4 in which water-run urea had been applied. Emissions from the “*non-irrigated furrow not near the pre-plant fertiliser band*” were small compared to the “*irrigated furrow near the fertiliser band*”. Emissions were very high at most sampling positions in the other two treatments, although there were distinct differences in emissions according to position. In T1, N<sub>2</sub>O emissions remained low in the “*irrigated furrow not near the pre-plant fertiliser band*”, but was high in the “*non-irrigated furrow near the fertiliser band*”. In T2, all positions produced high N<sub>2</sub>O emissions, with the “*irrigated furrow not near the fertiliser band*” showing higher emissions than the “*irrigated furrow near to the fertiliser band*”, which followed the trend in soil nitrate concentrations seen in Figure 15-right.

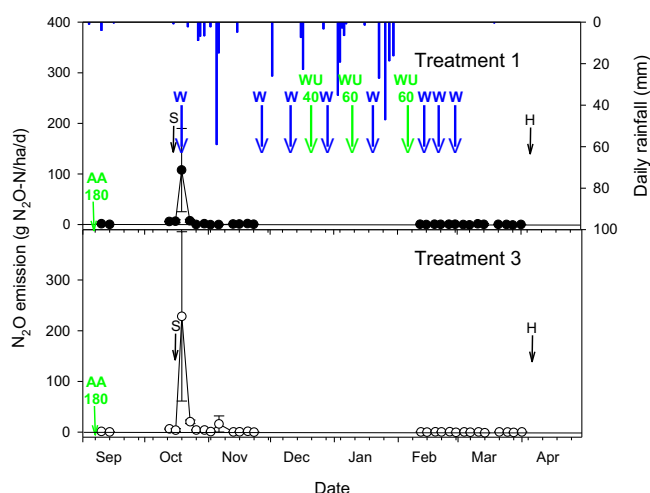
Emissions of N<sub>2</sub>O measured during the 5<sup>th</sup> manual sampling event in mid-January (after irrigation 6) were modest in comparison with the previous sampling, with most N<sub>2</sub>O loss occurring within the first two days after irrigation. This is despite the irrigation occurring just 5 days after a 74 mm rainfall event at the site. The “*irrigated furrow not near the pre-plant fertiliser band*” produced higher emissions in T1 and T2 than most other sampling locations, with least coming from the “*furrow nearest the fertiliser band*”. In T3 greatest emissions occurred in the “*fertilised hill*” position, as in the previous sampling event.



**Figure 16.** Daily nitrous oxide emission flux measured 4 times during the 7 days following specific irrigation events at the Moree AOTG-Cotton trial 2015-16. Chambers were located at four positions within each plot. Data are means of three replicate plots for each treatment.

The semi-auto sampling system at Moree was subject to numerous technical failures during the season and only successfully measured significant N<sub>2</sub>O emissions after the first irrigation (Figure 17). The emissions event at this time was short-lived, although the magnitude of the flux measured at this time was extremely high. Measurements from late in the season showed no impact of the last 3 irrigations on N<sub>2</sub>O emitted from the soil in either treatment.

There was no impact of water application treatment on plant population, boll number, dry matter, dry matter N content, lint yield (either hand-picked or machine picked), lint N content or seed N content (Tables 4 and 5). In conducting the hand cuts, we sampled in from both head-ditch and tail-drain ends, as well as in the mid-field area, with all samples tested individually. This sampling strategy showed up significant effects of sample location on total dry matter N content and plant N concentration, with plants more N-rich near the tail-drain end than the centre or the head-ditch end. Similarly, the N concentration of the lint was also higher at the tail drain end of the 960 m long plots.



**Figure 17.** Daily nitrous oxide emission rate within two treatments at the Moree AOTG-Cotton trial 2015-16. Daily rainfall is indicated in the top graph, and the timing of irrigation events is indicated for each treatment by the downward arrows. Blue arrows are water-only irrigations, while green arrows indicate water-run urea. Arrows labelled S and H indicate sowing and harvesting.

**Table 4.** Results of the biomass hand-cuts and lint hand-pick (immediately prior to commercial picking) sampling of the Moree trial plots

Measure	Treatment			Significant difference?	Least significant Difference
	T1	T2	T3		
<i>Biomass hand-cut results</i>					
Population (plants/ha)	95,520	92,660	95,520	no	n/a
Boll number (bolls/m <sup>2</sup> )	108	114	112	no	n/a
Plant dry matter (t/ha)	16.3	17.6	15.1	no	n/a
Dry matter N (kg N/ha)	215	212	195	no*	n/a
<i>Hand-pick results</i>					
Lint yield (kg/ha)	3092	3488	3236	no	n/a
Lint N (kg N/ha)	7.3	8.1	7.8	no**	n/a
Seed N (kg N/ha)	155	167	160	no	n/a

\*Dry matter N higher at tail drain end of plots as is %N (Head = 1.1%, Mid = 1.3%, Tail = 1.5%)

\*\*Lint N% was higher at tail drain end of plots (Head = 0.22%, Mid = 0.23%, Tail = 0.27%)

**Table 5.** Yield results of the commercial picking the Moree trial plots..

Measure	Treatment			Significant difference?	Least significant Difference
	T1	T2	T3		
Bales/ha	13.3	13.2	13.2	No	n/a
Colour	12.4	12.4	13.9	No	n/a
Strength	28.8	29.3	29.1	No	n/a
Length	1.2	1.2	1.2	No	n/a
Uniformity	79.9	80.3	79.7	No	n/a
Micronaire	4.29	4.31	4.32	No	n/a

#### *Conclusions from the Moree 2015–16 trial results:*

This site started the season with an average of 150 kg N/ha in the soil, had 180 kg N/ha added as anhydrous ammonia pre-plant, and another 160 kg N/ha added as water-run urea during the cropping season, thus giving the crop a potential 490 kg N/ha for growth. Of this, there was just 30 kg N/ha remaining in the soil post-harvest. Of the 460 kg N/ha used, we found 208 kg N/ha in the above-ground plant biomass and removed 169 kg N/ha in the harvested cotton (lint and seed). Apart from that removed in trash (leaf) or retained in plant stubble, much of the remainder is likely to have been lost through one or more N loss pathways. Our gas emissions measurements indicated some very high flux rates in response to several early irrigation events.

The experimental treatments examined here produced some clear indications that soil nitrate from pre-plant and water-run N applications can be highly mobile, both vertically within the soil profile and horizontally within the plant bed. The results we have are not as complete as planned, with the loss of the first-irrigation event samples a significant setback considering the large emissions indicated by the semi-auto sampler system at this time. Nevertheless, results from later irrigation events gave useful insight into the causes of variability in overall N<sub>2</sub>O emissions within a furrow-plant bed system. The alternative system trialled in T3 appeared to enhance rather than reduce N<sub>2</sub>O emissions, compared to the current practice (T1), while the system with every furrow irrigated (T2) produced results no better or worse than T1.

None of the treatments trialled at Moree affected the cotton yield results, which were below the grower's expectation for that field (as was the remainder of the crop in that field) and noticeably below those achieved in nearby paddocks of the same farm. Compared to the other two trial sites, Moree had a much lower boll number per hectare.

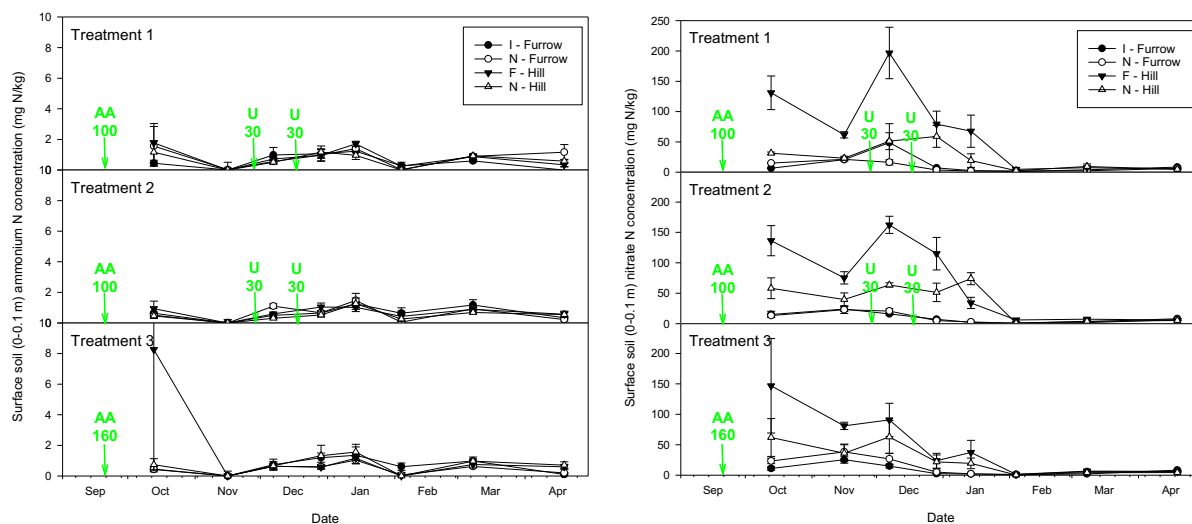
#### **4.2.3 Gunnedah 2015–16**

Soil ammonium N was negligible at all of the measurement occasions, with only one sample collected from the fertilised hill position in mid-October showing any residual NH<sub>4</sub> after the application of the pre-plant anhydrous ammonia (Figure 18-left).

The soil nitrate results were initially high in the fertilised hill position, with significant concentrations also seen in the non-fertilised hill position of T2 and T3 after the first irrigation in early October (Figure 18-right). This indicates sideways movement of nitrate across the bed, regardless of which side of the bed was irrigated. Nitrate concentration in the 0-10 cm of the fertilised hill position dropped substantially over the next month, but then increased again in T1 and T2 after the second irrigation with water-run urea. Through

December and January, nitrate concentrations declined until February when levels tested low at all sample positions for the remainder of the season. Nitrate in the non-irrigated position remained high until December (T1 and T3) or January (T2), then also declined as crop growth increased. Nitrate concentrations in the furrow positions were mostly low, except in the irrigated furrow of T1 during early December after the first water-run application.

There were no significant effects of either N treatment or sample location on the mineral N at any depth to 90 cm when sampled soon after harvest. There was an average of 34 kg N/ha remaining in the soil to 90 cm depth, with half of this found in the top 0-30 cm.



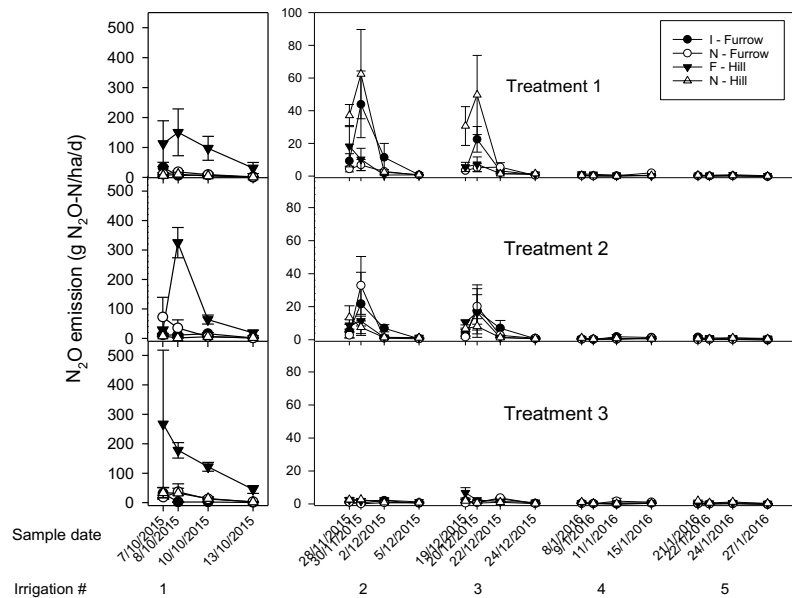
**Figure 18.** Soil ammonium N concentration [left] and soil nitrate N concentration [right] (0-10 cm) at four positions within each of the three treatments at the Gunnedah AOTG-Cotton trial 2015-16. The timing of N application events is indicated for each treatment by the green downward arrows.

The manual chamber results showed the influence of location within the plot on  $N_2O$  emitted (Figure 19). Highest emissions occurred following the first irrigation event, with one chamber in T3 recording a flux of 768 g  $N_2O$ -N/ha/d on the first day after irrigation. This and other high fluxes were measured in chambers located on the fertiliser band, while fluxes from the other positions were much lower and not significantly different. The high fluxes from the fertiliser band location decreased after 4 days, but, unlike the other chamber positions, had not reached the baseline emission level even after 7 days post-irrigation.

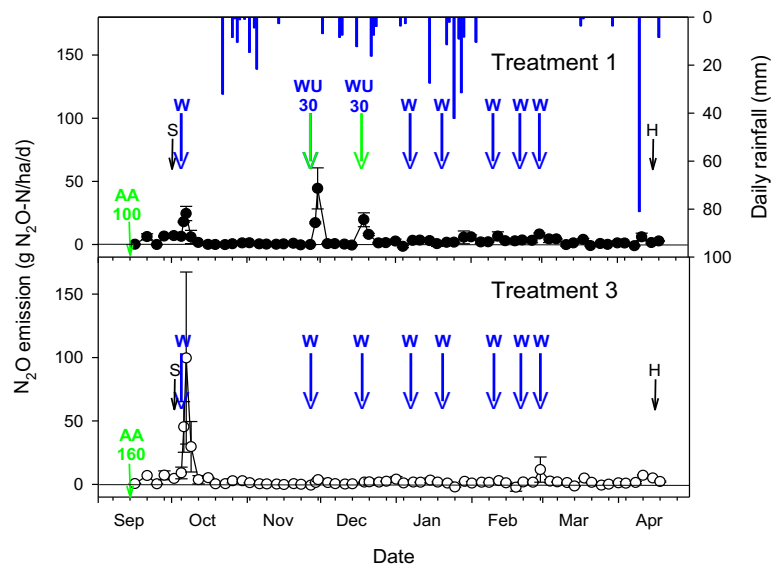
In T1 and T2, moderate  $N_2O$  emissions occurred in response to the water-run urea applied in irrigations 2 and 3. Highest fluxes in T1 were found in the non-fertilised hill position (next to the irrigated furrow). By contrast, fluxes in T2 were not affected by chamber position. There were negligible  $N_2O$  emissions in response to irrigations 4 and 5 (T1 and T2) and irrigations 2–5 for T3. Cumulative emissions across the 5 sampling occasions showed no significant difference between the three treatments, but the fertilised band position was clearly the greatest overall source of  $N_2O$  emitted.

Using the semi-auto chambers, regular measurements of  $N_2O$  emitted from the plant beds showed several distinct peaks of emission activity during the season (Figure 20), with most in response to the first 3 irrigations. Emissions during the remainder of the season were low to negligible. After the initial injection of anhydrous ammonia, the lack of rainfall kept  $N_2O$  emissions at low levels until directly after the first irrigation, when  $N_2O$  flux increased dramatically in both treatments. One of the two chambers in T3 recorded a peak emission of 167 g  $N_2O$ -N/ha/d two days after the irrigation ended.

Emissions quickly subsided in T1 but continued for an additional week in T3, which had more initial N applied. Emissions during the remainder of October and most of November were negligible, despite several rainfall events in this period. The application of additional N fertiliser to T1 as water-run urea in irrigations 2 and 3 water led to distinct peaks in N<sub>2</sub>O emission lasting for a week on each occasion. Irrigations 2 and 3 in T3 used water only and caused only a small short-lived increase in emissions. Further N<sub>2</sub>O emissions in response to either rainfall or irrigation water (irrigations 4–8) were low from both treatments, although emissions in one of the two chambers in T3 increased to 22 g N<sub>2</sub>O-N/ha/d after the final irrigation, double that recorded in either chamber of T1. There was no significant difference in cumulative N<sub>2</sub>O emissions between these treatments T1 and T3 (mean = 688 g N<sub>2</sub>O-N/ha) or N<sub>2</sub>O emission factor (mean EF = 0.43%).



**Figure 19.** Daily nitrous oxide emission flux measured 4 times during the 7 days following the first 5 irrigation events at the Gunnedah AOTG-Cotton trial 2015-16. Chambers were located at four positions within each plot. Data are means of three replicate plots for each treatment.



**Figure 20.** Daily nitrous oxide emission rate within two treatments at the Gunnedah AOTG-Cotton trial 2015-16. Daily rainfall is indicated in the top graph, and the timing of irrigation events is indicated for each treatment by the downward arrows. Blue arrows are water-only irrigations, while green arrows indicate water-run urea. Arrows labelled S and H indicate sowing and harvesting.

There was no statistical difference in plant population, boll number, biomass N (Table 6), or commercially-harvested lint yield or lint quality (Table 7) attributable to the trial treatments. There was a treatment effect on the maximum plant biomass (dry matter) with plants in T1 smaller than those in T3, and those of T2 in between the two. There was also a treatment effect on %N in the biomass, with T3 (1.39%) less than either T1 (1.57%) or T2 (1.50%) which were statistically similar.

Plant population and boll number were affected by the sampling location in the paddock, with more plants (and therefore bolls) per square meter found near the tail drain end of the plots, regardless of N treatment. Plant dry matter was less in the mid paddock samples than in either head or tail ends of the paddock. This also affected the dry matter N results.

**Table 6.** Results of the biomass hand-cuts and lint hand-pick (immediately prior to commercial picking) sampling of the Gunnedah trial plots. Hand-picked lint results are not yet available.

Measure	Treatment			Significant difference?	LSD
	T1	T2	T3		
<i>Biomass hand-cut results</i>					
Population (plants/ha)	118,900	126,700	124,400	No*	n/a
Boll number (bolls/m <sup>2</sup> )	147	158	151	No*	n/a
Plant dry matter (t/ha)	15.7	17.6	19.4	Yes**	3.1
Dry matter N (kg N/ha)	248	266	270	No**	n/a
<i>Hand-pick results</i>					
Lint yield (kg/ha)	3880	3800	3430	No**	n/a
Lint N (kg N/ha)	7.9	7.8	7.1	No**	n/a
Seed N (kg N/ha)	219	195	171	Yes**	35

\*Plant population was significantly higher in samples from the tail drain end of the plots, as was boll number.

\*\*Plant dry matter, dry matter N, lint yield, seed %N, seed N uptake and lint N were all significantly affected by sampling location, with results from mid-paddock lower than those from either the head ditch or tail drain ends of the paddock.

**Table 7.** Yield results of the commercial picking and ginning of the Gunnedah trial plots.

Measure	Treatment			Significant difference?	Least significant Difference
	T1	T2	T3		
Bales/ha	14.2	14.1	14.1	no	n/a
Colour	21.0	22.7	21.0	No	n/a
Strength	29.7	30.0	29.2	No	n/a
Length	1.2	1.2	1.2	No	n/a
Uniformity	80.8	81.1	81.2	No	n/a
Micronaire	4.7	4.7	4.6	No	n/a

### *Conclusions from the Gunnedah 2015–16 trial results:*

The current practice of applying the majority of fertiliser N pre-sowing, followed by several in-season applications as water-run urea, produces N<sub>2</sub>O emissions lasting up to a week in response to each N application/irrigation event. The low rainfall conditions of the 2015-16 season kept N<sub>2</sub>O losses to a minimum between irrigation events despite occasional rainfall and high concentrations of nitrate in the soil for the first 4 months of the growing season (Figure 18-right). The older practice of applying the whole season's N before sowing focussed N<sub>2</sub>O emissions on the first irrigation event, with little additional N<sub>2</sub>O lost during later irrigations. However, there was no significant difference between treatments in cumulative N<sub>2</sub>O emitted for the season. Further information on indirect N<sub>2</sub>O emissions from N-laden runoff water would be useful to better define the environmental impact of these alternatives.

Irrigating the furrows close to the fertiliser band rather than those on the other side of the hill from the fertiliser band increased the intensity of N<sub>2</sub>O released after the first irrigation, but there was no net difference in N<sub>2</sub>O emitted across the whole season. Following the water-run urea applications, N<sub>2</sub>O emissions were greater from the non-fertilised hill of T1 than T2, but were similar elsewhere. Overall, there was no net difference in total N<sub>2</sub>O emitted between the three treatments when losses for the five key irrigation measurement periods were combined.

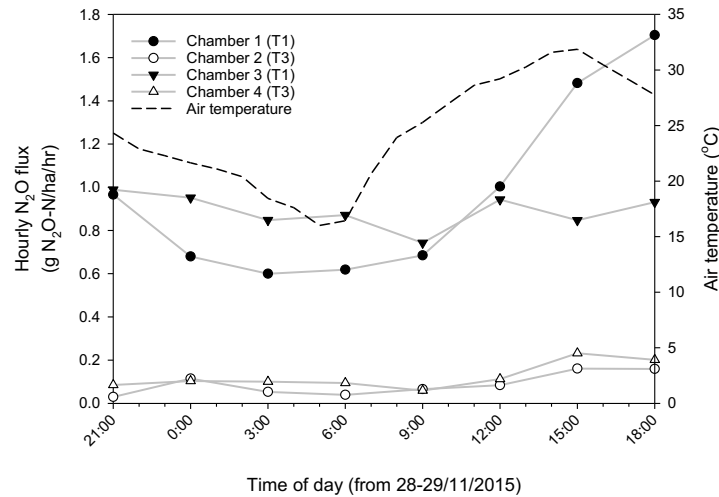
Agronomically, there were some differences in the amount of biomass produced and its N concentration, with the greater pre-plant N application producing a larger plant biomass with a lower %N content and lower seed N offtake. However, these changes did not translate into any measureable differences in harvested lint yield.

#### **4.2.4 Additional gas sampling exercises at Gunnedah**

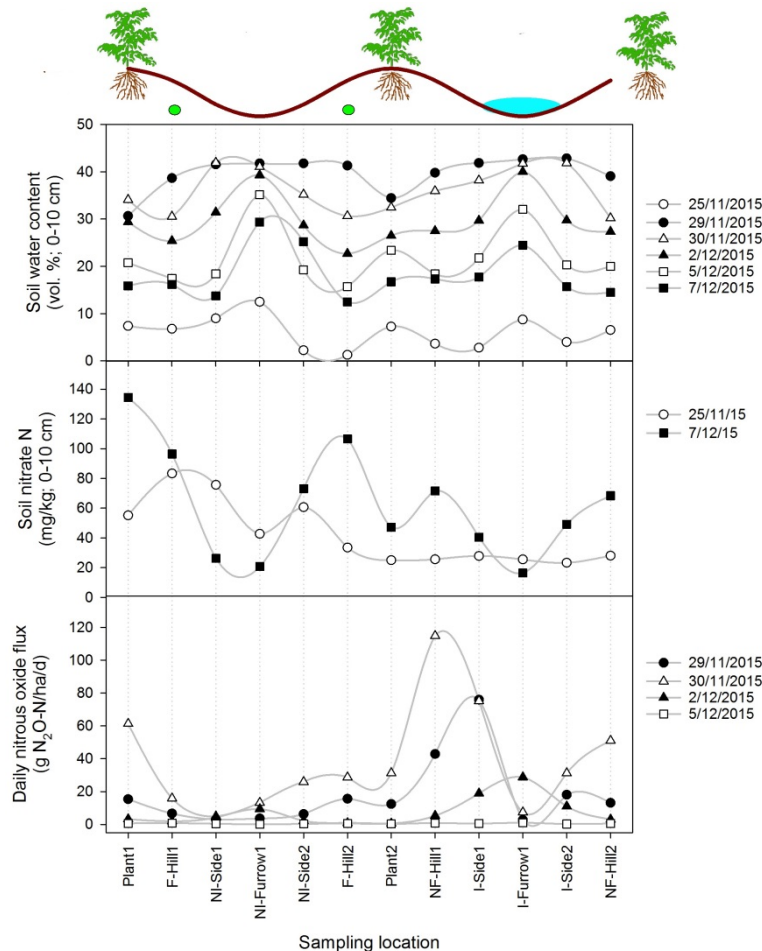
(a) Variation in N<sub>2</sub>O emissions over a full 24 hour period: Our regular measurements were typically carried out between 9am and 12pm (EST). In this exercise, we used the semi-automated chambers to measure N<sub>2</sub>O flux in four chambers (2 chambers each in T1 and T3) every 3 hours, over one 24 hour period (Figure 21). As seen in Figures 19 and 20, there was significant emission activity from T1 but not T3 during the first few days after the 2<sup>nd</sup> irrigation, with T1 being irrigated with water-run urea at this time. The influence of time of day (latent soil temperature) can clearly be seen in the flux response after 9 am for 3 of the 4 chambers in this test. Across all 4 chambers, the flux as measured during the 60 minute closure time starting at 9 am, when used as an average for the whole day, would have underestimated the daily flux by 30% compared to an average of all 8 measurements. It should be remembered that this data is from one single day and may not represent the diurnal flux pattern occurring on other sampling days throughout the season. Further such testing at a number of key times during the season would be needed to confirm this finding.

(b) Variation in N<sub>2</sub>O emissions across all positions in a 2 metre transect: For our routine sampling we used 4 chamber locations within each individual plot. In this exercise we compared the results gained using the usual 4 chambers against that measured when a total of 12 chambers were used. The 12 chambers covered all hill and furrow positions in a 2-m wide transect including two plant rows and two furrows, one irrigated one non-irrigated. We also compared the soil mineral N concentration before and after the week of gas sampling. Figure 22 shows the location of the 12 chambers and the soil moisture, nitrate N and N<sub>2</sub>O flux results from each sample location at 1, 2, 4 and 7 days after the 2<sup>nd</sup> irrigation (with water-run urea).

Ammonium-N was also measured but concentrations were inconsequential compared to the nitrate results. This data is from a single plot only, so is unreplicated.



**Figure 21.** The influence of time of day of sampling on hourly nitrous oxide flux on the 1<sup>st</sup>-2<sup>nd</sup> day following the second irrigation (with water-run urea in T1) at the Gunnedah trial site 2015-16. Air temperature at the site shown in relation to right-hand axis.



**Figure 22.** The influence of sampling position within the 2-m wide transect on surface soil moisture [top], soil nitrate [middle], and daily nitrous oxide flux [bottom] following the second irrigation (with water-run urea) at the Gunnedah trial site 2015-16. The diagram at the top indicates each sample position. Green circles indicate the position of the pre-plant anhydrous ammonia. The blue furrow indicates the furrow that was irrigated.

Before the irrigation event, soil moisture content was very low in the surface and soil nitrate was unevenly concentrated in the top 10 cm of the soil, with high concentrations near the location of the pre-plant ammonia injection bands on either side of the non-irrigated furrow. After irrigation, the water content was high and even across all positions but the plant rows, which were drier. Over the week of emissions sampling, the moisture content dropped in all but the mid-furrow positions where it stayed wet.

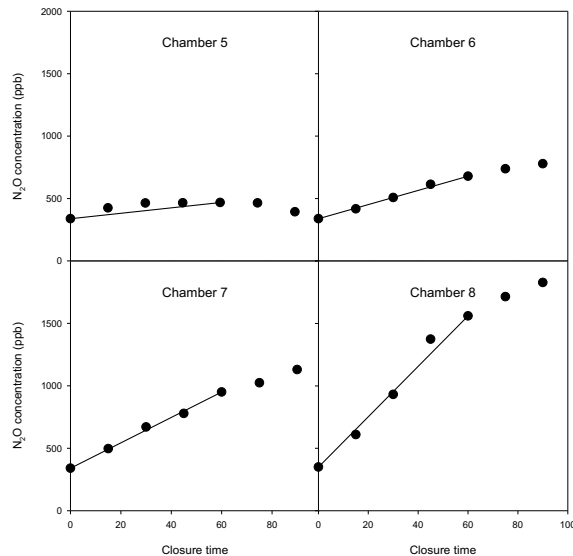
The soil sampling that was done 9 days after the irrigation showed significant changes in the distribution of nitrate within the soil transect, with increased nitrate concentrations associated with the pre-plant fertiliser bands, but also increased nitrate found on the sides of the water-run irrigated furrow. A large increase in soil nitrate under the first plant row is not easily explained and does not match the more modest increase under the 2<sup>nd</sup> plant row position.

Nitrous oxide fluxes in most positions increased in response to the changes in soil moisture and soil nitrate concentration caused by the irrigation event. One day after the irrigation concluded, N<sub>2</sub>O flux was greatest on the sides of the irrigated furrow and also the hillsides adjoining the irrigated furrow. Fluxes in these areas increased further by the 2<sup>nd</sup> day. The sides of the non-irrigated furrow also showed increased emissions on the 2<sup>nd</sup> day. Conversely, by the 4<sup>th</sup> day, emissions had subsided on the sides of the irrigated furrow but increased from the irrigated furrow itself. By the 7<sup>th</sup> day after irrigation, all fluxes had returned to a low baseline.

The average flux from all 12 chambers on each day of measurement was approximately equal to the average of the 4 chambers normally used for the routine sampling of all plots in the experiment. In terms of calculating cumulative N<sub>2</sub>O emitted, there was little difference between 4 and 12 chamber calculations, thus supporting our choice of positions for the 4 chambers in this situation.

(c) Variation in nitrous oxide emissions in relation to chamber closure time: In our regular sampling, the chamber lid was closed for 60 minutes and the change in N<sub>2</sub>O concentration between samples collected at the start and end of the closure period was used to calculate the emission rate. This calculation assumes a linear rate of N<sub>2</sub>O emission during the 60 minute period. Longer closure periods may lead to non-linear fluxes at times of high emissions if the already-emitted N<sub>2</sub>O in the chamber headspace has a feedback effect on N<sub>2</sub>O still being emitted. Shorter closure times may not give sufficient resolution above background noise to enable flux calculation.

In this test, we measured N<sub>2</sub>O concentrations in four different chambers at 15 minute intervals for a total of 90 minutes (Figure 23). Nitrous oxide emission rates varied greatly between the four chambers, but the increases in N<sub>2</sub>O concentration with closure time were essentially linear for at least 60 minutes in 3 of the 4 chambers. The rate of N<sub>2</sub>O concentration increase with time in these 3 chambers became non-linear for closure times greater than 60 minutes, so longer times are not advised when emissions are quite high, as at this sampling time. The other chamber in the 4 tested had a much lower flux, but also showed an unusual pattern of N<sub>2</sub>O concentration with time. After an initial increase in N<sub>2</sub>O concentration between 0 and 30 minutes, the N<sub>2</sub>O concentration then remained stable until 75 minutes after which it declined.



**Figure 23.** *Change in N<sub>2</sub>O concentration with chamber closure time in four individual chambers measured on the 2<sup>nd</sup> day after the end of the 2<sup>nd</sup> irrigation with water-run urea. Lines indicate the 0–60 minute linear relationship used to calculate fluxes for all other manual chamber measurements.*

#### 4.2.5 Irrigation water analysis at Gunnedah

It was estimated that 1.5, 0.99 and 0.95 ML/ha of water was applied at irrigations 1, 2 and 3, respectively. Estimated water leaving the paddocks via the tail drain was 0.45, 0.58 and 0.47 ML/ha at the same irrigation events.

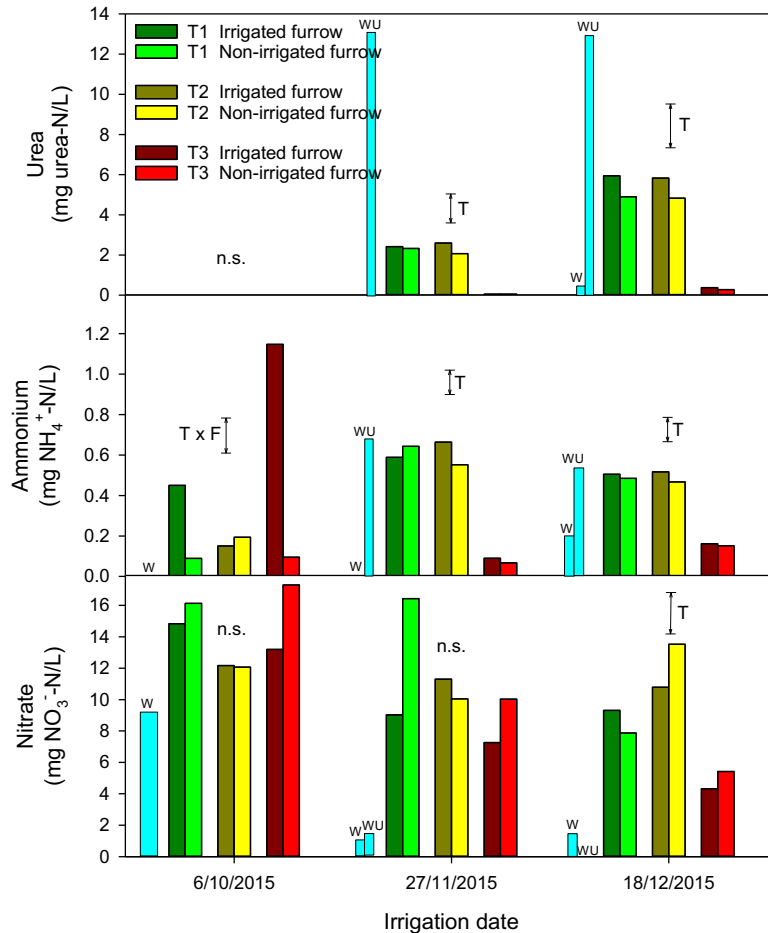
There was no urea detected in either head ditch or tail drain furrows during the first irrigation, which was expected because only water was used in this irrigation. The next two irrigations included water-run urea in treatments T1 and T2, but not T3, (Figure 24-top). As expected, there was a clear treatment difference in urea concentration in the tail drain water between the treatments with urea added (T1, T2) and the one with only water added (T3).

There was no significant effect of which furrow the sample was collected from at either the 2<sup>nd</sup> or the 3<sup>rd</sup> irrigation. The concentration of ammonium in the water was much lower than either urea or nitrate forms. The results for the 1<sup>st</sup> irrigation showed a significant treatment by furrow interaction effect, with more ammonium coming from the irrigated furrow in T1 and T3, but no difference between furrows in T2. Results from the latter two irrigations were higher in T1 and T2 than T3, indicating the transformation of some of the applied urea to ammonium was occurring in the water as early as in the head ditch before being applied to the field (Figure 24-middle).

Of the three forms of N measured, most of the N exiting the field occurred as nitrate (including nitrite). There was a sizable concentration of nitrate entering the field in the water used for the first irrigation, but much less in the later irrigations. There was no treatment difference in nitrate concentration in tail drain water at either 1<sup>st</sup> or 2<sup>nd</sup> irrigations, but in the 3<sup>rd</sup> irrigation, nitrate concentration was higher in T2 than T1 which was higher than T3. There was no significant effect of furrow on nitrate concentration at any sampling time, despite apparent trends for more nitrate from the non-irrigated furrows of T1 and T3.

Using the estimated inflow and outflow figures for each of these irrigation events along with the N concentrations in the sampled head ditch and tail drain areas, we can estimate total N movement in and out of the paddock. At the 1<sup>st</sup> irrigation, 11.1 kg N/ha entered the field in the irrigation water, while 7.1

kg/ha left the field from T1 and T3, but less from T2 (5.5 kg N/ha). In the 2<sup>nd</sup> irrigation, 1 kg N/ha entered in the irrigation water, and another 14 kg N/ha entered the paddock in the water-run treatments. Note, these water-run treatments were meant to have 30 kg N/ha added as urea-N. It is not clear why there was a difference here. N leaving the paddock in the tail drains was least in T3 (5.1 kg N/ha) compared to T2 (7.9 kg N/ha) and T1 (9.1 kg N/ha). In the 3<sup>rd</sup> irrigation, 2.1 kg N/ha was present in the water, with another 10.6 kg N/ha added in the water-run treatments. Again, this is much less than the 30 kg N/ha applied according to the farmer's calculations. N outflow from the paddock was again least from T3 (2.5 kg N/ha), intermediate from T1 (6.8 kg N/ha) and highest from T2 (8.5 kg N/ha).



**Figure 24.** Concentrations of urea, ammonium and nitrate in head ditch and tail drain water samples collected at the 1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> irrigations at the Gunnedah trial site. W and WU indicate the concentrations in the irrigation water and water-run urea as measured in the channel. Significant treatment differences are indicated at each irrigation event (n.s. = not significant, T = significant treatment effect, T x F = significant treatment by furrow effect). Vertical lines indicate the least significant difference for treatment comparisons.

#### 4.2.6 Soil collection from non-cropped areas of irrigated cotton paddocks (head ditch and tail drain)

Measured properties of the 20 soil and sediment samples collected for the incubation experiment are given in Table 8. The water-holding capacity WHC was measured to give a water content that would approximate the content after irrigation has ceased and the soil allowed to drain for 24 hours. This sample set represents a good cross section of the northwest NSW (and Emerald, CQ) soils used for irrigated cotton production and covers a range of soil organic carbon from 0.48% to 1.26%. The soil C/N ratio is typically around 10 for most soils, so those with lower ratios, e.g. Nh, have a greater than expected amount of total N, of which the majority is typically found in the organic form. Interestingly, the tail drain soil from this farm

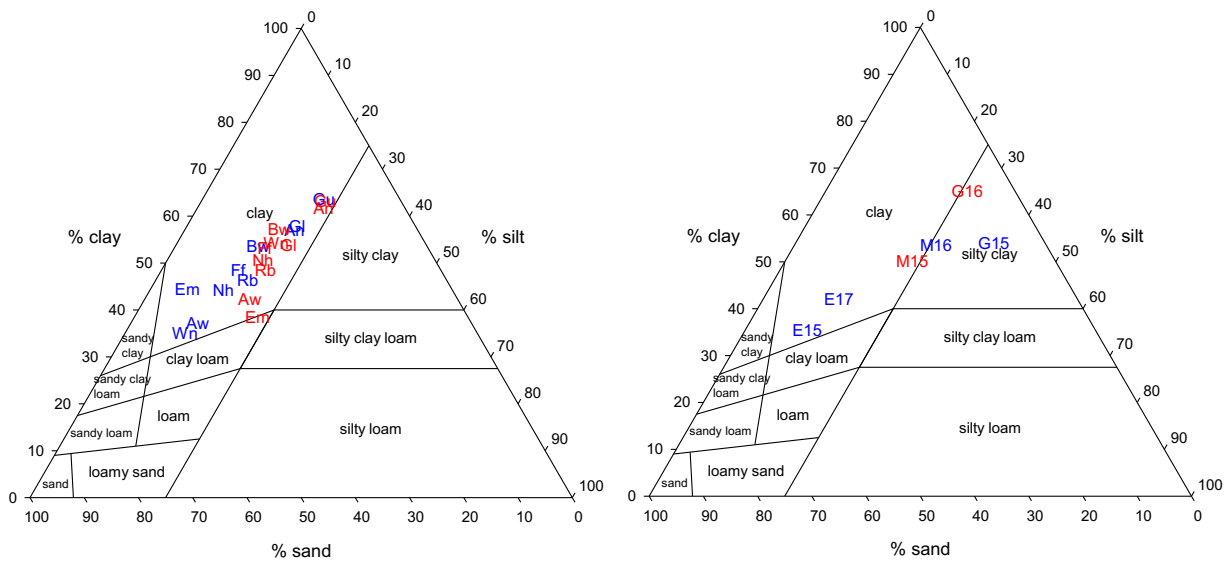
had a surprisingly high concentration of ammonium due to recent N fertiliser application. Nitrate nitrogen at most sites was high to very high, which was to be expected as the samples were collected early in the cotton growing season and most, if not all, farms apply the majority of nitrogen fertiliser pre-plant.

**Table 8.** *Soil properties of the sediment samples collected for the incubation study.*

Location	Farm	Sample	%C	%N	C/N	DOC	Nitrate (mg/kg)	Ammonium (mg/kg)	Water holding capacity (g/g)
Narrabri	An	head ditch	0.48	0.056	8.6	29.1	21	1	0.50
Narrabri	An	tail drain	1.07	0.121	8.9	67.4	65	7	0.59
Warren	Aw	head ditch	0.74	0.086	8.6	38.2	21	1	0.35
Warren	Aw	tail drain	1.19	0.112	10.6	143.9	47	3	0.40
Burren Junction	Bw	head ditch	0.55	0.067	8.2	53.6	43	2	0.49
Burren Junction	Bw	tail drain	0.81	0.099	8.2	134.6	136	2	0.50
Emerald	Em	head ditch	0.69	0.067	10.3	46.8	15	1	0.30
Emerald	Em	tail drain	0.74	0.074	10.1	115.4	19	2	0.35
Narrabri	Ff	head ditch	0.65	0.08	8.1	44.7	38	1	0.46
Narrabri	Ff	tail drain	0.95	0.117	8.1	107.3	37	2	0.50
Wee Waa	Gl	head ditch	0.70	0.079	8.8	17	58	1	0.45
Wee Waa	Gl	tail drain	1.08	0.128	8.5	186	22	14	0.46
Gunnedah	Gu	head ditch	1.26	0.117	10.8	47.2	29	3	0.44
Gunnedah	Gu	tail drain	1.25	0.119	10.6	91.4	101	2	0.53
Narromine	Nh	head ditch	0.78	0.099	7.8	97.7	53	3	0.37
Narromine	Nh	tail drain	0.98	0.135	7.3	128.2	64	96	0.41
Moree	Rb	head ditch	0.74	0.076	9.8	32	48	2	0.38
Moree	Rb	tail drain	1.11	0.118	9.4	162.9	141	4	0.43
Narrabri	Wn	head ditch	0.75	0.093	8.1	59.5	41	2	0.34
Narrabri	Wn	tail drain	1.10	0.112	9.8	123.2	11	3	0.44

Particle size analysis of the soils and sediments confirmed that all samples were dominated by clay-sized particles, but the sample set differed markedly in the proportions of clay, silt and sand, with clay contents ranging from 35–64% (Figure 25-left). The lightest textured samples bordered on clay loams, while the heaviest textured soils were medium–heavy clays. The tail drain sediment samples had a similar range in clay contents to the head ditch soil samples. However, as a group, the tail drain samples tended to have more silt and less sand than the head ditch samples. When these texture results were compared with the water holding capacity results (Table 8), we found a strong positive correlation between the amount of water held by the soil and clay content ( $r^2 = 0.69$ ).

Figure 25 [right] shows a soil texture diagram for the soils used for the field trials at Emerald, Moree and Gunnedah from 2014–2017. The Emerald soils had lighter texture (less clay, more sand) than the Moree and Gunnedah sites, with Gunnedah 15–16 quite high in silt.

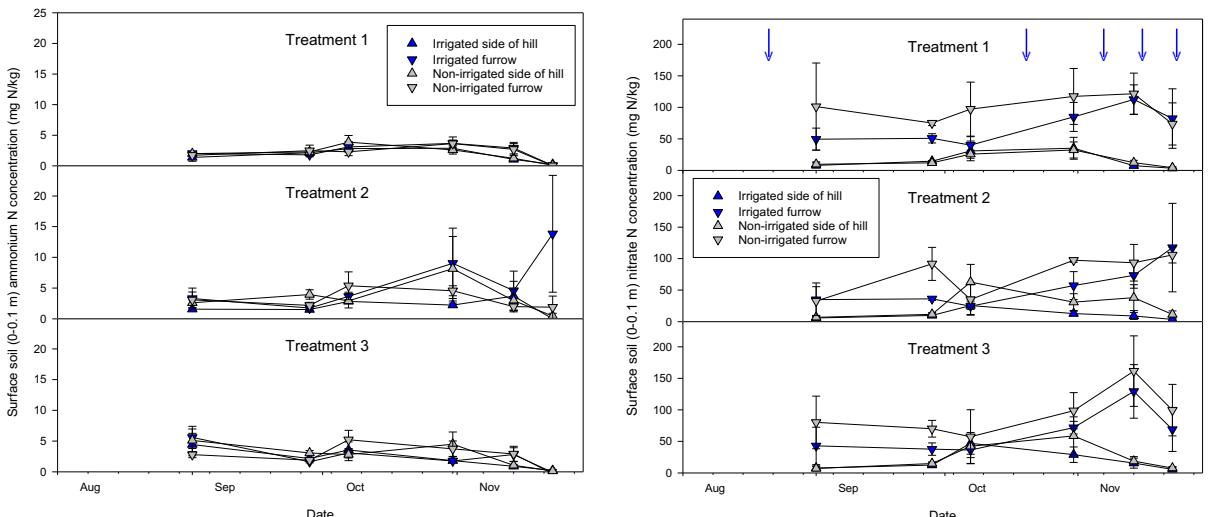


**Figure 25.** Australian soil textural class diagrams showing [left] the 10 head ditch soils (blue) and 10 tail drain sediments (red) collected for the incubation study, and [right] the trial site soils (0–30 cm) at Emerald, Moree and Gunnedah (G16 = G17, E15 = E16).

**4.3 2016-17 Nitrification inhibitor trials**

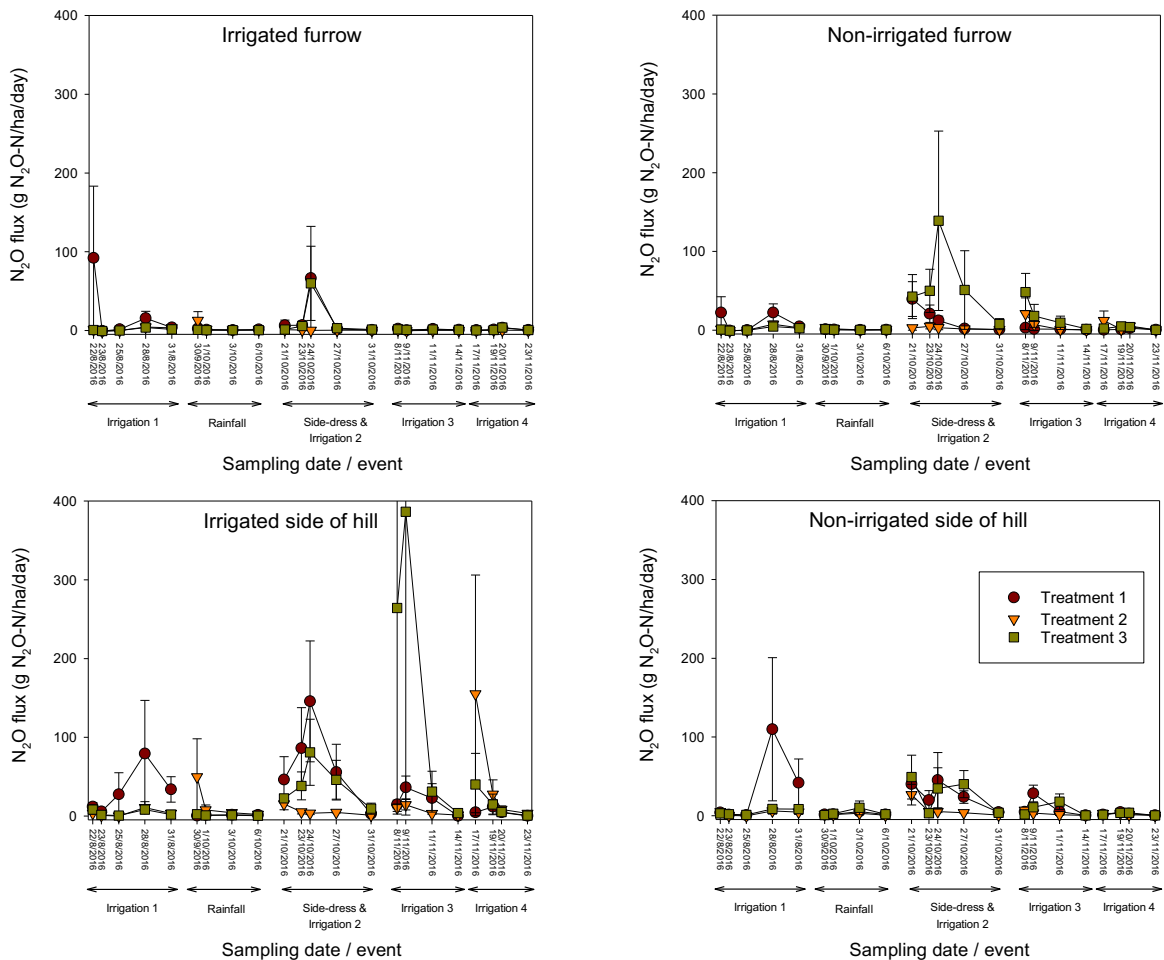
**4.3.1 Emerald 2016–17 trial**

There was an average of 34 kg N/ha as mineral N in the soil to 90 cm prior to planting. The paddock used in this year’s trial was located on a different farm to that used for the previous two years trials at Emerald. The soil at this paddock had a heavier texture than the one previously used (see Figure 25-right), but was still much lower in clay % than any of the NSW sites.



**Figure 26.** Soil ammonium N concentration [left] and soil nitrate N concentration [right] (0–10 cm) at four positions within each of the three treatments at the Emerald trial 2016-17. No further measurements after 23<sup>rd</sup> November 2016. Blue arrows in top graph indicate dates of irrigation. The side-dressing operation occurred on 17<sup>th</sup> October, just prior to the 2<sup>nd</sup> irrigation.

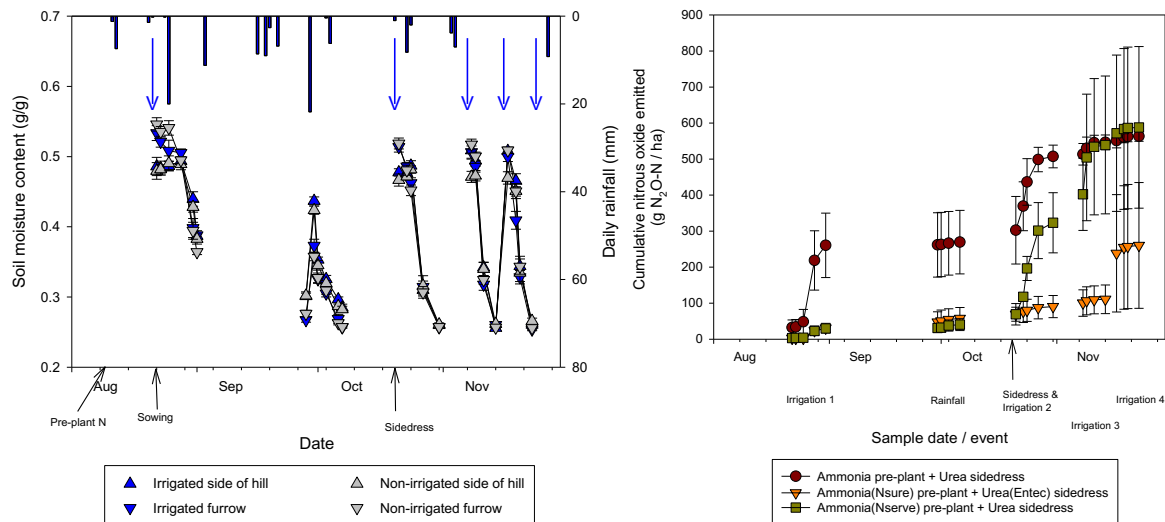
There was little ammonium N (Figure 26-left) found in surface soil (0-10 cm) sampling in September and October 2016, which is likely due to the greater depth of the fertiliser application than soil sampling. After the mid-season side-dressing operation in mid-October, soil ammonium concentration was higher in treatment 2 during late October, due to the ENTEC-coated urea inhibiting conversion of the ammonium to nitrate, but levels were effectively nil in all treatments by late November. Surface soil nitrate concentrations (Figure 26-right) were much higher than ammonium at most sampling times and locations. In the first two months, soil nitrate was very low in the hill positions, with much higher concentrations found in the furrows, indicating some washing out of the applied N from the hills as nitrate. The side-dress N application increased nitrate levels in all treatments, peaking in mid-November. Post-harvest soil sampling was not conducted due to insufficient funds.



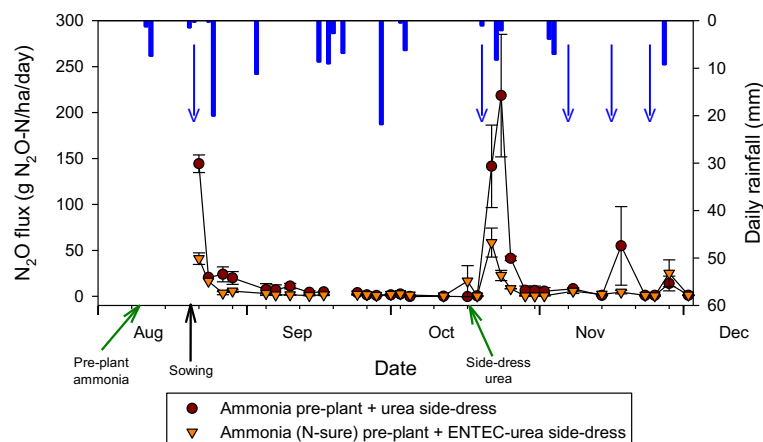
**Figure 27.** Nitrous oxide flux measured at 4 positions within each of 3 treatments at the Emerald 2016-17 trial during 5 measurement periods between pre-plant N application and early December 2016. Each point is a mean of 3 replicate plots ( $\pm$  standard error).

The nitrous oxide flux from each manual chamber location in each treatment is shown in Figure 27. In general, emission rates were low throughout much of the season, with the first irrigation causing only a few temporary and highly variable emission peaks in treatment 1 (control). There was almost no response to the 21.8 mm rainfall event at the end of September 2016. Side-dressed urea followed by irrigation increased fluxes for at least 4 days in most chamber locations of treatments 1 and 3, which had ordinary urea applied. Treatment 2, side-dressed with ENTEC-coated urea, showed little nitrous oxide loss during the same period. Further irrigations led to some larger but highly variable emissions responses, mostly from the irrigated side of the hills. The soil moisture contents on the days of gas sampling (Figure 28-left) show how

quickly the surface soil dried after rainfall or irrigation events and thus why nitrous oxide emission events at this site were typically short-lived. The net result of these manual chamber measurements is shown as a cumulative emission of nitrous oxide in Figure 28-right. While the sampling of target events meant that there were significant gaps in the timeline, it is likely that losses during these gaps would have been minimal based on the low fluxes measured at the end of each sampled event. From pre-plant N application until side-dressing, use of inhibitors reduced N<sub>2</sub>O losses by 66% compared to the untreated control (treatment 1). After the side-dressing, treatments 1 and 3, which received untreated urea, continued to increase in N loss while the ENTEC-coated urea kept emissions of nitrous oxide to a minimum, at least until the final event when a high emission from one of the three replicate plots of treatment 2 led to an increase in the average cumulative nitrous oxide loss. As a proportion of the N applied, these losses were only 0.2% (treatments 1 and 3) or 0.09% (treatment 2).



**Figure 28.** Rainfall and soil moisture content at 4 plot positions on gas and soil sampling days [left], and cumulative nitrous oxide emission [right] from each of 3 treatments at the Emerald 2016-17 trial during 5 measurement periods between pre-plant N application and early December 2016. Each point is a mean of 3 replicate plots ( $\pm$  standard error). Blue arrows indicate irrigation events.



**Figure 29.** Daily nitrous oxide flux from 2 treatments at the Emerald 2016-17 trial during semi-auto measurements approximately 2-3 times per week between pre-plant N application and early December 2016. Each point is a mean of 2 replicate plots ( $\pm$  standard error). Daily rainfall is shown at the top of the graph. Blue arrows indicate dates of irrigation.

The results from the manual chambers were supported by those from the semi-auto chambers (Figure 29), with significant peaks in emissions from the untreated control (treatment 1) soon after pre-plant N application (+ irrigation) and the side-dress N application (+ irrigation) events. The emission peaks in each case lasted between 1 and 2 weeks.

The assessment of plant production at peak biomass (just prior to defoliation) found that the N-sure/ENTEC treatment (T2) resulted in significantly more plants per hectare than either of the other treatments (Table 9). However, despite the greater number of plants there was no significant difference in total numbers of bolls per square metre, which meant there were more bolls per plant (26) in the control treatment than in either of the inhibitor treatments (T2 = 17, T3 = 20). The imposed treatments also affected the amount of N removed from the paddock in lint, but not that removed in the seed. The treatments had no effect on the amount of plant vegetative matter, lint or seed produced, but there were significant differences in all of these measures according to the sampling position in the paddock, with all indicators showing poorer production at the head-ditch end of the paddock compared to samples taken near the middle or the tail-drain end of the paddock.

Cotton lint yield results from the machine harvesting of these plots (13<sup>th</sup> of February 2017) showed no significant treatment differences at Emerald, with a trial average yield of 10.9 bales/ha (Table 10). Fibre quality results also showed no significant treatment effects (Table 10).

**Table 9.** Results of biomass, lint and seed from hand-cuts done at maximum plant biomass (immediately prior to desiccation for picking) at the Emerald 2016-17 trial.

Measure	Treatment			Significant difference?	Least significant Difference
	T1	T2	T3		
<i>Biomass hand-cut results</i>					
Population (plants/ha)	52,200	77,800	63,300	yes	13,480
Boll number (bolls/m <sup>2</sup> )	132	135	121	no*	n/a
Plant dry matter <sup>a</sup> (t/ha)	15.8	16.4	14.8	no*	n/a
Dry matter <sup>a</sup> N (kg N/ha)	136	144	146	no*	n/a
Lint yield <sup>b</sup> (kg/ha)	3401	3631	3072	no	n/a
Lint N <sup>b</sup> (kg N/ha)	9.2	11.7	9.0	yes*	1.87
Seed N (kg N/ha)	122	123	108	no*	n/a

<sup>a</sup> All above-ground plant material excluding the lint and the seed. <sup>b</sup> Lint and seed collected during pre-desiccation biomass cut.

\* there was a significant effect of sample location on boll number with samples from the head ditch end lower (110 bolls/m<sup>2</sup>) than at either the mid field (142) or tail drain-end samples (136).

\* there was a significant effect of sample location on plant dry matter with samples from the head ditch end lower (13.7 t/ha) than either mid (17.0) or tail drain-end samples (16.3).

\* there was a significant effect of sample location on dry matter N uptake with samples from the head ditch end lower (95 kg N/ha) than either mid (161) or tail drain-end samples (170). This was due to a combination of both low plant dry matter and low N concentration in the plant in the head ditch end samples.

\* there was a significant effect of sample location on lint N with samples from the head ditch end lower (7.5 kg N/ha) than either mid (11.4) or tail drain-end samples (11.0).

\* there was a significant effect of sample location on seed N with samples from the head ditch end lower (95 kg N/ha) than either mid (134) or tail drain-end samples (124).

**Table 10.** Yield results of the commercial picking and ginning of the Emerald 2016-17 trial plots.

Measure	Treatment			Significant difference?	Least significant Difference
	T1	T2	T3		
Bales/ha	10.8	11.1	11.0	no	n/a
Colour	11-1	11-1	11-1	No	n/a
Strength	31.2	31.2	31.3	No	n/a
Uniformity	81.9	81.8	81.9	No	n/a
Micronaire	4.5	4.5	4.5	No	n/a

#### *Conclusions from the Emerald 2016–17 trial*

In the 2016–17 Emerald cotton season, there were no agronomic or environmental benefits from using a nitrification inhibitor in conjunction with anhydrous ammonia. However, these trial conditions may not be typical as pre-plant fertiliser is usually applied much earlier in the year at Emerald than it was at this trial site. A longer period of time between pre-plant application and plant establishment would provide greater opportunity for nitrous oxide losses to occur, although the potential for heavy winter rainfall tends to be low in the Emerald region. While both inhibitor products clearly reduced emissions during the first two measurement periods, it was apparent that the effectiveness of these products had dissipated by the time of the second irrigation. The additional inhibitor application with the side-dressed urea boosted the nitrous oxide reduction period for the DMPP treatment, while the application of untreated urea to the other treatments allowed further losses matching those of the untreated control after the initial pre-plant N application.

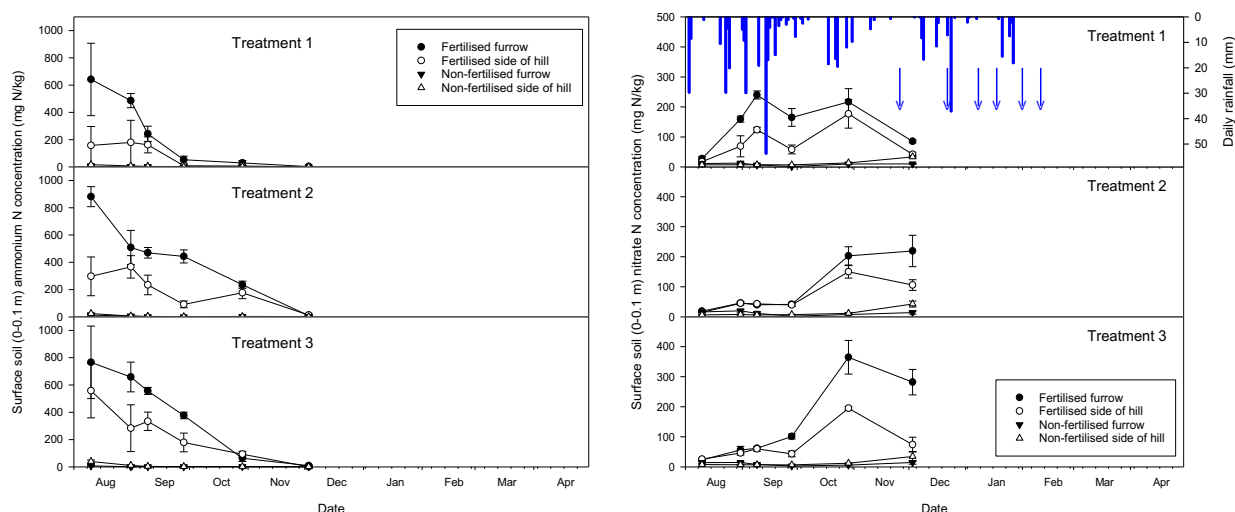
The DMPP inhibitor treatments (pre-plant + side-dress) did impact plant productivity but, at least from hand cut data, did not affect cotton lint yield. Most plant measures highlighted a distinctly lower productivity in the head-ditch end of the trial paddock, where the gas chambers were located.

#### **4.3.2 Gunnedah 2016–17 trial**

Soil was not sampled at the Gunnedah site before the 2016–17 trial treatments were imposed as we used the same site as the previous year with post-harvest soil cores showing that little N remained at the end of the season. Regular surface soil (0-10 cm) sampling began 12 days after the pre-plant anhydrous ammonia application, with results showing extremely high concentrations of ammonia in the fertilised furrows of all 3 treatments. Ammonium in the fertilised side of the hill was also high in all (Figure 30-left). The variation between replicate plots was large, which is typical of soil sampled from a recently applied band of concentrated fertiliser. While it can't be seen due to the scale of the graph, the ammonium results from the non-fertilised side of the hill were high, at 27 mg/kg, compared to normal soil results <2 mg/kg from most unfertilised soils. Over the next 4 months, soil ammonium declined to normal soil baseline levels, but the rate of decline was noticeably slower where nitrification inhibitors were used (T2, T3), with T2 probably slower than T3 (Figure 30-left). The opposite result was observed in the nitrate results of the same samples, with very little found at the first sample event in early August (Figure 30-right). Nitrate concentrations increased rapidly in the untreated control treatment (T1) but were delayed for two months in the two

inhibitor treatments (T2, T3). By the time of the final soil sampling event after the first irrigation in early December, nitrate concentrations had greatly declined in T1, but were still at a maximum in T2 and T3. As with the ammonium results, highest nitrate concentrations were found in the fertilised furrow position, with the fertilised side of the hill significantly lower in nitrate. This seems counterintuitive as the injection of anhydrous ammonia was via a delta-T applicator with approximately 85% of the ammonia applied as a super-cooled liquid out the sides of the inverted T (coldflow) and about 15% of the N applied as ammonia vapour into the middle of the furrow. However, as the liquid was applied sideways under the hills, when we came to take soil samples, our shallow 10 cm deep soil corer would have sampled only into the top of the band, whereas a soil core pushed into the centre of the furrow would have sampled much more or all of the applied N as there was less soil above that band.

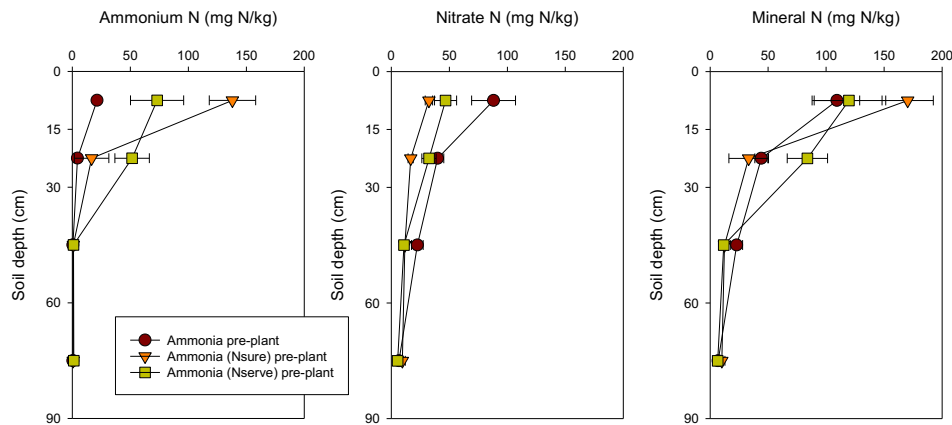
It is likely that the 280 mm of rainfall experienced between pre-plant N application in July and sowing in October (see Figure 30-right), on top of what was already a very wet soil, caused nitrate denitrification and possibly also leaching losses of the nitrate from the pre-plant applied N, particularly in T1, where no nitrification inhibitor was added. The decrease in soil nitrate in T1 between the third and fourth sampling event appears to support this assumption. The subsequent increase by the next sampling time may indicate some upward movement of nitrate within the soil, particularly in the hill side position (Figure 30-right).



**Figure 30.** Soil ammonium N concentration [left] and soil nitrate N concentration [right] (0-10 cm) at four positions within each of the three treatments at the Gunnedah AOTG-Cotton trial 2016-17. No measurements after 3<sup>rd</sup> December 2016. Daily rainfall measured at the site is shown up to 1<sup>st</sup> February 2017 [right]. Blue arrows indicate dates of irrigation.

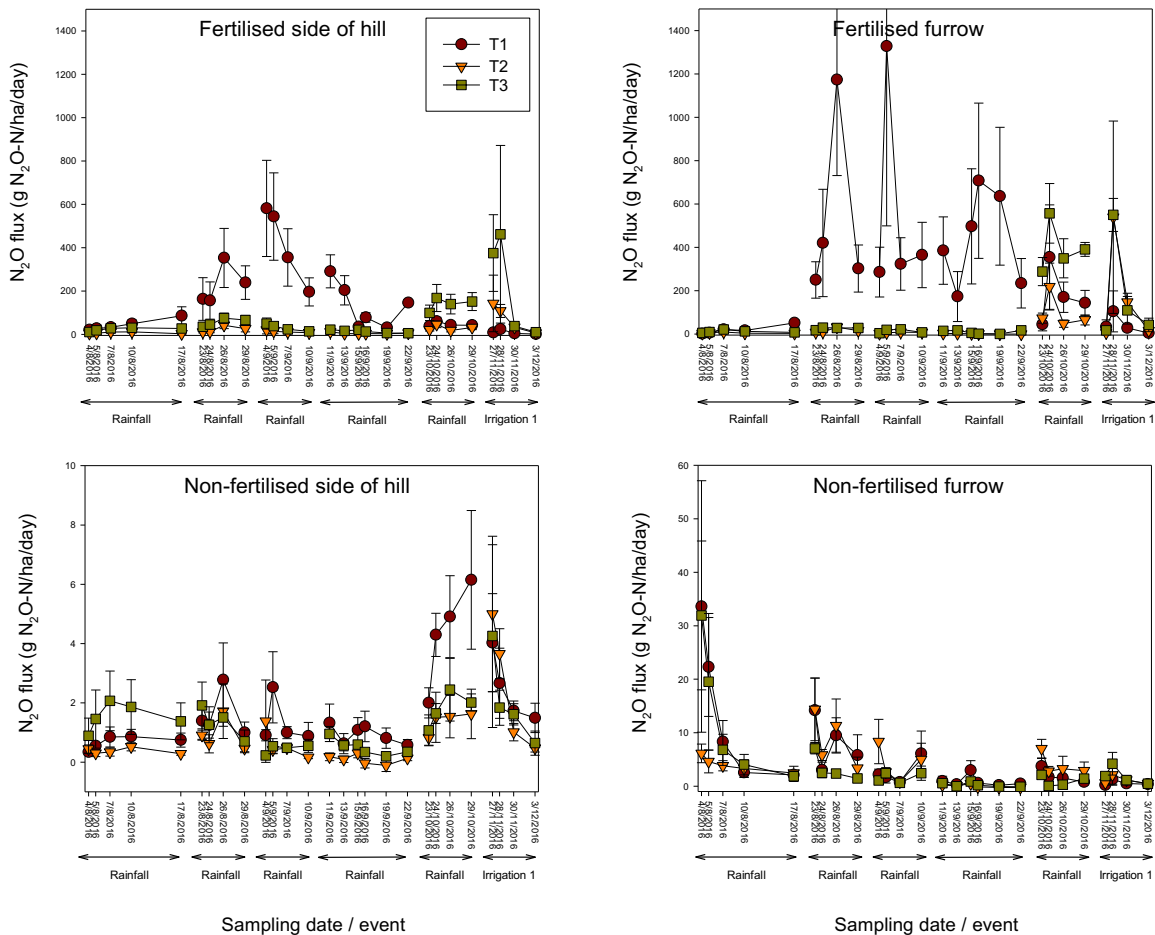
We attempted to assess whether there had been wholesale losses of mineral N from the soil profile between pre-plant application and sowing by deep-soil coring just prior to sowing in each plot. In each plot, we took 2 cores to 90 cm and another 3 cores to 30 cm. These were composited by depth before analysis. The highly concentrated nitrogen bands made accurate quantification of remaining mineral N stocks difficult, as a small difference in location of the soil core could mean either sampling directly through the band or skimming the edge of it and getting a much lower concentration as a result. Figure 31 shows some interesting trends with the N-sure treatment (T2) clearly retaining much more of the applied N as ammonium than either the N-serve (T3) or the non-inhibited NH<sub>3</sub> (T1) in the top 0-15 cm. The N-serve treatment had more ammonium in the subsoil (15-30 cm) than either of the other treatments. Nitrate-wise, both inhibitors had done a good job of keeping nitrate levels at around half the levels seen in the uninhibited treatment. However, there was no statistically significant difference in total mineral N different

between the three treatments, thanks to the high variation involved in sampling across plots with high rates of N concentrated in narrow bands. Similar soil analysis was not done at Emerald as the site was planted within a week of applying fertiliser.



**Figure 31.** Soil ammonium [left], nitrate [centre] and combined mineral N [right] concentrations to 90 cm depth within each of the three treatments at the Gunnedah AOTG-Cotton trial 2016-17 at planting.

The nitrous oxide flux from each manual chamber location in each treatment is shown in Figure 32. Emission rates were extremely high in the fertilised furrow and hill positions, especially in the untreated control treatment (T1), and mostly low in the non-fertilised furrow and hill positions throughout much of the season. These graphs show that the nitrification inhibitors were highly effective in reducing nitrous oxide emissions induced by heavy rain falling on an already very wet soil for several months after application. Emissions after the first rainfall event were small in comparison to later events with a maximum flux of 86 g N<sub>2</sub>O-N/ha/day from the fertilised hillside of T1 two weeks after the trigger rainfall event of 36 mm. Maximum fluxes from T2 and T3 during this period were 12 and 31 g N<sub>2</sub>O-N/ha/day, respectively. During the following three rainfall events, emissions surged from T1, especially from the fertilised furrow position (up to 1328 g N<sub>2</sub>O-N/ha/day), while those in T2 and T3 remained of the same order as previously. The effects of the inhibitors appeared to be wearing off by the time of the last rainfall and first irrigation sampling events, particularly T2, which showed some high and highly variable emissions from the fertilised hillside and furrow positions.

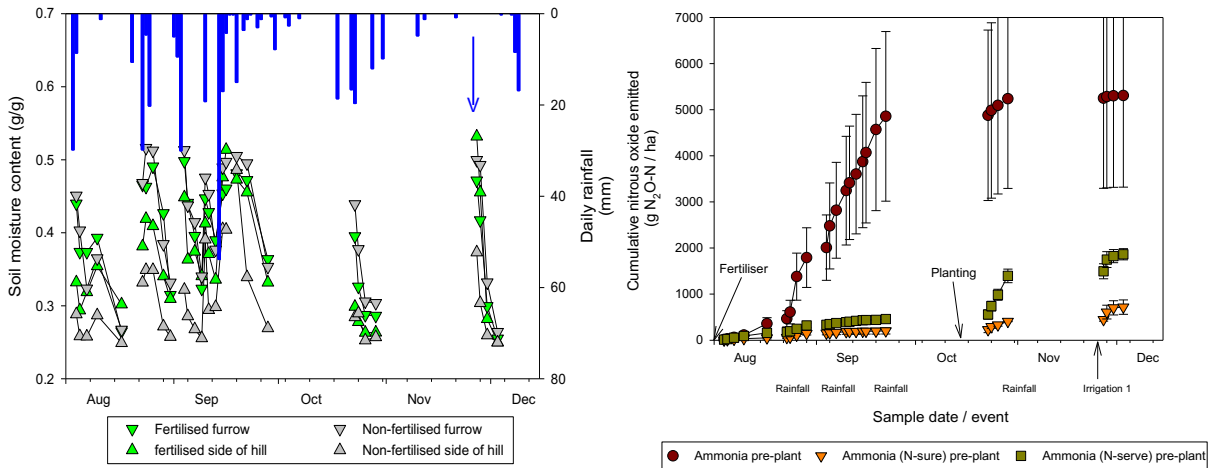


**Figure 32.** Nitrous oxide flux measured at 4 positions within each of 3 treatments at the Gunnedah 2016-17 trial during 6 measurement periods between pre-plant N application and early December 2016. Each point is a mean of 3 replicate plots ( $\pm$  standard error). Note different scales used for the different sampling locations.

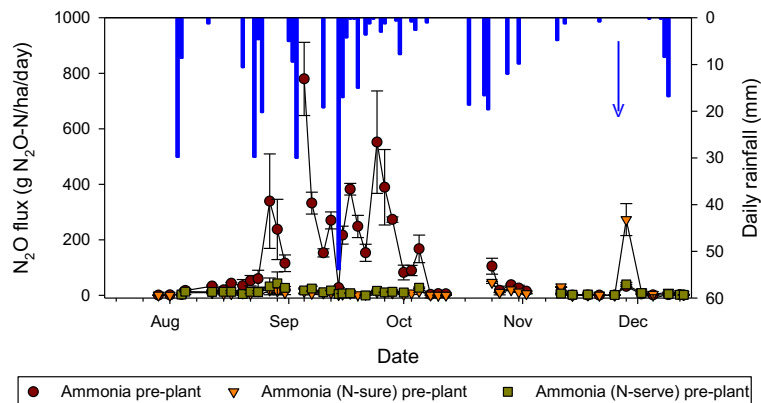
The cumulative N lost as nitrous oxide (during the measurement periods only) is shown in Figure 33-right, with clear differences according to treatments. In total, N-sure reduced nitrous oxide emissions by 84% and N-serve by 58%, compared to anhydrous ammonia applied without any nitrification inhibitor. Figure 33-left shows the large and rapid changes in surface soil (0-10 cm) moisture content during the measurement events. As expected, soil in the furrows tended to stay wetter longer than the soil sampled from the sides of the hills.

The semi-automated chambers at Gunnedah were located across the fertilised furrow, unlike at Emerald and at Gunnedah the previous year, where the chambers were located on the hill. This was because at Gunnedah in 2016–17 the fertiliser was applied using the delta-T applicator that was centered on the non-irrigated furrow. Had we centered the chamber on the hill we would not have covered 2/3 of the fertiliser band location. As a result of the furrow positioning, we had to create a diversion for any water running down the non-irrigated furrow during irrigation. Through “subbing” the soil water content in the chamber became similarly wetted as in the surrounding un-diverted furrow but the chamber did not become submerged and inoperative. Figure 34 shows the daily nitrous oxide fluxes measured using these semi-automated chambers. At Gunnedah, we were able to deploy two sets of chambers allowing measurement of all three treatments, whereas only two treatments could be measured at Emerald. As with the manual chamber measurements, there is a clear impact of the inhibitor treatments shown by nearly two months of extremely high emissions from the untreated control (T1) compared to only small emissions from T2 and T3

during this time. The drier period during early October reduced emissions from even the untreated control plots, with only a small increase after more rain in mid-October. We do not have any results for T3 throughout this period until mid-November due to operational issues. Interestingly, T2 showed a brief spike of high nitrous oxide emissions after the first irrigation event which was not seen in either T1 or T3. This spike coincided with a similar brief spike on the 28<sup>th</sup> of November from the fertilised furrow position of T2 as measured with the manual chambers (Figure 33-top right).



**Figure 33.** Rainfall and soil moisture content at 4 plot positions on gas and soil sampling days [left], and cumulative nitrous oxide emission [right] from each of 3 treatments at the Gunnedah 2016-17 trial during 6 measurement periods between pre-plant N application and early December 2016. Each point is a mean of 3 replicate plots ( $\pm$  standard error). Blue arrow indicates irrigation event.



**Figure 34.** Daily nitrous oxide flux from each of 3 treatments at the Gunnedah 2016-17 trial during semi-auto measurements approximately 2-3 times per week between pre-plant N application and early December 2016. Each point is a mean of 2 replicate plots ( $\pm$  standard error).

There were no treatment effects on plant biomass, lint or seed N from the hand cut biomass (Table 11), nor were there any treatment effects on cotton lint yield from the commercial picker. The inadvertent application of top-dress urea at 75 kg/ha of N as urea across the paddock on the 18<sup>th</sup> of January 2017 probably made up any shortfall in N that may have developed between the treatments as a result of the wet conditions pre-plant. Cotton quality data from the trial area is not yet available from the cotton gin.

**Table 11.** Results of biomass, lint and seed from hand-cuts done at maximum plant biomass (immediately prior to desiccation for picking) at the Gunnedah 2016-17 trial.

Measure	Treatment			Significant difference?	Least significant Difference
	T1	T2	T3		
<i>Biomass hand-cut results</i>					
Population (plants/ha)	132,500	135,200	131,100	no	n/a
Boll number (bolls/m <sup>2</sup> )	117	118	120	no	n/a
Plant dry matter <sup>a</sup> (t/ha)	12.2	12.1	11.7	no	n/a
Dry matter <sup>a</sup> N (kg N/ha)	123.6	121.5	127.8	no	n/a
Lint yield <sup>b</sup> (kg/ha)	2470	2472	2180	no	n/a
Lint N <sup>b</sup> (kg N/ha)	4.7	5.2	4.7	no	n/a
Seed N (kg N/ha)	110.7	108.1	98.6	no	n/a

<sup>a</sup> All above-ground plant material excluding the lint and the seed. <sup>b</sup> Lint and seed collected during pre-desiccation biomass cut.

### Conclusions from the Gunnedah 2016–17 trial

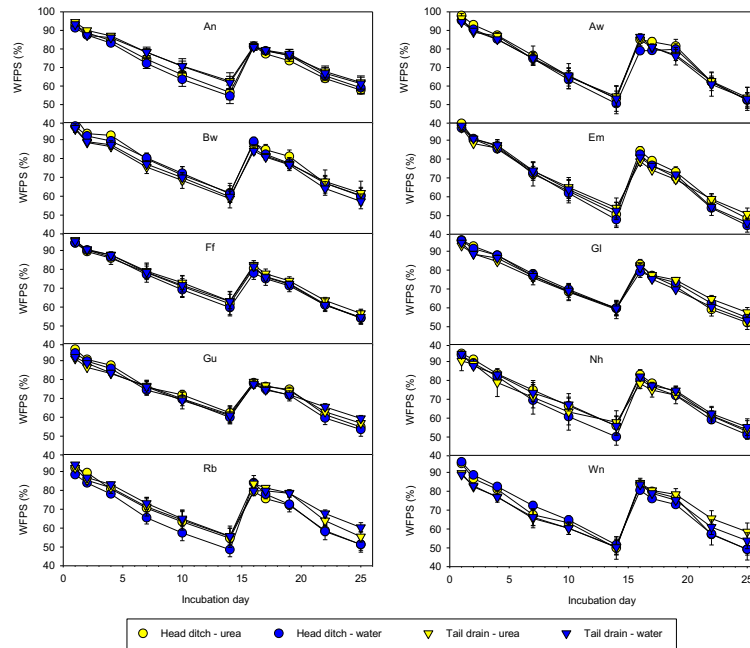
The 2016–17 Gunnedah trial provided the perfect testing conditions for the nitrification inhibitors. These inhibitors were specifically designed to retain mineral N from applied N fertiliser in the soil during periods of excessive rainfall that can lead to large losses of nitrate N through denitrification and leaching processes. Leaching occurs through downward movement of nitrate with water in the soil, but we found no evidence of this having occurred in the soil core samples we took just prior to sowing. For heavy clay soils such as this one at Gunnedah, denitrification of soil nitrate during periods of anaerobic soil conditions is the more likely major loss pathway. In the nearly 3 months between pre-plant N application and sowing, the site received 280 mm rainfall on top of an already very wet soil profile. The results of the gas sampling campaigns and semi-auto chamber samplers both highlighted the almost complete mitigation of nitrous oxide emissions during this period where inhibitors were added to the anhydrous ammonia during application. It was apparent that the N-serve inhibitor had “worn off” by the time of planting, while the N-sure “wore off” by the time of the first in-crop irrigation.

Soil mineral N sampling reinforced the effects of these inhibitors on the nitrification process with the conversion of ammonium to nitrate distinctly delayed during the pre-plant period. Longer-lasting nitrate levels in the soil may have improved plant production during the rapid growth phase. The key question was then whether the total loss of N prevented by using these products was significant in an agronomic sense. We attempted to answer this through soil coring and while it appeared that the inhibitor treatments had saved mineral N, the treatment variability was too high to discern significant treatment differences. The definitive proof of any treatment effects would be observed as a plant productivity response, but inadvertent top-dressing of the trial area has prevented any conclusive outcome of these inhibitors on crop performance and economic benefit. Despite this, both products demonstrated a clear environmental benefit on significantly reduced nitrous oxide emissions.

### 4.3.3 Soil/sediment incubation experiment

In August–September 2017, we conducted the soil and sediment incubation experiment in an air-conditioned room set to 25°C, an average daily temperature representative of the summer cotton growing areas or northern NSW and Qld. Figure 35 shows the water filled pore space (WFPS, %) for all the treated

soil and sediment samples during the conduct of the incubation experiment. This was measured by weighing each chamber on each day of sampling and also measuring the volume of the soil core sample periodically to account for bulk density changes due to swelling and shrinkage with changing moisture content. We saturated all samples at the beginning of the experiment and most were still above 90% WFPS one day after water application. All samples dried down to approximately 50% WFPS over the following two weeks through evaporation. It should be noted that the soils dried unevenly (dry at the top and moist below). In a few cases, the head ditch sample from a field dried out more than the corresponding tail drain sample (e.g. An, Nh, Rb).

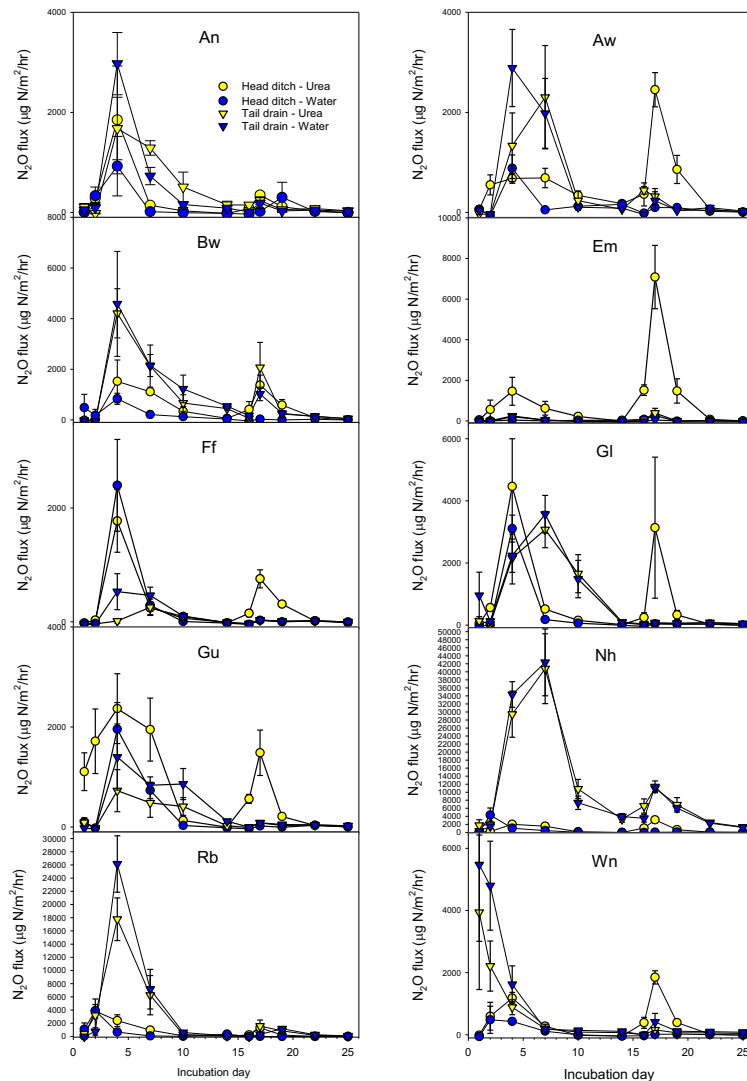


**Figure 35.** *Water-filled pore space (WFPS) throughout the incubation experiment for soils and sediments of 10 commercial paddocks after incubation with either added water or dissolved urea solution. Each point is a mean of 4 replicate chambers  $\pm$  standard error.*

Figure 36 shows the daily nitrous oxide flux for all the soil and sediment samples in the experiment. There was a very large range in flux results between sites and sample locations as indicated by the different scales in the graphs shown. In most samples, emissions were relatively low on days 1–2 of sampling, but Gu-head-urea and Wn-tail samples produced high fluxes from the first day of measurement. Fluxes in most other samples tended to peak on day 4 then decline in subsequent days until most reached a baseline by day 14. Extremely high fluxes were observed from the tail drain samples from Nh and Rb, both of which were initially very high in mineral N; Rb as nitrate-N and Nh as ammonium-N and nitrate-N (Table 8). However, another tail drain sample initially very high in mineral N (Bw) did not produce fluxes of the same magnitude. After the second wetting up of the incubated cores, fluxes of nitrous oxide again increased, but not to the same highs seen in the first part of the study. The most common increase was noted in head ditch samples with added urea, with this short-lived peak occurring on the second day after addition of water/solutions being the highest flux of the whole experiment for a few samples. After this time nitrous oxide emissions in all samples declined to a baseline level by day 25 of the experiment.

These daily fluxes were combined to give cumulative totals of nitrous oxide emitted for each sample in the study (Table 10). Statistical analysis of the whole dataset showed significant differences according to farm, sample location, solution used, and all interactions between these factors, except “farm x location x

solution". In general, the addition of urea solution increased fluxes in head ditch samples by between 111–2578% (median increase = 250%), while adding a less concentrated urea solution to the tail drain samples had no overall effect. Separate statistical tests on each sample showed that the solution used (water or urea solution) mostly affected nitrous oxide loss from samples with low initial mineral N concentrations. In all but one case (Ff-tail), there was significantly more nitrous oxide emitted from the treatment with urea solution added compared to that with just water. It can be seen from Figure 36 that most of the difference occurred during the second simulated irrigation event as fluxes during the first event were mostly similar between water and urea solution treatments.



**Figure 36.** Daily nitrous oxide flux throughout the incubation experiment for head ditch and tail drain samples of 10 commercial paddocks during incubation with either added water or dissolved urea solution. Each point is a mean of 4 replicate chambers  $\pm$  standard error. Note different scales used for each paddock.

**Table 12.** Cumulative nitrous oxide ( $\text{mg N}_2\text{O-N/m}^2$ ) emitted during the incubation experiment according to farm, sample location (head ditch, tail drain), and solution (water, urea). An overall analysis showed

significant differences according to farm, location, solution, and all interactions except “farm x location x solution”. Individual sample analysis showed significant “solution” effects on some samples, indicated by different letters for each pair.

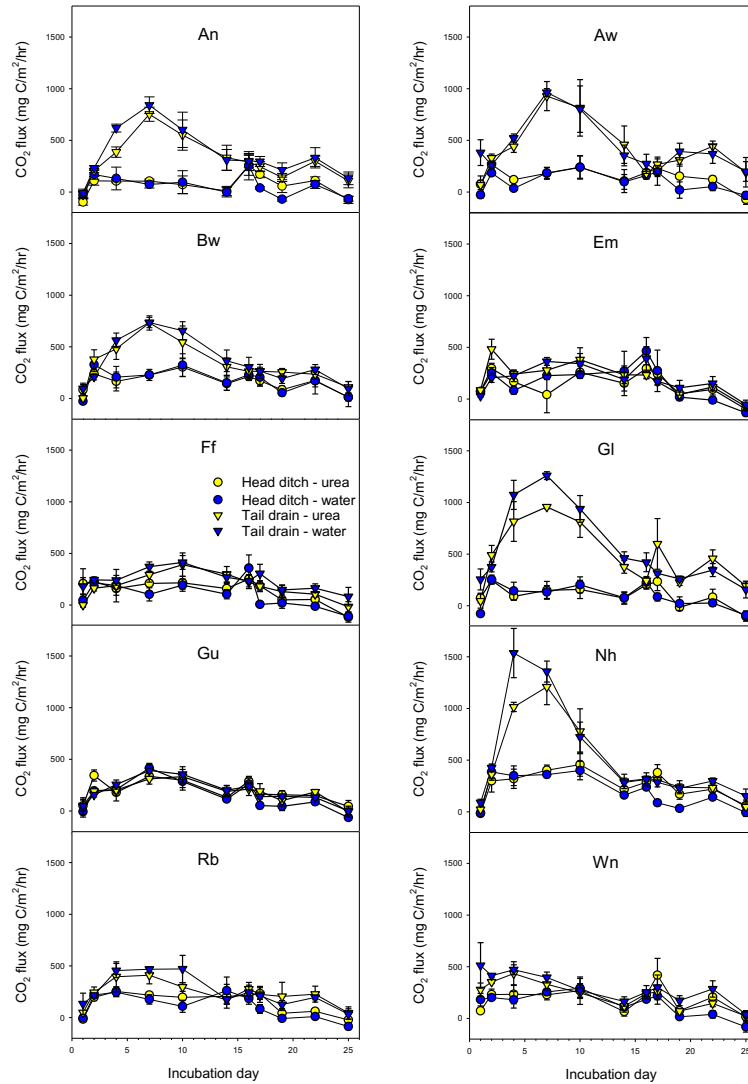
Farm	Head ditch		Tail drain	
	Urea	Water	Urea	Water
An	126	66	250	230
Aw	261 <sup>b</sup>	79 <sup>a</sup>	287	312
Bw	271	85	522	572
Em	464 <sup>b</sup>	18 <sup>a</sup>	24 <sup>b</sup>	7 <sup>a</sup>
Ff	147	132	22 <sup>a</sup>	63 <sup>b</sup>
Gl	383 <sup>b</sup>	167 <sup>a</sup>	472	518
Gu	405 <sup>b</sup>	150 <sup>a</sup>	110	207
Nh	386 <sup>b</sup>	189 <sup>a</sup>	6715	6635
Rb	339	188	1516	1925
Wn	168 <sup>b</sup>	34 <sup>a</sup>	232	386

All gas samples were analysed for carbon dioxide concentration, with the flux an indicator of soil microbial activity. As with the nitrous oxide fluxes, carbon dioxide fluxes were initially low, rising to a peak during the initial simulated irrigation. However, in contrast to the nitrous oxide flux, the peak for carbon dioxide in most samples occurred on day 7, whereas the nitrous oxide peak for most was several days earlier. Greatest microbial activity occurred in the tail drain samples from most farms, but for some there was no difference in activity according to sample location. There was only a small increase in carbon dioxide flux in response to the second water/solution addition, with none of the large surges in microbial activity seen after the first wetting repeated after the second.

Cumulative carbon dioxide emitted results (Table 11) showed significant differences between farms, sample locations on farm and an overall lower emission from urea-treated tail drain samples than those treated with water. There was a significant positive relationship between cumulative nitrous oxide emitted and carbon dioxide emitted, but only for chambers where the cumulative nitrous oxide loss was greater than 900 mg N<sub>2</sub>O-N/m<sup>2</sup> ( $r^2 = 0.81$ ). There was no link between the two gases below this level of N loss.

Methane fluxes during the incubation study (Figure 38) did not appear to be affected by either farm, sample location or solution applied, but instead fluctuated throughout the incubation similarly across the sample set. Several results from three samples were an order of magnitude greater than any others in the whole trial set, but these occurred in individual replicate chambers so were either an error in the laboratory analysis or an isolated occurrence of extreme anaerobic conditions promoting accelerated methane production. These few results were treated as outliers and excluded from the calculation of cumulative methane.

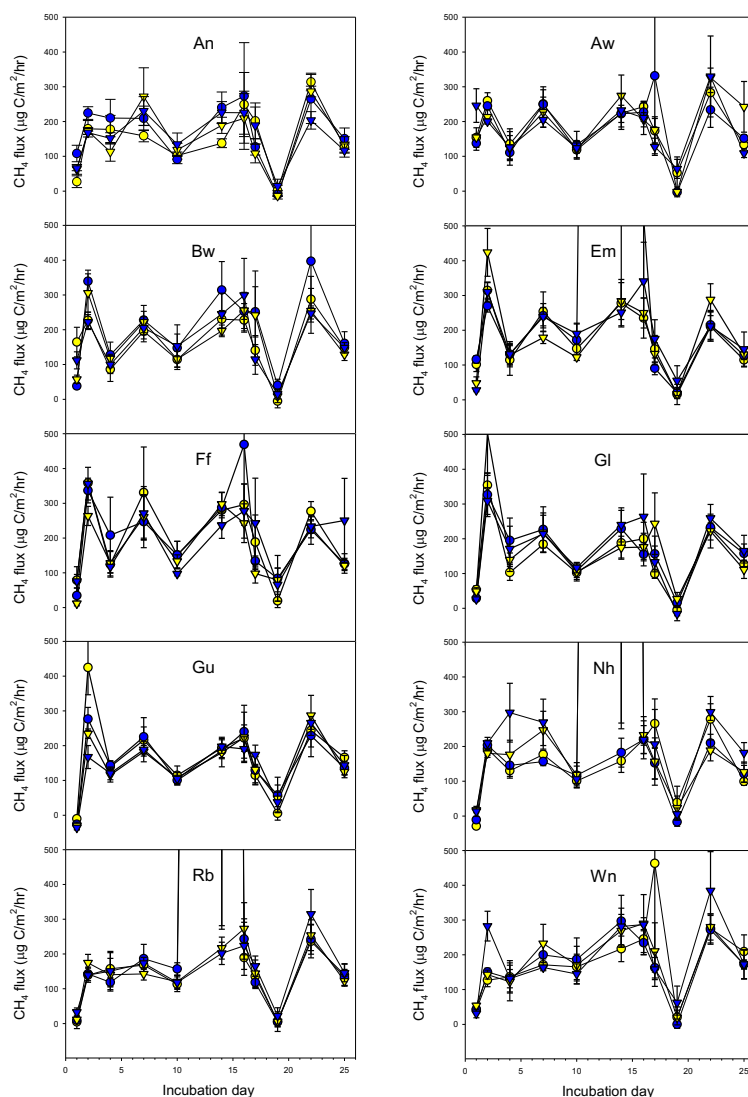
The cumulative amounts of methane emitted (Table 12) were significantly different between farms, but not affected by either sample location or solution added. This result suggests that there may be some local differences in soil microbial communities responsible for methane production in waterlogged soils.



**Figure 37.** Daily carbon dioxide flux throughout the incubation experiment for head ditch and tail drain samples of 10 commercial paddocks during incubation with either added water or dissolved urea solution. Each point is a mean of 4 replicate chambers  $\pm$  standard error.

**Table 13.** Cumulative carbon dioxide flux ( $\text{g CO}_2/\text{m}^2$ ) emitted during the incubation experiment according to farm, sample location (head ditch, tail drain), and solution (water, urea). An overall analysis showed significant differences according to farm ( $\text{LSD} = 27.4$ ), location ( $\text{LSD} = 12.3$ ), farm  $\times$  location ( $\text{LSD} = 38.8$ ), and location  $\times$  solution ( $\text{LSD} = 17.3$ ).

Farm	Head ditch		Tail drain	
	Urea	Water	Urea	Water
An	41	32	205	234
Aw	80	60	276	279
Bw	100	103	210	227
Em	75	90	115	121
Ff	78	56	118	147
Gl	54	52	299	346
Gu	116	94	112	121
Nh	156	120	284	329
Rb	87	67	141	154
Wn	101	79	122	159



**Figure 38.** Daily methane flux throughout the incubation experiment for head ditch and tail drain samples of 10 commercial paddocks during incubation with either added water or dissolved urea solution. Each point is a mean of 4 replicate chambers  $\pm$  standard error.

**Table 14.** Cumulative methane ( $\text{mg CH}_4/\text{m}^2$ ) emitted during the incubation experiment according to farm, sample location (head ditch, tail drain), and solution (water, urea). An overall analysis showed significant differences only according to farm ( $\text{LSD} = 14.9$ ), not location, solution, nor any interaction.

Farm	Head ditch		Tail drain	
	Urea	Water	Urea	Water
An	94	108	100	100
Aw	113	110	121	111
Bw	103	133	104	108
Em	110	118	113	118
Ff	127	130	113	123
Gl	91	104	100	109
Gu	102	98	94	94
Nh	91	86	98	115
Rb	91	95	95	101
Wn	114	114	118	124

Soil properties of the samples used in the experiment were regressed against the various results described above to discover what aspects had the most influence on emissions. Several of the soil properties were strongly correlated. For example, clay concentration was strongly correlated with water holding capacity, which determined how much water was added to each chamber to reach the desired water content, described in terms of water filled pore space WFPS. However, WFPS was largely independent of soil texture until near the end of each incubation period when the samples were at their driest. Soil texture also determined the bulk density of the sample inside the chamber at any day of the incubation through the influence of texture on soil shrinkage during drying, with higher clay samples linked to lower bulk density ( $r = -0.84$ ).

Soil organic carbon (and soil total nitrogen) levels were strongly correlated to dissolved organic carbon (DOC) in pre-trial samples ( $r = 0.60$  and  $0.72$ , respectively). DOC was strongly related to carbon dioxide flux from days 4–14, and 17-25, but only weakly linked to nitrous oxide emission. Pre-trial soil ammonium concentration was linked to carbon dioxide flux on days 4–10 and strongly correlated with nitrous oxide flux throughout the experiment from day 4 onwards, courtesy of two very high ammonium samples that had very high nitrous oxide losses. Soil nitrate concentration measured mid-trial, was more strongly correlated with nitrous oxide flux from day 4 until the end of the incubation than pre-trial measures as it incorporated the initially high pre-trial ammonium (converted to nitrate during the trial) plus the applied N in the urea treatments.

Daily methane fluxes showed some positive correlations with carbon dioxide flux measured on the same days, with the strongest relationship found on day 16, 1 day after the second water addition ( $r = 0.74$ ). There was no link between fluxes of the two gases on day 10, but on this day methane flux was negatively correlated with WFPS ( $r = -0.42$ ).

#### *Conclusions from the incubation experiment*

Nitrous oxide emissions from head ditch and tail drain samples of irrigated cotton paddocks were overwhelmingly driven by the concentration of mineral N present in the sample before the simulated irrigation. Nitrate and, in one case, ammonium were extremely high, particularly in tail drain samples of several farms. These high mineral N concentrations produced losses up to 100 times greater than those from some of the low mineral N samples. Applying urea in the simulated irrigation water increased nitrous oxide losses from samples with low initial mineral N, particularly in the second irrigation. This indicates that the drying conditions restricted emissions emanating from the added urea which restarted again as the samples were rewetted.

The influence of soil organic C or N on the nitrous oxide losses (through mineralisation of mineral N) were difficult to discern with the presence of large mineral N concentrations that had been recently added through fertilisers. However, DOC from the soil organic matter did positively influence soil microbial activity once the initial waterlogged stages had passed.

Tail drain samples tended to lose more nitrous oxide than head ditch samples, though this may be mostly due to the typically higher initial mineral N concentrations from both naturally higher soil organic matter and from sedimentation of nutrient-rich water during irrigation in the field. The application of additional N to tail drain samples in the simulated water-run urea treatments caused little change in nitrous oxide emission as the N amount added was quite small in relation to most of the high initial soil mineral N concentrations.

These non-cropped areas of the paddock are of concern, not because they behave similarly to soils within the cropped section of the paddock in terms of high N supply leading to high nitrous oxide fluxes, but because they will retain high soil mineral N concentrations throughout the season unlike the remainder of the paddock where the growing plants deplete the available N. In a typical paddock, such as that used for the Gunnedah experiments, this area may make up about 2% of the total paddock area. The tail drain area is likely to receive much of the nutrient-laden sediment from the paddock during irrigation events. Further research is required to devise management options to minimize the emissions from these areas.

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## IMPLICATIONS FOR AUSTRALIAN AGRICULTURE

*Explain the significance of these findings for policy makers and the Australian agricultural industry.*

The Australian cotton industry is striving to present an environmentally considerate image to national and global markets and consumers. The outcomes of this research will firstly help quantify the greenhouse gas emissions (nitrous oxide) associated with commercial cotton production by adding to the existing data more measurements that may be considered when revising national emission factors used in national greenhouse gas inventory accounting. Our data mostly sit well below the current Australian emissions factor of 0.55% for irrigated cotton. We have documented emissions resulting from both new and old fertiliser N application and irrigation strategies used by farmers in the three regions studied. Outcomes of this research can help answer questions about the potential environmental effects of variations in practice. Our most recent trial results provide data on a nitrification inhibitor product that was previously untested in Australian agriculture.

These results represent a significant addition to the existing knowledge of nitrous oxide emissions from irrigated cotton production in northern Australia, covering some regions where such work has not been previously done. We have also researched several strategies for potential nitrous oxide mitigation that have not previously been examined. Several of these strategies can potentially be developed for inclusion in methodologies for reducing greenhouse gas emissions in irrigated cotton.

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## ENDORSEMENT

Include a signed statement by the peer reviewer(s) endorsing the report.

**Reviewer A:** Dr Nilantha Hulugalle (ret. Principal Research Scientist, NSW DPI)

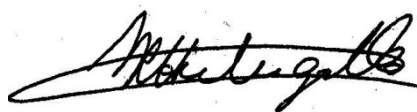
I have reviewed this report and find it suitable for submission to the funding organization. Minor comments have been noted in an annotated copy of report. *[author: all comments have been addressed]*

N. R. Hulugalle, 8.03.2017

Visiting Fellow

Fenner School of Environment and Society,

Australian National University, Canberra, ACT, Australia



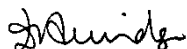
**Reviewer B:** Prof. David Herridge (Research Professor, UNE)

I have read the report by Dr Graeme Schwenke 'Determining optimum nitrogen strategies for abatement of emissions for different irrigated cotton systems' and endorse it as a valuable, high-quality report. The author provides a comprehensive account of a 3-year study of nitrous oxide emissions from eight experiments in cotton fields at three sites in NSW and Qld, together with a laboratory-based incubation study of emissions from head ditch soils and tail-drain sediments from 10 sites in NSW and Qld. The report itself is well-written with excellent presentation of quite complex data sets. Dr Schwenke is to be commended for the quality of the report.

I only have two suggestions for consideration by the author. The first is to dot point the major conclusions/implications of the study, i.e. what does this mean for cotton growers. The conclusions/implications are in the executive Summary and in the Conclusions of each experiment, but are somewhat lost in the large volume of text and graphs/tables of the report. There might be 10 dot points from the 3-year study, including a statement about the value or otherwise of excessive N rates (2014-15 expts), N application and irrigation strategies (2015-16), relationships between fertilizer N in the soil, water and emissions, etc. *[author: dot points have been added to the executive summary]*

My second suggestion is for the author to think about combining data from this study with LCA (life cycle assessment), similar to what has been done with nitrous oxide emissions associated with rainfed grain cropping. *[author: this could be a possible future project]*

David Herridge



Research Professor, Soil Productivity

School of Environmental and Rural Science

University of New England, Armidale, NSW

Australia

06.03.2017

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## ACKNOWLEDGEMENTS

This project was supported by funding from the Australian Government through the Carbon Farming Initiative.

This project was conducted with the funding, resources and infrastructure support of the NSW Department of Primary Industries. We also acknowledge the time and efforts of the cooperating farm managers Rod Smith, Ray Fox, Cam Geddes and Ross Burnett in accommodating the trials and helping to impose the treatments. As well, we thank the farm owners for the use of the land. The final year on-farm trials were greatly assisted by the time, equipment and products supplied by the Incitec-Pivot “Big-N” team. Dow Agrosiences supplied the N-serve product. We also kindly acknowledge the efforts of the contractors associated with the remote trial sites at Emerald and Moree, including Amanda Noone, Renee Anderson, Brooke Cutler, Alice Devlin, and Megan Adams. Thanks also to a range of NSW DPI technical and professional staff who helped out in various field and laboratory activities including, Wayne McPherson, Clarence Mercer, Mandy Holland, Tara Burns, Jon Baird, Lloyd Finlay, Mark Watkins, Guna Natchimuthu, Tim Grant, Steve Kimber, Brad Keen, Nicole Morris, Ashley Webb and Tim Grant.

Special thanks go to the dedicated service of Annabelle McPherson, technical officer with NSW DPI who did the lion’s share of the field work in this project, as well as organized contractors and collated data from every aspect of this trial.

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## ATTACHMENTS

1. Plain English Summary – limited to two pages, endorsed by the peer reviewer(s), summarising the key findings and outcomes of the project.
2. List all intellectual property created or arising over the life of the project.
3. List all submitted publications arising from this project. Include the name of the publication, the publication date/edition. Include the web address where applicable. Include the status of the submitted publication.
4. Consent to use photographic and audiovisual recordings.

## PLAIN ENGLISH SUMMARY

Please provide a Plain English summary for public release using the template below.

The summary will be uploaded to the department's website and should stand alone as a summary of the project that can be understood by people without expertise in the field.

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### PROJECT TITLE

Determining optimum nitrogen strategies for abatement of emissions for different irrigated cotton systems.

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### PARTNER ORGANISATIONS

NSW Department of Primary Industries, Cotton Research and Development Corporation

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### PROJECT SUMMARY

Irrigated cotton production in central Qld and northwest NSW is a high input–high return agricultural industry. Well-informed management of nitrogen fertiliser application and irrigation can minimize the potentially significant production of the greenhouse gas nitrous oxide from the system. We investigated variations to existing management practices and new technologies to mitigate the formation of nitrous oxide. These strategies can also improve the efficiency of use of the applied nitrogen fertilisers.

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### OBJECTIVES

The objective of this project was to investigate strategies of nitrogen fertiliser and irrigation management that will reduce nitrous oxide emissions and maintain the high productivity of irrigated cotton systems in central Queensland and northwest NSW.

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### KEY ACTIVITIES

We conducted three sets of field trials during three summer cotton growing seasons at Emerald (central Qld), Moree (northern NSW) and Gunnedah (Liverpool Plains, NSW). At each trial, we compared the co-operator's current practice with two alternative treatment. Each treatment was replicated three times and randomly located within the trial area, giving a total of nine plots in each trial. Each plot was either 8 or 12 cotton rows wide (depending on the farm equipment used) and the whole length of the paddock (from 650–1500 m long).

In the first season, trials focused on different nitrogen fertiliser rates. In the second season, the treatments compared timing of nitrogen fertiliser application, and the location of irrigated furrows in relation to the location of the fertiliser band. The third season's trials evaluated the effectiveness of two nitrification inhibitor products in terms of reducing nitrous oxide emissions and retaining more of the applied fertiliser in the soil for the crops to use.

We also conducted a laboratory incubation study using head ditch and tail drain soil/sediment samples from 10 farms across the region, including those farms where our trials were located. Emissions of nitrous

oxide, carbon dioxide and methane were compared under simulated irrigation with water or water-run urea.

Originally, this project also proposed to quantify the potential of these techniques for improving carbon sequestration in the soil. However, measureable treatment effects on soil carbon levels from single season treatments were unlikely so repeated monitoring for soil carbon was not pursued.

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## OUTCOMES

In the first season, each trial incorporated the cooperators' nitrogen fertiliser regime, plus two additional treatments where the total nitrogen rate applied was either 25% more or 25% less. Nitrous oxide emissions increased with the fertiliser rate used, but cotton yields did not, thus all farms used more fertiliser than needed and produced more nitrous oxide than needed for optimum production.

In the second season, trials investigated either applying all nitrogen fertiliser before planting, or applying some pre-plant and some in-crop (split N). Nitrous oxide emissions were observed after each application of nitrogen fertiliser, but there were no clear differences between treatments in cumulative losses over the season. Yields were also not affected. We also looked at the proximity of irrigation water to the location of the pre-plant fertiliser and found that irrigating the opposite side of the hill to the fertiliser produced less nitrous oxide, but did not affect cotton yields—nor did irrigating every furrow rather than every second furrow. At Emerald, a slow-flow long-duration irrigation (old practice) was found to be worse than a fast-flow short-duration irrigation (current practice), both in terms of nitrous oxide loss and crop production.

In the third year's trials, we tested two different nitrification inhibitor chemicals applied to the injected stream of anhydrous ammonia during pre-plant fertiliser application. Both chemicals, DMPP (N-sure™, Incitec Pivot Fertilisers) and nitrapyrin (N-Serve™, Dow Agrosiences) were highly effective in reducing nitrous oxide emitted during both pre-sowing and early crop growth periods. Cotton yields were not affected by the use of the inhibitors.

Of the samples collected for the incubation study, the tail drain sediments were typically more concentrated in organic carbon, organic nitrogen and mineral nitrogen. These uncropped areas of cotton paddocks can have extremely high mineral nitrogen concentrations (from fertiliser application and irrigation deposition) which lead to high rates of nitrous oxide emission after the simulated irrigations in the incubation study. Unlike the cropped areas of the paddock, there is no crop uptake of the mineral nitrogen so the nitrous oxide losses will likely occur with each irrigation whereas those in the cropped area typically only follow the first one or two irrigation events.

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## IMPLICATIONS

The Australian cotton industry is striving to present an environmentally considerate image to national and global markets and consumers. The outcomes of this research will firstly help quantify the greenhouse gas emissions (nitrous oxide) associated with commercial cotton production by adding to the existing data more measurements that may be considered when revising national emission factors used in national greenhouse gas inventory accounting. Our data mostly sit well below the current Australian emissions factor of 0.55% for irrigated cotton. We have documented emissions resulting from both new and old fertiliser N application and irrigation strategies used by farmers in the regions studied. Outcomes of this research help answer questions about the potential environmental effects of variations in practice. Our

most recent trial results provide data on nitrification inhibitor products that were previously untested in Australian conditions, or anywhere in the case of the N-sure™.

These results represent a significant addition to the existing knowledge of nitrous oxide emissions from irrigated cotton production in northern Australia, covering some regions where such work has not been previously done. We have also researched several strategies for potential nitrous oxide mitigation that have not previously been examined. Several of these strategies could potentially be developed for inclusion in methodologies for reducing greenhouse gas emissions in irrigated cotton.

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