**Introduction**

Cotton is a high value commodity and crops normally require N fertiliser to optimise lint production. Growers cannot afford to under-fertilize with N (or other nutrients) and tend to manage risk by ensuring their cotton crop yields are not limited by N deficiency. Cotton-growing soils are typically medium to heavy clays and are prone to waterlogging following furrow irrigation or heavy rain (Scheer et al., 2008, Scheer et al., 2013, Han et al., 2014). Losses of 50-100 kg N/ha can occur during the growth of a cotton crop through denitrification and leaching (Rochester 2003), resulting in inefficient use of N fertiliser. Periodic waterlogging and drying drives soil the denitrification processes which leads to the production of nitrous oxide (N₂O) and nitrogen (N₂) gases. Measured losses from the fertilised hills in furrow irrigated systems are typically below 3% of the applied fertiliser (Rochester 2003, Mahmood et al. 2008, Scheer et al. 2013). In cotton production systems emissions of N₂O from the furrows can be greater than the hills when urea is water-run down the furrows (Grace et al., 2010). Grace et al. (2010) also indicated there was substantial movement of nitrate-N from the mounds into the furrows. In furrow systems which are over-irrigated, up to 18.6 kg N/ha can be lost into the irrigation network (McHugh et al., 2008). Once the nitrate enters the tail water it is lost from the field and may undergo denitrification to N₂O and N₂ in water storages. Harrison and Matson (2003) have shown in furrow irrigated wheat production in Mexico that N₂O losses can be large, averaging 40 N₂O-N g/ha/day. This paper seeks to identify key nitrogen loss pathways in Australian cotton production systems.

**Methods**

**Land surface N₂O Measurements and N₂ estimate**

Emissions from the soil and crop were measured using chambers (see Scheer et al. 2013) connected to a fully automated system that enabled N₂O emissions from each of the four fertiliser treatments. The N₂O concentrations were measured with gas chromatography. N₂O was measured during all phases of a 2-year cotton-faba bean-fallow rotation. N₂ emission was estimate from the N₂O:N₂ mole relationship determined by Rochester (2003).

**Dissolved nitrate, organic nitrogen and nitrous oxide in the irrigation network**

Filtered (0.45 μm) water samples were collected for the determination of nitrate, total ammonia nitrogen (TAN), and total dissolved nitrogen (TDN). Total nitrogen (TN) was determined on unfiltered samples. Collected samples were placed in an insulated box and stored at 4°C, returned and analysed in the laboratory within 7 days. Nitrate and TAN were measured using the cadmium reduction method (Method 4500 Nitrate F; Rice et al., 2012) and automated phenate method (Method 4500 Ammonia G; Rice et al., 2012). The TN and TDN samples were digested using the persulphate method (Method 4500-N; Rice et al., 2012) and the nitrate concentration in the digest.
was measured using the cadmium reduction method. Dissolved nitrous oxide concentration was determined using the headspace equilibrium technique (Weiss and Price, 1980).

Estimations of N\textsubscript{2}O flux
Nitrous oxide flux was estimated from dissolved nitrous oxide concentrations using the following equation:

\[
flux = k_{total} \times (N_{2O(water)} - N_{2O(eq)})
\]

Where \(N_{2O(water)}\) is the measured concentration of N\textsubscript{2}O in the water, \(N_{2O(eq)}\) is the concentration the water would have if it were in equilibrium with the atmosphere and \(k\) is the gas transfer coefficient (m.s\(^{-1}\)) (Clough et al., 2007; Cole & Caraco, 2001).

The gas transfer coefficient, \(k_{total}\), was calculated as the sum of the transfer velocities attribute to wind \(k_{wind}\) and water \(k_{water}\) speed; and were calculated using the following equations (Clough et al., 2007; Wanninkhof, 1992).

\[
k_{wind} = 0.31u_{10}^{2} \left( \frac{Sc}{666} \right)^{0.5} \quad \text{and} \quad k_{water} = \frac{Du}{h}
\]

where \(u_{10}\) is the windspeed at 10m above the height of the water body, \(Sc\) is the Schmidt number for N\textsubscript{2}O, \(D\) is the diffusion coefficient of N\textsubscript{2}O in water, \(U\) is the velocity of water (m.s\(^{-1}\)) and \(h\) is the average depth of the water body (m). Where water speed was unavailable, \(k_{wind}\) was used instead of \(k_{total}\).

The wind speed at 10m height was calculated using the logarithmic wind profile law:

\[
\frac{U_2}{U_1} = \ln \left( \frac{Z_1}{Z_0} \right) + \ln \left( \frac{Z_2}{Z_0} \right)
\]

where \(Z_1\) is the ‘effective roughness height’, here assumed to be 0.001m, and \(U_1\) and \(U_2\) are the respective wind speeds at heights \(Z_1\) and \(Z_2\), respectively (Kubik et al., 2011). \(Sc\) and \(D\) were calculated in R, using the package ‘marelac’ (Soeraert et al., 2010; R Core Team, 2014).

Measurements of deep drainage loss of nitrogen
Water samples were analysed for dissolved N from the drainage lysimeter at the ACRI and used to estimate nitrogen loss from the upper profile.

Results and Discussion
Nitrous oxide emissions from the land surface
Overall for the 0, 120 and 200 kg N/ha fertiliser applications, 40-50% of the N\textsubscript{2}O was emitted from the cotton phase, 5-10% from the faba bean phase and 30% from the fallow. For the over-fertilised 320 kg N/ha treatment, 80% of the N\textsubscript{2}O was emitted from the cotton phase, 6% from the faba bean phase and 14% from the fallow. The N\textsubscript{2}O-N emission factor corrected for the background for the 320 kg N/ha treatment was 3.2% compared with <0.9% for the other measured rates It is evident that during the measurement period that to minimise N\textsubscript{2}O production and maintain yield the fertiliser rate should not have exceeded 200 kg N/ha.

Dissolved nitrate, organic nitrogen and nitrous oxide in the irrigation network
The water chemistry of the irrigation waters shows that the DON+TAN fraction is as large as the NOx fraction (Table 1) and should be considered for nitrogen budgeting. Further, it was observed that there was significant variation in the water nitrogen concentration during irrigation and between irrigations. The soil physical and moisture characteristics also vary within each row and hill and as a result the irrigation water and dissolved nitrogen compounds will transit through the soil at different rates.

The NOx and DON+TAN concentration in the water increases during its transit down the field. The NOx and DON+TAN appear to be sourced from the adjacent hill and are collected as the irrigation water seeps through into the next furrow. It was observed during one irrigation that the irrigation furrow was less saline than the non-irrigated furrow. This indicates that irrigation water is removing salts from the furrow and adjacent hills and transporting them into the tail drain and return channel. As expected, concentrations of N\textsubscript{2}O within the irrigation network were small in comparison to other forms of N, with concentrations ranging from 162ng/L to 6530ng/L (e.g. Cole & Caraco, 2001; Harrison & Matson, 2003). Throughout the sampling period, flux of N\textsubscript{2}O from the irrigation network ranged from 9.76 to 7795.90 g N\textsubscript{2}O-N ha\(^{-1}\) d\(^{-1}\), averaging 222.54 g N\textsubscript{2}O-N ha\(^{-1}\) d\(^{-1}\).

Deep drainage loss of nitrogen
During the 2008-2009 cotton season we measured nitrogen leaching from the surface down to 2 meters depth. About 10 kg of N/ha was lost by deep drainage during that cotton season which equated to 6% of the applied fertiliser (160 kg N/ha).

| TABLE 1. The flux of nitrate and DON+TAN from each field and its potential contribution to N\textsubscript{2}O emissions (per irrigation per ha). |
|-----------------|-----------------|-----------------|
| Irrigation Network Component | Nitrate Pool | DON+TAN Pool |
| | kg N | g N\textsubscript{2}O-N | kg N | g N\textsubscript{2}O-N |
| Tail Drain D4 | 1.1 (0.9)* | 102 (87)* | 2.7 (5.8) | 80 (23) |
| Return | 0.4 (0.0)* | 34 (0)* | 2.8 (56.1) | 85 (224) |
| Tail Drain F3 | 2.4* | 215 (NA)* | 7.9 | 711 (NA) |
| Tail Drain F7 | 2.3* | 206 (NA)* | 1.8 | 157 (NA) |
| Storage | 108 (0.7)^ | 5771 (4649)^ | 73 | 1290 (NA) |

*Conversion from NO\textsubscript{x} to N\textsubscript{2}O based on Seitzinger and Kroeze 1998 method; Conversion from DON based on Kyoto Protocol estimates for waste water; ^Assuming 1 ML/ha irrigation at 75% efficiency; *Assuming 33 ML irrigation water in storage.
Conclusions

Our measurements estimate that ~40% of the applied urea-N was lost from the field (Figure 1) into the atmosphere and into the subsoil and removed in run-off irrigation water, including water storages. The surface water and nitrogen gas components represent the greatest loss pathways. In the systems we studied, urea was drilled into the hill to a depth of 20 cm prior to sowing and irrigation was applied to alternate furrows that resulted in N leaching from the hills. It is evident that N$_2$O emissions from the tail water can increase the GHG footprint of the irrigated system. Mitigation strategies include reducing irrigation volumes, placing the N fertiliser deeper in the soil, and strategically use N-rich tail water in adjacent fields.

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References


