Nitrogen use efficiency in summer sorghum grown on clay soils

M. Bell[1], D. Lester[2], M. De Antoni Migliorati[3], D. Rowlings[3] P. Grace[3]

[1] Queensland Alliance for Agriculture and Food Innovation, University of Queensland, Gatton Campus, Gatton, QLD, 4343. m.bell4@uq.edu.au.

[2] Department of Agriculture and Fisheries, Queensland. PO Box 102, Toowoomba, QLD, 4350. david.lester@daf.qld.gov.au david.lester@daf.qld.gov.au

[3] Institute for Future Environments, Queensland University of Technology, Brisbane, QLD 4000, max.deantonimigliorati@qut.edu.au, d.rowlings@qut.edu.au, pr.grace@qut.edu.au

Abstract

Nitrogen fertilizer inputs dominate the fertilizer budget of grain sorghum growers in northern Australia, so optimizing use efficiency and minimizing losses are a primary agronomic objective. We report results from three experiments in southern Queensland sown on contrasting soil types and with contrasting rotation histories in the 2012-2013 summer season. Experiments were designed to quantify the response of grain sorghum to rates of N fertilizer applied as urea. Labelled ^{15}N fertilizer was applied in microplots to determine the fate of applied N, while nitrous oxide (N_2O) emissions were continuously monitored at Kingaroy (grass or legume ley histories) and Kingsthorpe (continuous grain cropping). Nitrous oxide is a useful indicator of gaseous N losses. Crops at all sites responded strongly to fertilizer N applications, with yields of unfertilized treatments ranging from 17% to 52% of N-unlimited potential. Maximum yields ranged from 4500 (Kupunn) to 5450 (Kingaroy) and 8010 (Kingsthorpe) kg/ha. Agronomic efficiency (kg additional grain produced/ kg fertilizer N applied) at the optimum N rate on the Vertosol sites was 23 (80 N, Kupunn) to 25 (160N, Kingsthorpe), but 40-42 on the Ferrosols at Kingaroy (70-100N). Cumulative N_2O emissions ranged from 0.44% (Kingaroy legume) to 0.93% (Kingsthorpe) and 1.15% (Kingaroy grass) of the optimum fertilizer N rate at each site, with greatest emissions from the Vertosol at Kingsthorpe. The similarity in N_2O emissions factors between Kingaroy and Kingsthorpe contrasted markedly with the recovery of applied fertilizer N in plant and soil. Apparent losses of fertilizer N ranged from 0-5% (Ferrosols at Kingaroy) to 40-48% (Vertosols at Kupunn and Kingsthorpe). The greater losses on the Vertosols were attributed to denitrification losses and illustrate the greater risks of N losses in these soils in wet seasonal conditions.

Key words

Nitrogen fertilizer, grain sorghum, NUE, denitrification, ^{15}N balance

Introduction

Grain production in north-eastern Australia (the Northern Grains Region, NGR) predominantly is on Vertosols which have a high soil moisture storage potential. The cropping system is opportunistic, with either summer or winter crops being sown once adequate stored moisture is available. Rapid increases in yield potential and agronomic management systems for grain sorghum (Sorghum bicolor L.) have seen this crop become increasingly dominant in the rotation. At the same time there has been a decrease in soil organic matter status and mineralisable N reserves in the cropped Vertosols (Dalal and Probert 1997) that has resulted in an increasing fertilizer N demand to meet water-limited yield potential. This is illustrated in the contrasting N requirements for 'new' (<10 years cropping history) and 'old' (>40 years cropping history) cropping soils reported by Lester et al. (2008), with the combined effect of increased yield potentials and decreasing native N supply resulting in fertilizer N application rates increasing from negligible to >100 kg N/ha/year in some higher yielding areas.

Fertilizer costs often exceed 30% of the total variable costs in a cropping season, with nitrogen (N) the dominant fertilizer input for grain crops. It is therefore imperative that growers are able to optimise fertilizer N use efficiency (NUE), both in terms of crop recovery of applied N and conversion of that N into improved grain yields. One of the factors than can reduce fertilizer recovery and subsequent NUE is gaseous losses through the process of denitrification – the reduction of soil NO_3-N to N_2O and N_2 which are subsequently lost to the atmosphere. These losses are favoured when soil NO_3-N concentrations are high, there are sufficient levels of organic carbon and there is a deficit of oxygen such as would occur when clay soils become waterlogged. The summer sorghum crop in the NGR is typically sown into soil profiles that already are wet, at the beginning of the summer rainy season with N fertilizer typically applied in advance of sowing. The variable rainfall patterns preclude in-season N applications in most rainfed areas, so the full complement of N to meet expected crop demand is available in the soil well in advance of crop N demand – a situation that is high risk for denitrification losses and inefficient use of fertilizer N.

This study explored the fertilizer N response of sorghum crops at three locations in southern Queensland, determining crop N recovery and the efficiency with which fertilizer N was converted into grain yield. It also monitored N_2O emissions continuously or periodically, depending on site, as an indicator of denitrification events, and used ^{15}N recoveries in soils and plants to indicate the fate of applied N fertilizer and the extent of N losses.

Methods

Field experiments were conducted in 2012-2013 on research stations in the South Burnett (Kingaroy) and near Toowoomba (Kingsthorpe), as well as in a commercial sorghum field at Kupunn, in the central Darling Downs. The soil types were a Brown Ferrosol (Kingaroy) and a Black (Kingsthorpe) and Grey (Kupunn) Vertosol, respectively. The Kupunn crop was sown in mid-October 2012 following a short fallow and a previous sorghum crop in 2011-2012 and was grown solely rain-fed; Kingsthorpe was sown on 26 November, after a short duration winter forage crop of barley removed for hay; however Kingaroy, which was sown on 10 December, was sown onto contrasting grass or legume ley pasture histories (detailed in Migliorati et al. 2015). The different rotations were continued until spring of 2012 and although supplementary irrigation was used, the soil profile in the 2012-2013 planting window was quite dry, necessitating a 20 mm irrigation to allow planting and 100 mm split over three subsequent irrigation events until mid-January to ensure good crop establishment and tillering. After mid-January the crop was also solely reliant on rainfall.

The 2012-2013 season was unusually wet, with in-season rainfall totalling 360 mm (Kupunn), 392 mm (Kingsthorpe) and 770 mm (Kingaroy), respectively, although heavy rainfall over a 2-3 day period in late January 2013 contributed 30-45% of the seasonal total and, in the case of Kupunn, lead to a 4-5 day period of inundation from floodwater.

Nitrogen fertilizer was applied as banded urea either 25 d prior to planting (Kupunn), at planting (Kingsthorpe) or split between planting and a side dressing application 4 weeks after planting (Kingaroy). Rates of application were 0, 70, 100 and 120 kg N/ha at Kingaroy, 0, 20, 40, 60, 80, 120 and 160 kg N/ha at Kupunn and 0, 70, 140, 280 and 420 kg N/ha at Kingsthorpe. Urea labelled with ^{15}N (10% enrichment) was applied in solution in micro plots embedded within a subset of the N rate main plots in each field trial at the time of fertilizer application.

During the season, N_2O emissions were monitored using a fully automated greenhouse gas measuring system at both Kingaroy and Kingsthorpe, providing a long-term high temporal resolution dataset to quantify cumulative N_2O emissions during the growing season and the subsequent fallow. Twelve automated sampling chambers were deployed in each experiment, with chambers placed adjacent to the crop row and encompassing the fertilizer band in the targeted N rates and in a similar position in the 0N treatment to provide quantitation of background N_2O emissions. The measuring system was deployed immediately after planting and temporarily withdrawn to permit farming operations (side dressing, harvest, post-harvest cultivations) as appropriate. At Kupunn, periodic measurements were made using manual chambers deployed on band and inter-band positions, with measurements used as a relative assessment of emissions in different N rates at different times after fertilizer application.

Biomass samples were collected at physiological maturity, dried and analysed for total N content, with fertilizer N recovery calculated as the difference between the N content of the unfertilized Control and the respective N rate treatments. Grain yields were determined after the crop was sprayed with glyphosate at Kupunn, but directly harvested at Kingsthorpe and Kingaroy, and grain N concentration was determined to quantify net N balance of the different N rates. In the case of the ^{15}N microplots, plant samples (including roots and crowns in the top 10-15 cm) were collected at harvest and separated into above (grain and stover) and below ground biomass before analysis to quantify fertilizer N recovery.

Soil samples were collected to 100-120 cm in both the ^{15}N microplots and selected treatments in the main agronomy trial immediately after harvest. In the agronomy trial these were used to determine residual mineral N and in the ^{15}N trial both mineral N and total N determinations were made. There was no evidence of significant leaching of ^{15}N fertilizer deeper than 50 cm (Kingsthorpe) – 70 cm (Kingaroy and Kupunn). The fate of applied fertilizer N was therefore calculated as the sum of labelled ^{15}N recovered in the soil and plant pools, with the difference between the applied N and N recovered at harvest determined as lost via gaseous N loss pathways.

Results

Crop response to applied N

Crops at all sites responded strongly to fertilizer N applications. Yields in the unfertilized treatments were lowest after the grass ley history at Kingaroy (940 kg/ha), but ranged between 2500 and 3700 kg/ha at the other locations (Table 1). These yields represented 17% (Kingaroy, grass ley history) to 52% (Kupunn, short fallow after sorghum) of the N-unlimited yield potential (Y_{max}) across the sites, with differences in Y_{max} related to low plant populations (Kupunn) and excessively wet and overcast conditions at critical growth stages (Kingaroy). There were relatively small differences in mineral N contents in the soil profile prior to planting (50-70 kg N/ha to 90cm), but much larger differences in crop N accumulation in above ground biomass in the unfertilized treatments (25-113 kg N/ha), suggesting significant differences in net N mineralization and crop acquisition during the growing season.

The fertilizer N rate at which yields closely approximated 90% of the N-unlimited yield potential ($Y_{90\%}$) was similar at Kupunn and the Kingaroy sites (70-100 kg N/ha), but was higher at Kingsthorpe (160 kg N/ha). This was consistent with the differences in yield potentials (5200-5400 kg/ha vs 8010 kg/ha), and hence crop N demand. Agronomic efficiency (kg additional grain produced/kg applied N fertilizer) at the N rate resulting in $Y_{90\%}$ was 23 (80 N, Kupunn) to 25 (160N, Kingsthorpe) but 40-42 at Kingaroy (70-100N), with the former suggesting much more efficient use of applied N on the Ferrosol soils at Kingaroy.

Table 1. Agronomic data describing the fertilizer N response at Kingaroy (grass and legume ley histories), Kupunn and Kingsthorpe in 2012/13.

	Kingaroy (grass)	Kingaroy (legume)	Kupunn	Kingsthorpe
Y_0 (kg/ha)	940	2520	2700	3680
Y_{max} (kg/ha)	5440	5440	5220	8010
N rate for $Y_{90\%}$	100	70	80	160
AgronEff$_{Y90}$ (AE_{90}; kg additional grain/kg N applied)	42.5	39.6	28.7	25.9

Cumulative N_2O emissions

Nitrous oxide emissions for the sorghum growing season and the immediate period post-harvest are shown in Figure 1 for Kingaroy and Kingsthorpe, with the contribution of emissions resulting from fertilizer application clearly evident at both locations relative to the unfertilized controls. What is also evident is the episodic nature of emissions, especially in response to significant rainfall events producing waterlogging (e.g. late Jan-early Feb 2103) and also to irrigation events earlier in the season at Kingaroy.

The net effect of fertilizer application (i.e. discounting emissions from unfertilized treatments) was higher on the Vertosol at Kingsthorpe (2150 $\pm$ 112 g N_2O-N/ha) than at Kingaroy on the Ferrosol, despite much lower seasonal rainfall – especially in the event in late January 2013. However, at Kingaroy there was a significant difference between grass and legume ley histories, with the lower emissions in the legume history than the grass (413 v 1267 g N_2O-N/ha, respectively). When the Kingaroy and Kingsthorpe sites with automated monitoring were compared on the basis of N_2O emissions intensity (kg N_2O-N/t grain yield), the legume ley treatment at Kingaroy (0.12 kg N_2O-N/t) was less than half that recorded in the grass ley at Kingaroy or on the site at Kingsthorpe (0.29 and 0.30 kg N_2O-N/t, respectively).

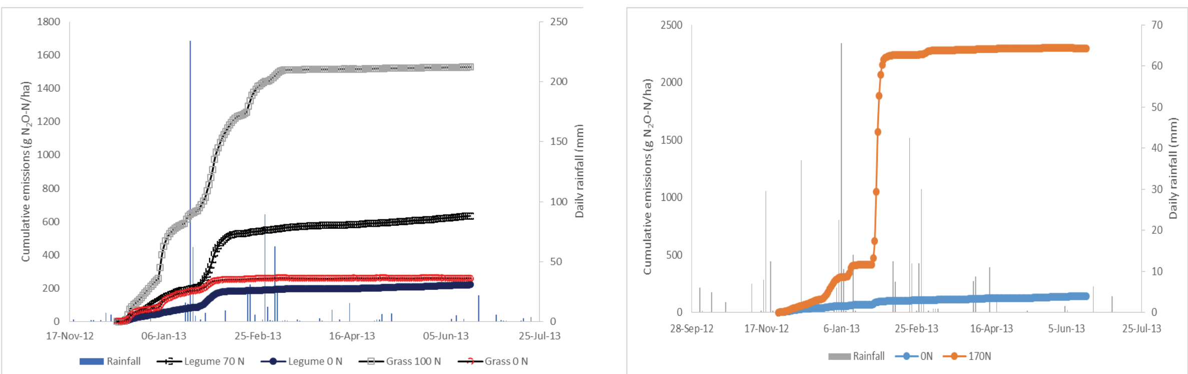

Figure 1 Cumulative N_2O emissions for (a) Kingaroy and (b) Kingsthorpe for the 2012/13 growing season. Daily rainfall is shown for each location.

Fate of applied N fertilizer

Soil and plant samples taken from ^{15}N microplots at maturity in the N rates at which yields were ca. 90% of Y_{max} indicated strong contrasts between the ley histories on the Ferrosols and the two trials on the Vertosols in terms of fertilizer recovery in crop biomass (60-80% on the Ferrosols v's ~40% on each of the Vertosols) and the residual fertilizer N in the soil profile (30-35% on the Ferrosols v's 10-20% in the Vertosols). Collectively, the data (Table 2) suggest that most of the applied N was accounted for in the Ferrosol treatments (losses of 0-5%), which was consistent with findings of Migliorati et al. (2014). However losses equivalent to 40% (Kupunn) to 48% (Kingsthorpe) of the applied N were recorded in the Vertosols. There was no evidence of leaching of fertilizer ^{15}N to the 100cm depth of soil sampling, confirming that most of the unaccounted ^{15}N was lost to denitrification.

Table 2. Recovery of applied fertilizer N from ^{15}N labelled urea (kg fertilizer N/ha) in the 2012/13 season. Measured ^{15}N is partitioned between plant parts and soil, with unaccounted N deemed to be lost to the environment. Data are presented as means (± SE).

	Brown Ferrosol		Grey Vertosol	Black Vertosol
	Kingaroy (grass)	Kingaroy (legume)	Kupunn	Kingsthorpe
Applied N	100	70	80	160
Fertilizer N in plants	58.1 (±8.2)	59.2 (±6.1)	30.5 (±4.3)	66.7 (±4.3)
Fertilizer N in soil	36.3 (±12.1)	19.1 (±1.1)	17.3 (±5.3)	15.8 (±4.9)
Total (soil+plant)	94.4 (±16.2)	78.3 (±7.2)	48.1 (±7.4)	82.5 (±2.2)
Missing N	5.6 (±16.2)	-8.3 (±7.1)	31.9 (±7.4)	77.5 (±2.2)

Discussion

The observed variation in optimum fertilizer N rate between sites, despite similar starting N in the soil profiles at planting, was consistent with differences in crop yield potential and hence crop N demand. However, the contrast between N dynamics in the experiments on Vertosols and Ferrosol soil types in what was an unusually wet growing season was marked. The variation in AE_{90} values between sites was within the range described by Lester et al. (2008) for short fallow grain sorghum crops and consistently indicated a profitable return from N use. The higher AE_{90} on the Ferrosols was consistent with high fertilizer N recoveries in plant biomass and little fertilizer N loss, while the lower AE_{90} values at the Vertosol sites with similar (Kupunn) or higher (Kingsthorpe) yield potentials were consistent with much poorer recoveries of fertilizer N in crop biomass and evidence of significant proportions of fertilizer N lost to the atmosphere.

The total N_2O emissions recorded at the Kingaroy and Kingsthorpe sites were related to optimum N rate, but in this case were not a good indicator of fertilizer N loss. For example, despite a 3-fold increase in cumulative emissions in the grass v legume history at Kingaroy there was no substantial increase in apparent fertilizer N losses, while a further doubling of emissions at Kingsthorpe resulted in almost 50% of fertilizer N lost. These differences may relate to variation in the N_2O:N_2 ratio during the denitrification events, but the consistency of N losses on both Vertosol sites illustrates the risks to N use efficiency on those soils in summer grain cropping.

References

Dalal RC, Probert ME (1997). Soil nutrient depletion. Pp. 42-63. In: Sustainable crop production in the subtropics – An Australian perspective. AL Clarke and PB Wylie (Eds.). Qld Department of Primary Industries. ISBN 0 7242 5985 6.

Lester DW, Birch CJ, Dowling CW (2008). Fertilizer N and P applications on two Vertosols in north-eastern Australia. 1. Comparative grain yield responses for two different cultivation ages. *Australian Journal of Agricultural Research* **59**, 247-259.

Lester DW, Birch CJ, Dowling CW (2008). Fertilizer N and P applications on two Vertosols in north-eastern Australia. 3. Grain N uptake and yield by crop/fallow combination, and cumulative grain N removal and fertilizer N recovery in grain. *Crop and Pasture Science* **61** 59, 24-31.

Migliorati M de A, Bell MJ, Grace PR, Rowlings DW, Scheer C, Strazzabosco A (2014). Assessing agronomic and environmental implications of different N fertilization strategies in subtropical grain cropping systems on Oxisols. *Nutrient Cycling in Agro-Ecosystems* **100**, 369-382.

Migliorati M de A, Bell MJ, Grace PR, Scheer C, Rowlings DW, Liu S (2015). Legume pastures can reduce N_2O emissions intensity in subtropical cereal cropping systems. *Agriculture Ecosystems and Environment* **204**, 27-39.