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# Agronomic responses of grain sorghum to DMPP-treated urea on contrasting soil types in north-eastern Australia

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**Abstract.** Grain sorghum grown in north-eastern Australia's cropping region increasingly requires nitrogen (N) fertiliser to supplement the soil available N supply. The rates of N required can be high when fallows between crop seasons are short (higher cropping intensities) and when yield potentials are high.

Fertiliser N is typically applied before or at crop sowing and is vulnerable to environmental loss in the period between application and significant crop N demand due to potentially intense rainfall events in the summer-dominant rainfall environment.

Nitrification inhibitors added to urea can reduce certain gaseous loss pathways but the agronomic efficacy of these products has not been explored. Urea and urea coated with the nitrification inhibitor DMPP (3,4-dimethylpyrazole phosphate) were compared in sorghum crops grown at five research sites over consecutive summer sorghum growing seasons in south-east Queensland. Products were compared in terms of crop responses in dry matter, N uptake and grain yield, with DMPP found to produce only subtle increases on grain yield. There was no effect on dry matter or N uptake. Outcomes suggest any advantages from use of DMPP in this region are most significant in situations where higher fertiliser application rates (>80 kg N/ha) are required.

**Additional keywords:** agronomic efficiency, enhanced efficiency fertilisers, urea.

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## Introduction

North-eastern Australia has a subtropical cropping belt that extends from the Liverpool Plains region of New South Wales (~32°S) to the Central Highlands of Queensland (~22°S). Major cropping soils are black, grey and brown Vertosols, black, red or brown Sodosols, red and brown Chromosols and Ferrosols (Webb *et al*. 1997). Since change in land use from grazing to cultivation, native soil carbon and nitrogen (N) fertility has reduced (Dalal and Mayer 1986) such that N is one of the most limiting nutrients for grain production (Dalal and Probert 1997).

Agro-ecological conditions allow production of summer and winter cereal, legume, oilseed and fibre crops, with sowing primarily occurring once the soil profile accumulates sufficient water to avoid crop failure from lack of soil water supply (Freebairn *et al*. 1997). Fallows are essential for successful dryland cropping in the region (Shaw 1997) and are a key management tactic in rainfed farming (Freebairn *et al*. 2002).

Flexibility is therefore important when planning crop sequences, and the term 'opportunity cropping' describes the recommended approach (Russell and Jones 1996; Shaw 1997). Opportunity cropping is the planting of a crop as soon as the soil profile has stored sufficient moisture to ensure economic viability; however, response to N fertiliser may alter with cropping intensity under this framework as it may limit N mineralisation from soil organic matter to fully meet crop requirements.

Grain sorghum (*Sorghum bicolor*) is the dominant summer cereal crop in the region (Unkovich *et al*. 2009) and responses to fertiliser N have been shown to vary depending on the length of the preceding fallow. Fallow lengths of >12 months (long-fallow) have shown little or no response to fertiliser N; by contrast, fallows of <6 months are highly N responsive on soils with a cropping history of more than 30 years (Lester *et al*. 2008). Further intensification of cropping is required in attempts to further increase food production, requiring larger and more frequent inputs of fertiliser N. A proportion of this fertiliser can be lost to the environment by gaseous (denitrification and volatilisation) or water (leaching) mediated loss pathways, with production of nitrous oxide ($N_2O$), a potent greenhouse gas, an issue of current concern. To improve the crop utilisation of applied N, 'enhanced efficiency fertilisers' (EEFs) have the potential to enhance the agronomic and recovery efficiencies of fertiliser, while simultaneously reducing its environmental losses. One of the available approaches is the addition of a nitrification inhibitor, which has a higher potential to reduce $N_2O$ emissions from soil than other measures (Ruser and Schulz 2015).

A preliminary study on a Vertosol comparing several EEFs found the nitrification inhibitor 3,4-dimethylpyrazole phosphate (DMPP) was highly effective at reducing annual $N_2O$ losses by 83% (or 1.91 kg $N_2O$-N/ha.year), compared with standard urea, but had no significant effect on grain yield or dry matter N uptake of a grain sorghum crop (Scheer *et al*. 2016). De Antoni Migliorati *et al*. (2014) reported that addition of DMPP to a Ferrosol cropped to both wheat and maize in combination substantially reduced $N_2O$ loss during the summer season, when the majority of emissions occurred, and endorsed future research focusing on fertilisation of the summer crop.

The aim of this study was to evaluate DMPP coated urea and untreated urea in grain sorghum production systems with differing cropping intensities grown on two contrasting soil types (Ferrosol and Vertosol).

## Materials and methods

### *Experimental site descriptions and crop agronomy*

Research locations used where the J. Bjelke Petersen Research Station (Kingaroy, 26°34′S, 151°50′E) and Kingsthorpe Research Station (west of Toowoomba, 27°31′S, 151°47′E), and a commercial property at the locality of Irongate in southern Queensland (27°35′S, 151°30′E). Climatically the region is subtropical with warm humid summers and mild dry winters. Soils are classified as manganic eutrophic Brown Ferrosol at Kingaroy (Isbell 2002), and self-mulching Black Vertosols at Kingsthorpe (Isbell 2002; Powell *et al*. 1988) and Irongate (Beckmann and Thompson 1960; Isbell 2002).

Soil samples were collected to 1.2 m using depth increments shown in Table 1. Chemical methods for soil analysis were conducted according to those described in Rayment and Lyons (2011). Site bulk density was determined using the intact core method of Cresswell and Hamilton (2002). Mineral N at sowing was measured using the sum of depth increments (Table 1) with nitrate and ammonium determined using method 7B1 (Rayment and Lyons 2011) multiplied by the bulk density for the increment layer (Dalgliesh and Foale 1998). Plant available water content (PAWC) was estimated using gravimetric moisture at 105°C, site bulk density, and a sorghum crop lower limit at analogous sites in accordance with Dalgliesh and Foale (1998).

Comparison rates for urea and DMPP-treated urea (Entec®) at Kingsthorpe in 2013–14 were 0, 40, 60, 80, 100 and 160 kg N/ha (four replicates); at Kingaroy in both 2013–14 and 2014–15 were 0, 40, 60, 80, 100, 120 and 240 kg N/ha (three replicates each year); and 0, 40, 80 and 160 kg N/ha for both Kingsthorpe and Irongate in 2014–15 (six replicates each year). Nitrogen treatments were band applied at 5 cm depth to the side of the crop row at sowing, with the exception of the Irongate site where an earlier sowing attempt (10 Sept 2014) was removed with herbicide and replanted in December due to poor crop establishment. Agronomic management at each site is summarised in Table 2.

Aboveground biomass was collected at physiological maturity (Vanderlip and Reeves 1972) from either 1 or 2 m of crop row, oven-dried at 65°C, weighed and processed (mulched, subsampled and finely ground to 0.5 mm) for determination of N concentration using the combustion (Dumas) method. Nitrogen uptake at maturity (kg/ha) was calculated by multiplying the aboveground biomass (kg/ha) by the biomass N concentration (mg/kg). Grain was machine harvested from two crop rows and grain yield calculated with correction to grain receival moisture

**Table 1. Key chemical properties for profile soil layers of three field sites**

TC, Total carbon; TN, total nitrogen; Col P, Colwell P; ECEC, effective cation exchange capacity

| Depth (m) | pH ($CaCl_2$) | TC (%) | TN (mg/kg) | Col P (mg/kg) | Exchangeable Cations: Ca (cmol/kg) | Mg (cmol/kg) | Na (cmol/kg) | K (cmol/kg) | ECEC (cmol/kg) |
|---|---|---|---|---|---|---|---|---|---|
| Method | 4B2 | 6B2a | 7A5 | 9B2 | 15D3 | | | | |
| *Kingaroy (Brown Ferrosol)* | | | | | | | | | |
| 0.0–0.1 | 5.7 | 1.4 | | 44 | 8.5 | 3.4 | 0.57 | 0.61 | 13.1 |
| 0.1–0.3 | 4.3 | 1.2 | | 15 | 7.0 | 4.4 | 0.41 | 0.14 | 11.9 |
| 0.3–0.6 | 5.8 | | | – | 4.7 | 6.7 | 0.05 | 0.78 | 12.2 |
| 0.6–0.9 | 5.9 | | | – | 4.5 | 9.9 | 0.05 | 1.40 | 15.8 |
| 0.9–1.2 | 6.2 | | | – | 7.5 | 20.0 | 0.07 | 2.80 | 30.4 |
| *Kingsthorpe (Black Vertosol)* | | | | | | | | | |
| 0.0–0.3 | 7.1 | 1.65 | 1150 | 27 | 29.3 | 26.2 | 0.59 | 2.19 | 58.2 |
| 0.3–0.6 | | | | 21 | 29.7 | 26.6 | 0.56 | 2.22 | 59.1 |
| 0.6–0.9 | | | | – | 25.6 | 25.2 | 0.66 | 3.95 | 55.4 |
| 0.9–1.2 | | | | – | 23.6 | 24.2 | 0.78 | 5.41 | 54.0 |
| *Irongate (Black Vertosol)* | | | | | | | | | |
| 0.0–0.1 | 7.1 | 1.66 | 1180 | 52 | 34.1 | 28.7 | 0.74 | 2.05 | 65.5 |
| 0.1–0.3 | 7.8 | | | 14 | 32.9 | 32.5 | 1.69 | 0.88 | 68.0 |
| 0.3–0.6 | 7.9 | | | 4 | 26.0 | 36.6 | 3.93 | 0.83 | 67.4 |
| 0.6–0.9 | 8.2 | | | – | 19.4 | 40.2 | 7.11 | 1.00 | 67.7 |
| 0.9–1.2 | 8.3 | | | – | 14.9 | 40.4 | 9.36 | 1.10 | 65.8 |

**Table 2. Agronomic details of experiments comparing DMPP treatment against standard urea for five grain sorghum crops**

| Season | 13–14 | 13–14 | 14–15 | 14–15 | 14–15 |
|---|---|---|---|---|---|
| Site | Kingaroy | Kingsthorpe | Kingaroy | Kingsthorpe | Irongate |
| ID | KRY13–14 | KTH13–14 | KRY14–15 | KTH14–15 | IRN14–15 |
| Sowing date | 27 November 2013 | 10 December 2013 | 24 November 2014 | 29 October 2014 | 18 December 2014 |
| N application date | 27 November 2013 | 10 December 2013 | 24 November 2014 | 29 October 2014 | 10 September 2014 |
| Cultivar | Pioneer G22 | Pacific MR43 | Pioneer G22 | Pacific MR43 | Pacific MR Buster |
| Row spacing (m) | 0.90 | 1.00 | 0.90 | 0.75 | 0.75 |
| Mineral N to 1.2 m (kg/ha) | 60 | 62 | 127 | 65 | 89 |
| PAWC to 1.2 m (mm/ha) | 140 | 87 | 105 | 111 | 179 |
| Maturity biomass date | 3 April 2014 | 8 April 2014 | 24 April 2015 | 13 February 2015 | 15 April 2015 |
| In-crop rainfall (mm) | 357 | 241 | 372 | 285 | 355 |
| Harvest date | 10 April 2014 | 05 May 2014 | 24 April 2015 | 5 March 2015 | 13 May 2015 |

of 13.5%. Agronomic efficiency (AE, kg/kg) has been defined as the ratio of grain yield to N supply (Ladha *et al.* 2005) and is applied here as:

$$AE = (Y_F - Y_0)/F_n = \Delta Y/\Delta N$$

where $Y_F$ is grain yield (kg/ha) in treatment with fertiliser N applied per plot ($F_N$, kg/ha) and $Y_0$ is crop yield (kg/ha) measured in a control treatment with nil fertiliser application.

### *Experimental design and statistical analysis*

The experimental design at Kingaroy was a strip-plot for both years (KRY13–14, KRY14–15) and a randomised complete block design was used at Kingsthorpe (KTH13–14). Split-plot designs with N rate randomly allocated to the main-plot and the product randomly allocated to the sub-plots were used in 2014–15 at both Kingsthorpe (KTH14–15) and Irongate (IRN14–15).

The five trials (i.e. properties) were analysed together in a linear mixed model framework fitting separate residual variances for each experiment. Analyses were performed in GENSTAT 17th edition using the REML procedure (VSN International 2015) and the level of significance was set at the 5% level. The N rate was treated as a continuous variable and the square of the N rate was also added to account for curvature in the trend. Non-significant terms between product and properties with the linear and quadratic N rate were dropped from the final model. For the dry matter and dry matter N uptake the number of plants was used as a covariate, and if significant for the property this was included in the cross–trial analysis. Predictions of the fitted lines were made at N rates 0, 40, 60, 80, 100, 120, 160 for tables, and at intervals of 10 from 0 to 160 for producing graphs.

The focus of this paper is on the comparison between the two N products: DMPP and Urea. The agronomic measures associated with the N rate responses presented in this paper are a subset from a larger research program for publication at a future date, including fertiliser N recovery and assessment of N losses.

## Results

A consolidated table of significant effects on dry matter, N uptake and grain yield for the five sites indicates that the interaction between N rate and property was significant for all parameters (Table 3). The N product (Urea or DMPP) had a significant interaction with grain yield.

**Table 3. Consolidated table of significant effects on dry matter, nitrogen uptake and grain yield of grain sorghum comparing Urea and DMPP at five research sites**

DT, dropped term; NS, not significant; *, significant at the 0.05 probability level; **, significant at the 0.01 probability level; ***, significant at the 0.001 probability level

| Fixed term | Dry matter | Nitrogen uptake | Grain yield |
|---|---|---|---|
| Property | *** | *** | *** |
| Product | NS | NS | ** |
| N_rate (lin) | *** | *** | *** |
| N_rate (quad) | *** | *** | *** |
| Property.N_rate (lin) | *** | *** | *** |
| Property.N_rate (quad) | *** | DT | *** |
| Product.N_rate (lin) | DT | DT | NS |
| Product.N_rate (quad) | DT | DT | * |

### *Aboveground dry matter at maturity*

The influence of starting mineral N level and in-crop rainfall on overall fertiliser N responsiveness is seen in Fig. 1. The three sites with low starting N are highly responsive KRY13–14 (Fig. 1*a*), KTH13–14 (Fig. 1*b*) and KTH14–15 (Fig. 1*d*), and the remaining sites KRY14–15 (Fig. 1*c*) and IRN14–15 (Fig. 1*e*) show smaller increases with N application.

Significant effects on dry matter growth did not include product (i.e. DMPP *v.* Urea) either as a main effect or any interaction with Property or N rate (Table 3). Plant number had a significant effect and assisted in adjusting predicted means based on varying crop establishment for some plots. The significant Property × N rate interaction reflects the varying scale of N response.

### *Dry matter N uptake*

The N uptake at maturity was not significantly affected by the N product (Table 3). The interaction between property and N rate reflects the dry matter N uptake (data not shown) which is analogous to that of dry matter itself (Fig. 1).

### *Grain yield*

Grain yield increased with N rate at all sites except IRN14–15, which showed no response (Fig. 2). The analyses showed an overall difference in the curved lines across N levels for product (Table 3); however, this trend was not strong enough to show significant differences in product in the individual analyses of each trial.

As the Product.Property term and its interactions with N rate were not significant, we can explore the product effects averaged over the properties. Plotting the predictions of grain yield for DMPP and Urea suggests a slight efficiency gain with DMPP of ~200 kg/ha in grain yield for N applied at 80 to 120 kg N/ha (Fig. 3) but there were no significant differences between DMPP and Urea at any application rate so these results should be interpreted cautiously. Addition of DMPP increased the agronomic efficiency at the 80–120 kg N/ha by ≈2.2 kg grain/kg fertiliser N. At 90% of maximum grain yield the difference in N application rate between Urea and DMPP was ~10 kg N/ha.

The significant product by N rate interaction on grain yield (Table 3) was further explored for the three site years with the greatest N response (KRY13–14, KTH13–14 and KTH14–15) but no individual site produced any significant effects of product or its interactions due to high variability in the data.

## Discussion

Developing appropriate N management strategies that can be adopted by farmers is crucial for improving crop production and fertiliser N use efficiency, with the use of nitrification inhibitors providing a potential management option (Fageria and Baligar 2005). The effectiveness of nitrification inhibitors (and other EEFs) have been demonstrated to be strongly dependent on site-specific conditions, soil texture and climate (Irigoyen *et al.* 2003). Reduction in $N_2O$ emissions over the summer period from the use of DMPP-treated urea has been substantial (De Antoni Migliorati *et al.* 2016; De Antoni Migliorati *et al.* 2015; Scheer *et al.* 2016); however, there are no published studies evaluating the agronomic impacts of DMPP-treated urea on grain sorghum production in subtropical environments. Our study found that DMPP had a nominal grain yield advantage when considered over all the research sites in this study and this was only apparent at the higher fertiliser N application rates (Fig. 3).

A contradiction therefore exists between how DMPP can decrease $N_2O$ emission by over 60% (De Antoni Migliorati *et al.* 2016; De Antoni Migliorati *et al.* 2015; Scheer *et al.* 2016), but only nominally increases grain yield. The explanation may partly lie in the higher N application rates. De Antoni Migliorati *et al.* (2016) found that $N_2O$ emissions increased exponentially with increasing urea N rate in both the KRY13–14 and the KTH13–14 experiments, with the incremental increase in emissions at Kingaroy representing 0.5% and 2.2% of added fertiliser N (0–80N and 80–120N respectively), whereas at Kingsthorpe the incremental increase represented 1.0% and 1.6% of added N fertiliser (0–80N and

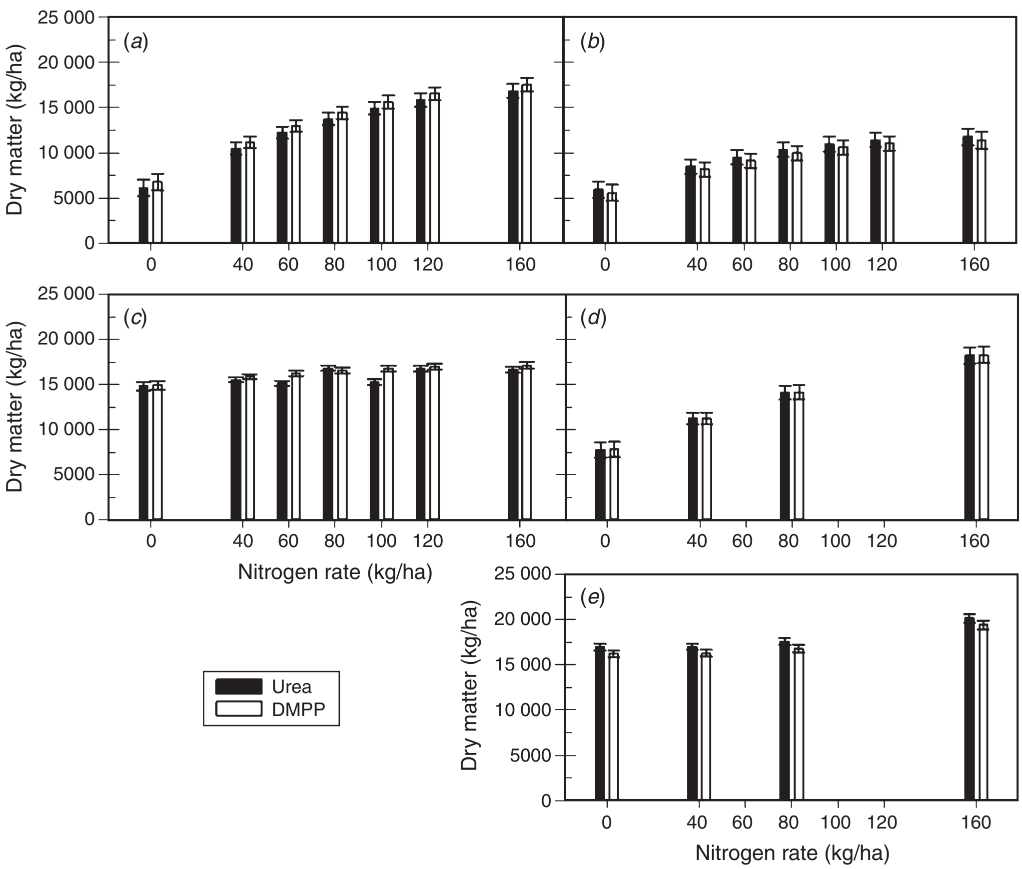


**Fig. 1.** Predicted dry matter (kg/ha) of grain sorghum at physiological maturity from Urea and DMPP treatments at the five sites: (*a*) KRY13–14; (*b*) KTH13–14; (*c*) KRY14–15; (*d*) KTH14–15; and (*e*) IRN14–15. Error bars represent standard error. There was no significant difference between the products.

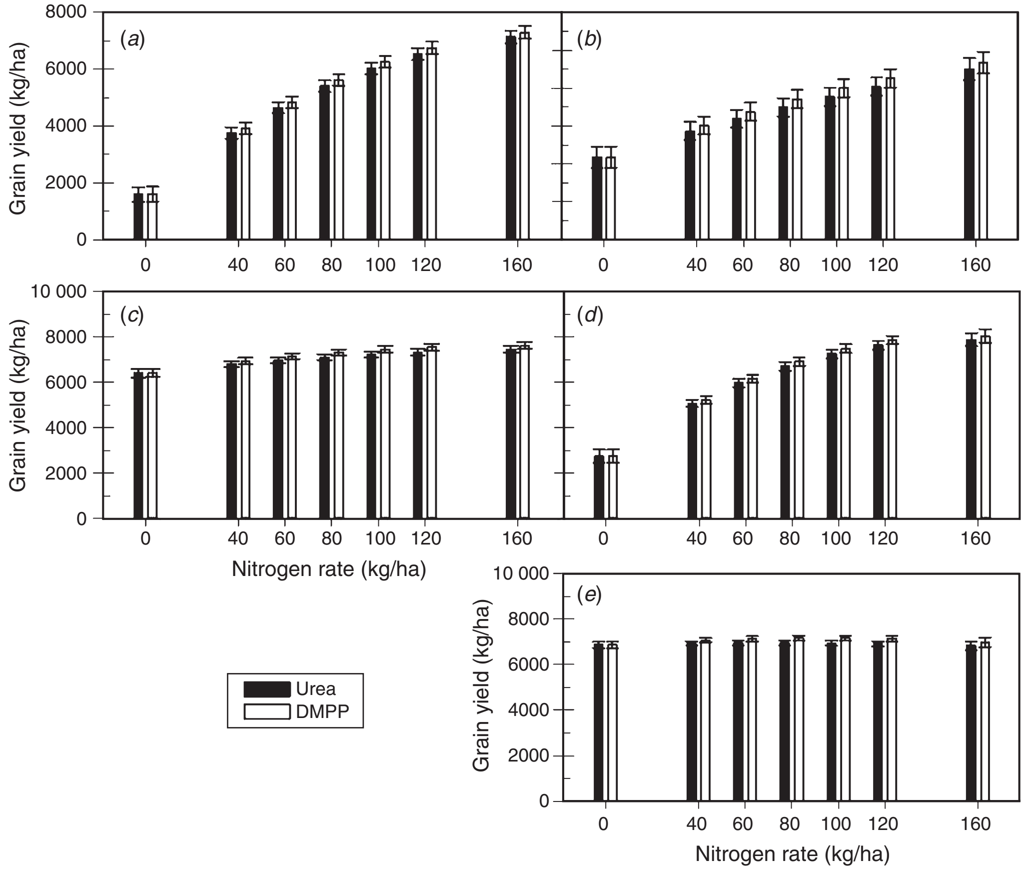


**Fig. 2.** Predicted grain yield (kg/ha) from DMPP and Urea treatments for grain sorghum at the five sites: (*a*) KRY13–14; (*b*) KTH13–14; (*c*) KRY14–15; (*d*) KTH14–15; and (*e*) IRN14–15. Error bars represent standard error. There was no significant difference between the products.

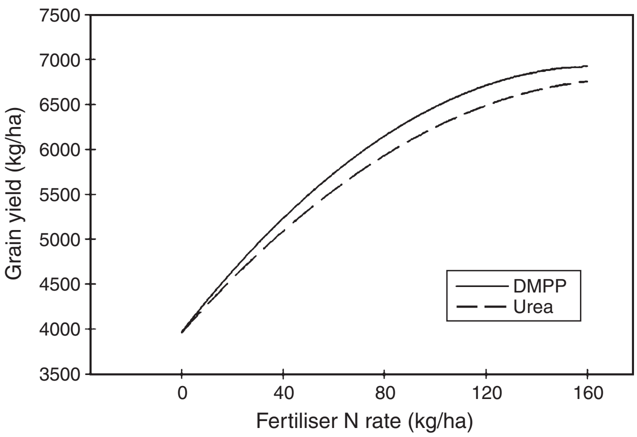


**Fig. 3.** Predicted grain yield of grain sorghum fertilised with DMPP or Urea.

80–160N respectively). Conversely, the AE (kg extra grain produced/kg additional N applied) decreased by 40% (Kingaroy) and 20% (Kingsthorpe) for the higher N increment (80–120 or 80–160 kg N/ha at Kingaroy and Kingsthorpe respectively) compared with the first 80 kg N/ha applied at each location (Fig. 2). Although emissions data for the 2014/15 studies are not yet available, the decrease in AE at higher incremental N rates in the equivalent studies at both Kingaroy and Kingsthorpe sites (KRY14–15 and KTH14–15) is again evident (Fig. 2), and at the more N-responsive Kingsthorpe site, the reduction in AE for the 80–160N increment relative to the 0–80N increment was >60%. Collectively, these data suggest that the relative reduction in emissions at high N rates are likely to always far exceed the incremental grain yield response to any reduction in total N losses.

Although not significant at any individual site, the nominal yield improvement from DMPP-treated urea is most likely where N application rates are in excess of 80 kg N/ha. Circumstances in which fertiliser rates in excess of 80 kg N/ha would be required in this region include cereals under irrigation (high crop N demand), in the higher rainfall areas where two summer crops can be grown in succession with a 6–8-month winter fallow, or where rainfall conditions allow double cropping opportunities (i.e. summer sorghum immediately following winter cereal harvest). At a long-term nitrogen × phosphorus experimental site, sorghum crops grown on the 6–8-month winter fallow had linear responses to N fertiliser rates commonly up to 80 or 120 kg N/ha (Lester *et al*. 2008) and average results across sites in this study suggest DMPP may reduce application rate by ~10 kg N/ha.

DMPP is unlikely to be beneficial where the relative contribution of fertiliser N to total crop supply is low, such as with higher starting mineral N profiles (i.e. typically fallows >12 months, termed 'long fallows') or where crop N demands are likely to be low due to use of moisture conservation techniques such as double skip sowing (Whish *et al*. 2005). Our results also suggest that at application rates <60 kg N/ha, there is currently no benefit in using DMPP. The linear polynomial contrast was not significant for product, therefore on that part of the response surface the crop appears to have utilised equivalent amounts of N from either DMPP or urea.

These findings were generated largely from research station sites at which conditions were managed through pre-cropping and mineral N removal to aid fertiliser responsiveness. This contrasts with commercial production systems in which farmers regularly apply N to meet water-limited yield potentials (Strong and Holford 1997). Further examination of enhanced efficiency fertilisers under commercially relevant conditions would provide an improved N decision framework for farmers. Conducting future studies using a common set of application rates across the sites would improve the model fitting, and comparing three or more products may allow better differentiation of EFFs from urea-based fertilisers.

## Conclusions

While there is consistent evidence that DMPP reduces $N_2O$ emissions, particularly at higher N application rates, results from our experiments are inconclusive for showing consistently greater N fertiliser use efficiency in subtropical grain sorghum production. However, agronomic efficiency gains of ~2.2 kg grain/kg N were apparent at high application rates in the range of 80–120 kg N/ha, with this increase delivering a reduction in the optimum N application rate of ~10 kg N/ha.

DMPP appears more likely to be beneficial under irrigated cropping with higher crop N demand and associated high N fertiliser requirement, or in higher cropping intensity rainfed systems in which N fertiliser is applied to meet a greater proportion of crop N demand. Further research evaluating DMPP under these circumstances would improve understanding.

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