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Agronomic responses of grain sorghum to DMPP treated urea on contrasting soil types in NE Australia

David W. Lester[A,D], Michael J. Bell[B], Kerry L. Bell[A], Massimiliano De Antoni Migliorati[C], Clemens Scheer[C], David Rowlings[C] and Peter R. Grace[C]

[A] Queensland Department of Agriculture and Fisheries, PO Box 2282, Toowoomba Qld 4350

[B] Queensland Alliance for Agriculture and Food Innovation, School of Crop and Food Sciences, University of Queensland, Gatton Qld 4343

[C] Institute for Future Environments, Queensland University of Technology, PO Box, Brisbane Qld 4000

[D] Corresponding author david.lester@daf.qld.gov.au

Abstract

Grain sorghum grown in north-eastern Australia's cropping region increasingly requires nitrogen (N) fertiliser to supplement the soil available nitrogen supply. The rates of nitrogen required can be high when fallows between crop seasons are short (higher cropping intensities) and when yield potentials are high. Fertilizer application times are typically prior to or at crop sowing, and combined with what can be intense rainfall events in the summer-dominated rainfall environments, there is a period prior to significant crop N demand when fertilizer N is vulnerable to environmental loss.

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 grown over consecutive summer sorghum growing seasons in southeast 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 may be most significant in situations where higher fertilizer application rates (>80 kg N/ha) are required.

Keywords

agronomic efficiency, enhanced efficiency fertilisers, urea

Introduction

North-eastern Australia has a sub-tropical cropping belt that extends from the Liverpool Plains region of New South Wales (about 32°S) to the Central Highlands of Queensland (about 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 fertility has rundown (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 in planning crop sequences is therefore important, 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, under this framework response to N fertiliser may alter with cropping intensity 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 (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 nitrogen, “enhanced efficiency fertilisers” (EEFs) have potential to improve fertiliser agronomic and recovery efficiencies, while simultaneously reducing these environmental losses. One of the available approaches is the addition of a nitrification inhibitor, which in comparison to other measures, has a high potential to reduce nitrous oxide emission from soil (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^{-1} yr^{-1}) compared to 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) on an Ferrosol cropped to both wheat and maize in combination reported DMPP substantially reduced nitrous oxide loss during the summer season when the majority of emissions occurred and endorsed future research focussing on fertilisation of the summer crop.

The aims 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 refer 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 in 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).

[Table 1 here]

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 reps); at Kingaroy in both 2013-14 and 2014-15 were

0, 40, 60, 80, 100, 120 and 240 kg N/ha (three reps each year); and 0, 40, 80 and 160 kg N/ha for both Kingsthorpe and Irongate in 2014-15 (six reps 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 sprayed out and replanted in December due to poor crop establishment. Agronomic management at each site are 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 ^{o}C, weighed and processed (mulched, subsampled and finely ground to 0.5 mm) for determination of N concentration using a combustion (Dumas) method instrument. Nitrogen uptake at maturity (kg/ha) was calculated by multiplying the above ground 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 of 13.5%. Agronomic efficiency (AE) has been defined as the ratio of grain yield to N supply (Ladha*et al.* 2005), and here is applied as:

$$AE = (Y_F - Y_0)/F_N = \Delta Y/\Delta N \text{ in kg kg}^{-1}$$

where Y_F is grain yield (kg ha^{-1}) in treatment with fertiliser N applied per plot (F_N, kg ha^{-1}) and Y_0 is crop yield (kg ha^{-1}) measured in control treatment with nil fertiliser application.

[Table 2 here]

Experimental design and statistical analysis

Experimental design at Kingaroy for both years (KRY13-14, KRY14-15) was a strip-plot and an incomplete randomised block design for Kingsthorpe (KTH13-14). Both Kingsthorpe (KTH14-15) and Irongate (IRN14-15) split-plot designs with N rate as the main-plot and product as split-plot were used in 2014-15.

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, 2013) and the level of significance was set at the 5% level. The N rate was treated as a continuous variable and the square of 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 across 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 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). Nitrogen product (Urea or DMPP) had a significant interaction with grain yield.

[Table 3]

Aboveground dry matter at maturity

The influence of starting mineral N level and in-crop rainfall on overall fertiliser nitrogen responsiveness is seen in Fig. 1 where three sites with low starting N are highly responsive

KRY13-14 (Fig. 1a), KTH13-14 (Fig. 1b) and KTH14-15 (Fig. 1d), and the remaining sites KRY14-15 (Fig. 1c) and IRN14-15 (Fig. 1e) having smaller increases with N application.

Significant effects on dry matter growth did not include product (i.e. DMPP vs 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 x N rate interaction reflects the varying scale of N response.

[Figure 1]

Dry matter nitrogen uptake

Nitrogen uptake at maturity was not significantly affected by 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

Yield was increased with N rate at sites apart from IRN14-15 which had 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.

[Figure 2]

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 was no significant differences between DMPP and Urea at any application rate. 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 approximately 10 kg N/ha.

[Figure 3]

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

Discussion

Developing appropriate N management strategies that can be adopted by farmers are 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 (Irigoyena *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) yet 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 then only apparent at higher fertiliser N application rates (Fig. 3).

A contradiction then 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. In the study by De Antoni Migliorati *et al*. (2016), nitrous oxide emissions were shown to be increasing 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 fertilizer N (0-80N and 80-120N, respectively), while at Kingsthorpe the incremental increase represented 1.0% and 1.6% of added N fertilizer (0-80N and 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 to 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, data suggest that the relative reduction in emissions at high N rates will always be likely to 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 were 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 x 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 suggests DMPP may reduce application rate by approximately 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 lower 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 where conditions were managed through pre-cropping and mineral N removal to aid fertiliser responsiveness. This contrasts with commercial production systems where 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 EFF compared to urea.

Conclusions

While there is consistent evidence that DMPP reduces nitrous oxide 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 approximately 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 approximately 10 kg N/ha.

DMPP appears more likely to be beneficial under irrigated cropping with higher crop N demand and associated high fertiliser N requirement, or higher cropping intensity rainfed systems where fertiliser N 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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Table 1. Key chemcial properties for profile soil layers of three field sites

					Exchangeable Cations				
Depth	pH	TC	TN	Col P	Ca	Mg	Na	K	ECEC
(m)	(CaCl$_2$)	(%)	(mg/kg)	(mg/kg)	(cmol/kg)	(cmol/kg)	(cmol/kg)	(cmol/kg)	(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	1.4	15.8
0.9-1.2	6.2			-	7.5	20.0	0.07	2.8	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			-	19.35	40.23	7.11	1.00	67.7
0.9-1.2	8.3			-	14.88	40.42	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-Nov-13	10-Dec-13	24-Nov-14	29-Oct-14	18-Dec-14
N application date	27-Nov-13	10-Dec-13	24-Nov-14	29-Oct-14	10-Sep-14
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-Apr-14	08-Apr-14	24-Apr-15	13-Feb-15	15-Apr-15
In-crop rainfall (mm)	357	241	372	285	355
Harvest date	10-Apr-14	05-May-14	24-Apr-15	05-Mar-15	13-May-15

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.

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	*

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.

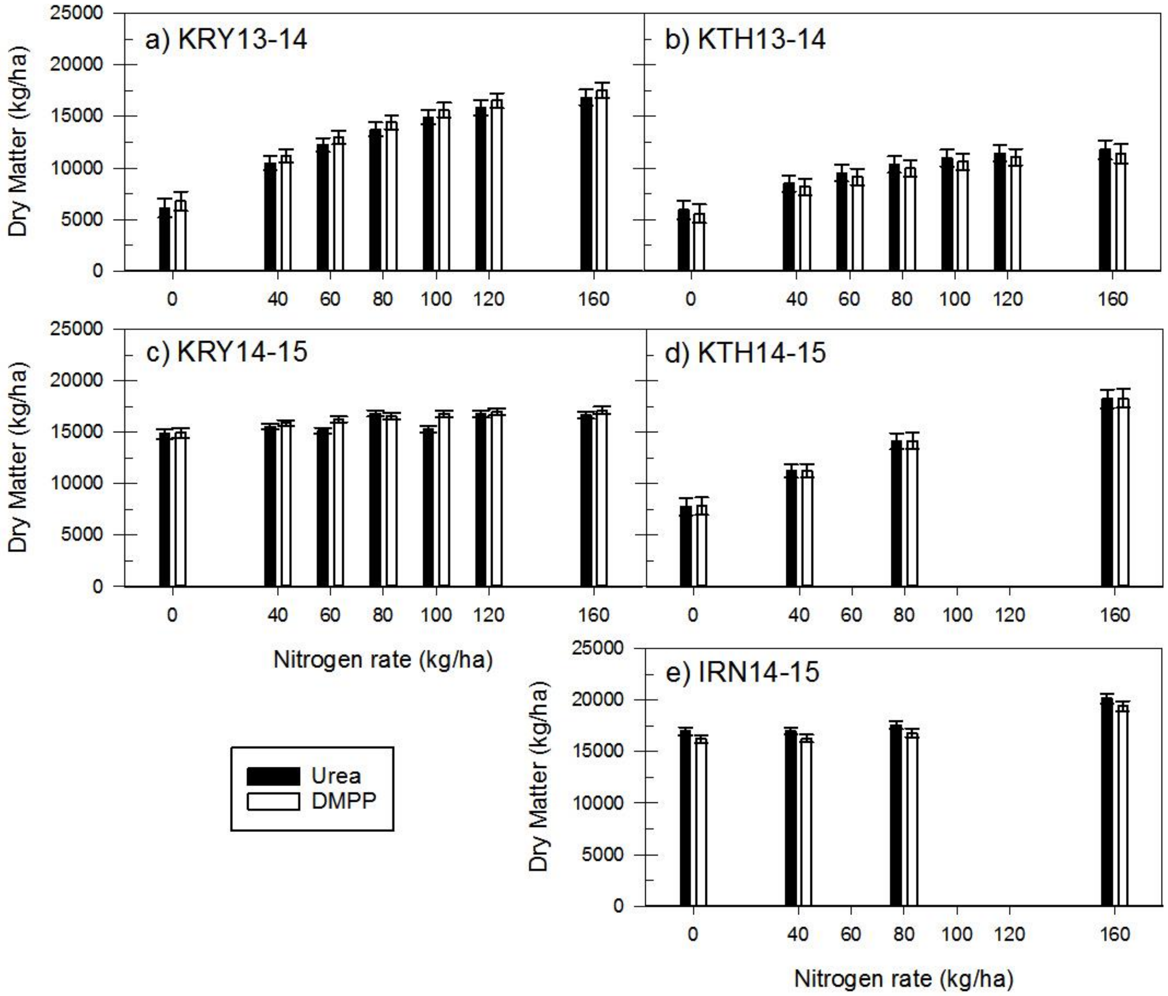

Figure 1. Predicted dry matter (kg/ha) of grain sorghum at physiological maturity from Urea and DMPP treatments at five sites. Error bars represent standard error.

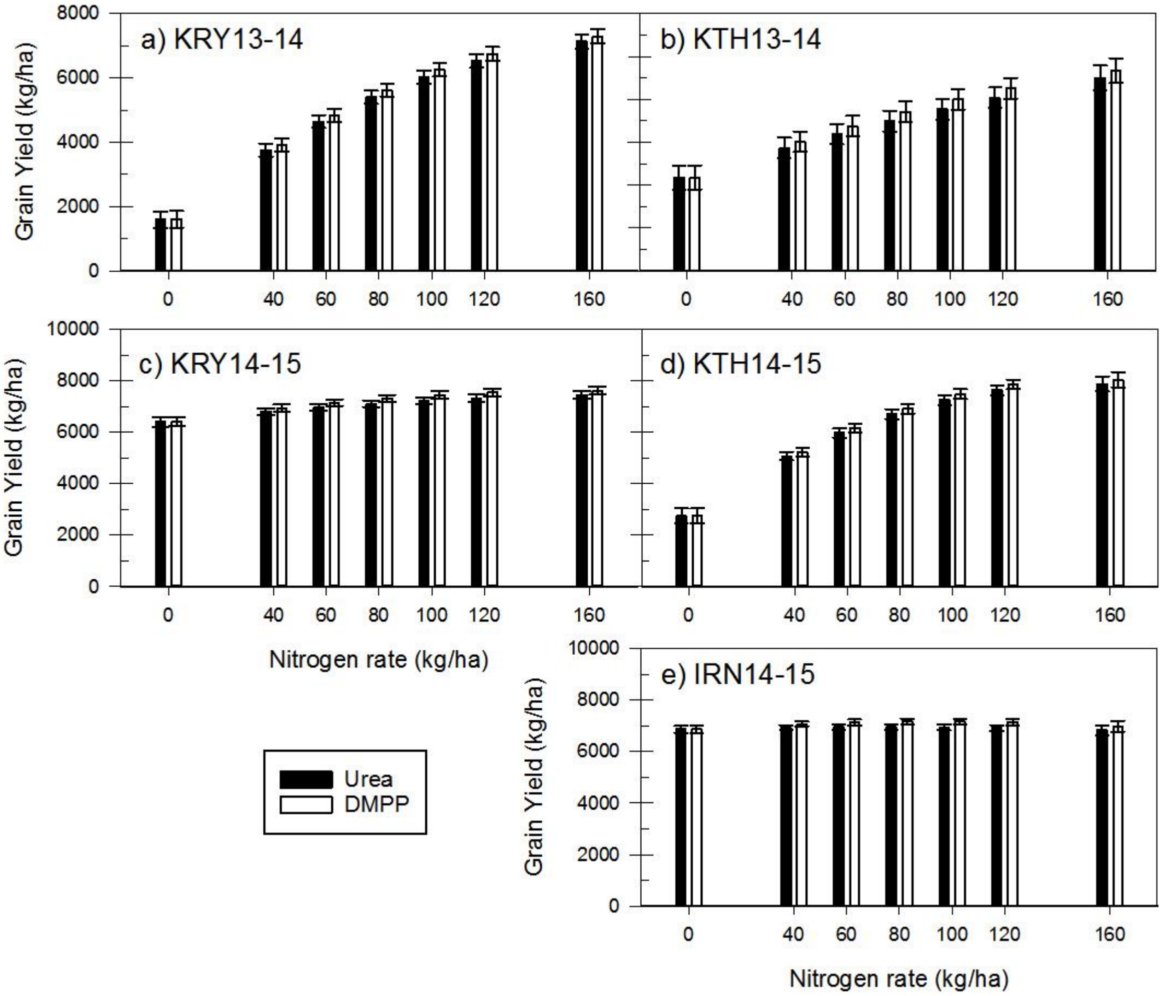

Figure 2. Predicted grain yield (kg/ha) from DMPP and Urea treatments for grain sorghum at five sites. Error bars represent standard error.

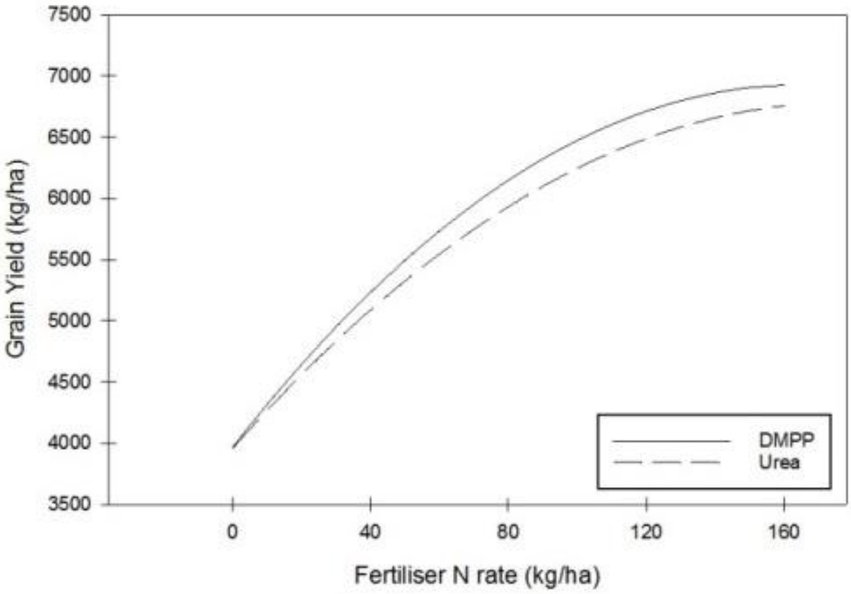

Figure 3. Predicted grain yield of grain sorghum fertilised with DMPP or Urea.