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Nitrogen Response of Grain Sorghum in Rotation with Soybean

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ABSTRACT

The grain sorghum [*Sorghum bicolor* (L.) Moench] and soybean [*Glycine max* (L.) Merr.] rotation is the major sorghum production system in Nebraska. Fertilizer N needs for rotations are commonly determined by adjusting the N rate for continuous sorghum by a fertilizer nitrogen replacement value (FRV). The FRV due to rotation with soybean varies widely and, given the importance of the soybean–sorghum rotation, a basis for direct determination of N rates for grain sorghum following soybean is needed that includes the cost of fertilizer N. Thirty-nine N rate trials for grain sorghum following soybean were conducted in southern Nebraska on medium to fine texture soils. The treatment structures varied but generally included five or more N rates in increments of 35 kg ha^{-1} or less. Grain sorghum yield response to applied N and the economically optimum nitrogen rate (EONR) increased as yield level increased. The agronomic efficiency of applied N increased with increased yield level and, within each yield category, decreased with increased N rate. Agronomic N efficiencies were <6 kg grain kg N^{-1} applied at sites with maximum yields of <6 Mg ha^{-1}, indicating presence of severe constraints other than N. The EONR decreased and the range of profitable N rates decreased as the N price–grain price (P_N:P_G) ratio increased. Expected sorghum yield, as well as P_N:P_G, was therefore important for the determination of EONRs. Soil organic matter (SOM; 17–37 g kg^{-1} in the 0- to 20-cm depth) and soil nitrate concentration (1.3–6.7 mg kg^{-1} in the 0- to 120-cm depth) were positively correlated with grain yield without N application, but showed no correlation with the yield response to applied N. Within the ranges represented by these trials, soil information was less essential for determining the EONR for grain sorghum following soybean than setting a realistic yield goal (YG).

Most grain sorghum in Nebraska is produced in rotation with soybean. Nitrogen application rates for grain sorghum following soybean are determined from continuous sorghum rates from which a FRV credit is deducted for the rotation effect (Franzleubbers et al., 1994; Ferguson, 2000). The FRV for grain sorghum following soybean varies and has been found to range from 0 to 144 kg ha^{-1} (Peterson and Varvel, 1989; Clegg, 1982; Gakale and Clegg, 1987, Varvel and Wilhelm, 2003). Several factors may affect the FRV amount, including weather conditions after harvest and the amount and N content of the cereal or soybean crop residue. However, Varvel and Wilhelm (2003) did not find a relationship between FRV and precipitation during the previous or current year. Given the variability of FRV and the potential for yield loss with underapplication of N, FRV used in determining N rates are conservatively low, such as 40 kg ha^{-1} in Nebraska (Ferguson, 2000).

Oberle and Keeney (1990) estimated that 3.5% of soil organic N was mineralized annually. Thus, mineralization of soil organic N is often credited in determining N application rates (Ferguson, 2000). The accuracy of predicting fertilizer N requirement has also been improved by accounting for available residual soil nitrate-N (RSN), which can be used as efficiently as fertilizer N if not lost to leaching and denitrification. Vanotti and Bundy (1994) found that for continuous corn, the relationship between optimum fertilizer N rate (Y) and RSN was $Y = 193 - 0.88$ RSN when the amount of RSN was between 45 and 195 kg ha^{-1} in the upper 90 cm of soil. When RSN concentration is <3 mg kg^{-1}, RSN may not be efficiently used (Bundy and Malone, 1988; and Schepers and Mosier, 1991). Current N rate recommendations for sorghum in Nebraska credit 17.3 and 12.4 kg N ha^{-1} for each 100 g of SOM and each 1 mg nitrate-N, respectively, per kilogram of soil (Ferguson, 2000).

Expected grain yield (or YG) is often considered in determining N application rates for corn and grain sorghum, as grain yield is related to the total N contained in the aboveground crop at harvest (Shapiro et al., 2003; Ferguson, 2000). Franzleubbers et al. (1994) determined the amount of N required, from all sources, to attain 95% of maximum predicted yield was 5.8 and 10.4 kg Mg^{-1} of grain yield for continuous grain sorghum and corn, respectively. Vanotti and Bundy (1994) found, however, that optimum N rate did not vary with corn yield obtained, probably due to improved N use efficiency with increased corn yield.

Previous algorithms for estimating optimal N rates for sorghum typically have not considered the price of fertilizer N relative to the price of grain. Rather, the N rate needed to achieve 95% or more of maximum yield was typically estimated (Franzleubbers et al., 1994). As fertilizer N prices (P_N, U.S. \$ kg^{-1}) increase relative to grain prices (P_G, \$ kg^{-1}), the EONR, defined as the N rate of maximum net return to N fertilizer application, is expected to decrease (Sawyer and Nafziger, 2005).

Given the importance of the grain sorghum and soybean rotation, the variability in FRV for rotations, and the need to fine-tune fertilizer N use as fertilizer prices increase, research was conducted in Nebraska to determine the response to applied N for grain sorghum following soybean in rotation. The agronomic efficiency of applied N was determined and a basis for determining the EONR was established for sorghum grown in the soybean–sorghum rotation.

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Abbreviations: AE_N, agronomic nitrogen use efficiency; EONR, economically optimum nitrogen rate; FRV, fertilizer nitrogen replacement value; NRF, net returns to fertilizer N; P_G, value of grain in U.S. \$ kg^{-1}; P_N, fertilizer nitrogen price in U.S. \$ kg^{-1}; RSN, residual soil nitrate-nitrogen; SOM, soil organic matter; YG, yield goal.

MATERIALS AND METHODS

Site Characteristics, Treatments, and Experimental Design

Fifteen and 24 fertilizer N rate trials for grain sorghum following soybean in rotation were conducted during 1993 to 1995 and 2001 to 2005, respectively, in southern Nebraska (Table 1). The soils varied with site but were primarily silt loams and silty clay loams. Rooting depth was typically >1 m, but occasionally shallower. Soil was sampled before planting at the 0- to 0.2-m depth and analyzed for SOM by loss on ignition, $pH_{1:1}$, Bray-P1, and available K (NCR-13, 1998). Soil was also sampled to a depth of 0.9 or 1.2 m in 0.3-m segments in the spring before planting and analyzed for nitrate-N (NCR-13, 1998). Soil organic matter ranged from 17 to 37 g kg^{-1} and soil pH ranged from 4.7 to 6.6 (Table 1). Bray-P1 ranged from very low to very high (4.2–70 mg kg^{-1}) and soil K availability was always very high (Ferguson, 2000). Rainfall and mean temperature for 1 July to 15 August were determined from nearby weather stations; when the sites were not within 2 km of a station, estimates were generally made considering the data from two nearby stations.

Table 1. Soil properties for 39 fertilizer N rate trials for grain sorghum following soybean in rotation conducted in southern Nebraska. Year–locations are listed by maximum treatment yield.

Year	County	Soil series†	Nitrate-N 0–60 cm	Nitrate-N 0–120 cm	pH	SOM	P
			— mg kg^{-1} —			g kg^{-1}	mg kg^{-1}
1993	Gage	Wymore	2.1	1.8	5.9	26.7	52.9
1993	Saunders	Yutan	3.6	3.3	5.5	24.2	7.5
1993	Lancaster	Wymore	2.7	2.3	5.8	16.5	8.0
1993	Lancaster	Judson	4.9	4.4	5.7	26.1	20.8
2005	Jefferson	Geary	4.3	3.7	5.7	23.7	15.8
1993	Saline	Crete	3.5	2.9	5.9	28.0	6.6
2002	Lancaster	Sharpsburg	NA	4.3	4.7	36.2	30.6
2002	Gage	Otoe	NA	5.3‡	6.2	29.8	16.6
1995	Lancaster	Crete	NA	NA	NA	NA	NA
2005	Jefferson	Hobbs	4.4	3.8	5.6	24.0	11.5
2004	Gage	Nodaway	2.0	1.9	5.6	17.1	4.4
1995	Cass	NA	NA	NA	NA	NA	NA
1993	Cass	NA	3.2	3.4	5.6	26.4	10.8
2001	Gage	Crete	5.7	4.3	6.6	24.0	32.5
2005	Jefferson	Crete	3.5	2.9	5.7	37.1	23.2
2002	Gage	Wymore	NA	4.8	5.8	29.7	16.8
1994	Saline	Muir	5.8	4.6	5.7	19.4	19.1
1994	Gage	Wymore	3.6	3.2	5.9	28.6	5.7
1994	Cass	NA	1.2	1.3	5.6	28.7	17.2
1994	Saunders	Yutan	1.9	2.2	5.5	18.3	6.5
2005	Saunders	Yutan	3.0	2.7	5.1	27.4	27.4
2005	Lancaster	Kennebec	6.7	5.4	6.1	30.0	9.6
2005	Saunders	Yutan	7.9	5.5	5.7	24.8	8.5
1994	Otoe	NA	2.5	2.8	5.7	29.9	35.5
2005	Lancaster	Wymore	4.6	3.3	6.6	30.4	17.1
1994	Gage	Pawnee	2.3	1.8	5.4	18.0	5.0
2004	Gage	Wymore	6.5	4.8	6.0	32.4	13.4
2004	Saunders	Yutan	5.5	6.7	5.8	26.8	44.4
2005	Nuckolls	Crete	4.1	3.2	5.1	22.4	28.8
2005	Nuckolls	Crete	5.9	4.3	6.0	26.2	70.0
2005	Lancaster	Sharpsburg	3.9	3.2	6.0	30.5	20.5
2004	Gage	Wymore	2.9	2.1	5.8	31.4	2.4
2004	Lancaster	Judson	5.7	4.2	6.0	35.0	14.4
2004	Saunders	Tomek	7.7	5.7	5.9	31.0	10.0
2004	Saunders	Yutan	3.9	3.6	5.9	29.9	4.2
2004	Lancaster	Sharpsburg	5.1	4.7	5.4	35.6	28.2
2004	Lancaster	Nodaway	5.7	4.2	5.7	35.8	25.5
2004	Lancaster	Sharpsburg	5.7	4.2	5.4	34.5	33.4
2004	Lancaster	Judson	5.1	4.7	5.9	32.8	37.5

† Crete: fine, smectitic, mesic Pachic Argiustolls; Geary: fine-silty, mixed, superactive, mesic Udic Argiustolls; Hobbs: fine-silty, mixed, superactive, nonacid, mesic Mollic Ustifluvents; Judson: fine-silty, mixed, superactive, mesic Cumulic Hapludolls; Kennebec: fine-silty, mixed, superactive, mesic Cumulic Hapludolls; Muir: fine-silty, mixed, superactive, mesic Cumulic Haplustolls; Nodaway: fine-silty, mixed, superactive, nonacid, mesic Mollic Udifluvents; Otoe: fine, smectitic, mesic Aquertic Hapludalfs; Pawnee: fine, smectitic, mesic Oxyaquic Argiudolls; Sharpsburg: fine, smectitic, mesic Typic Argiudolls; Tomek: fine, smectitic, mesic Pachic Argiudolls; Wymore: fine, smectitic, mesic Aquertic Argiudolls; Yutan: fine-silty, mixed, superactive, mesic Mollic Hapludalfs. NA = not available.

‡ 0–90 cm.

The treatments structures varied but generally included five or more N rates in increments of 35 kg ha^{-1} or less, including a 0 N rate and an upper N rate of 140 kg ha^{-1} or higher. Nitrogen as ammonium nitrate was surface-applied before planting. Plot size for the 1993 to 1995 trials was 7.5 by 4 m, and 12 m by either 4 or 6 m for the 2001 to 2005 trials. Trials were planted with four replications as randomized complete blocks, except for two trials with two replications. In another four trials, one or two replications were lost to harvest due to errors by the cooperating producers.

Harvest area for grain yield determination was 4.64 and 9.29 m^2 for 1993 to 1995 and 2001 to 2005, respectively. In most trials, the panicles were cut off with hand shears, dried, and threshed, after which the grain was weighed and tested for water content. In 2005, the trials were harvested with a plot combine, and the grain was weighed in the field and subsampled for determination of grain water content. Yields were adjusted to 155 mg kg^{-1} grain water content. The row spacing was 0.76 m in most cases, but at least two trials had 0.91-m and three had 0.30-m interrow spacing. Except for N management, the cooperating farmer made all management decisions including hybrid selection, planting rate and date, and weed and insect control. During 2001 to 2005, fertilizer P was uniformly applied at trial sites if the soil Bray-P1 was <15 mg kg^{-1}.

Data Analysis

The maximum yield for each trial was related to mean air temperature and total precipitation during the period of 1 July to 15 August with the forward stepwise regression function of Statistix 8 (Analytical Software, Tallahassee, FL) to better understand variation in yield across trials. The relationships of maximum yield for each trial with mean air temperature and precipitation during the period of 1 May to 31 August were also examined, but accounted for less variation in yield than for the July to August period.

The yield response function was determined for each trial using the mean grain yield of each N rate. The best fit in relating yield response to N rate was identified using forward stepwise regression analysis according to an exponential function, $Y = a - b\ (1 - \exp^{-cN})$, where Y was grain yield (Mg ha^{-1}); a was the Y-intercept or yield with no N applied (Mg ha^{-1}); b was the increase in yield due to N application (Mg kg^{-1}); c was a slope parameter representing N use efficiency; and N was the fertilizer N rate (kg ha^{-1}). The yield response functions were also determined according to an alternative exponential function, $Y = a + b\ N^c$. Both types of functions were capable of modeling a range of yield responses from linear responses to quadratic with near plateau responses. However, the first exponential function gave the best fit most frequently and the results of the latter function are therefore not reported here.

Yields at the N rates of 0, 35, 70, 105, and 140 kg ha^{-1} were estimated for each trial using the best-fit exponential response functions. The trials were grouped by maximum treatment yield in each trial into yield categories of <6, 6 to 8, and >8 Mg ha^{-1} with 11, 12, and 16 trials per category, respectively, with the categories representing low, medium, and high sorghum yields in southeastern Nebraska. The mean and the standard error of the mean for each N rate in each of the three yield categories were determined. These means were used to determine the exponential yield response functions for each category of trials.

The agronomic efficiency of applied N was determined for each yield category in two ways. Agronomic nitrogen use efficiency (AE_N) was determined for N rates of 35, 70, 105, and 140 kg N ha^{-1} according to the general equation $AE_N = (Y_{+N} - Y_{0N})/N$, with yields and N rates expressed in kg ha^{-1}. The incremental agronomic efficiency of applied N ($\delta Y/\delta N$), or the change in yield for each 1 kg ha^{-1} increase in N rate, was derived from the fitted N response functions and plotted against N rate (Cassman et al., 2003).

The frequency of response to applied N was determined for each category of trials. The net dollar returns above fertilizer cost (NRF) at different N rates were determined as $NRF = (P_G \times Y) - (P_N \times N)$, where P_G and P_N were the price of grain and nitrogen, respectively; Y was the increase in sorghum grain yield (Mg ha^{-1}) due to N application; and N was the N application rate (kg ha^{-1}). The NRF was calculated for five P_N:P_G ratios ranging from 4 to 12. The percentage of trials in each yield category that required higher N rates than the EONRs to achieve 95% of maximum yield was determined. Maximum yield for each trial was the maximum estimated using the response equation developed for that trial to an upper N rate limit of 160 kg N ha^{-1}.

The relationships of soil nitrate-N, SOM, yield, and P_N:P_G ratio to EONR were evaluated through regression analysis. Soil organic matter and nitrate-N were not found to be important to determination of EONR, and algorithms were developed to determine EONR from the P_N:P_G ratio by yield category using the forward stepwise regression function of Statistix 8 (Analytical Software, Tallahassee, FL). The best fit was determined using the exponential function $EONR = a + b(1 - \exp^{-cP_N:P_G})$, where a was the Y-intercept or the optimum N rate if fertilizer N has no cost (kg N ha^{-1}); b was the slope for the change in EONR for each unit change in P_N:P_G ratio; and c was an exponent modifying the effect of the P_N:P_G ratio.

Similarly, a function for determining EONR across yield levels was determined using YG (105% of the maximum treatment yield as determined from the yield response equation for each yield category) and the P_N:P_G ratio as the independent variables where $EONR = a + b\,[1 - \exp^{(-c\ YG)}] - d\,[(1 - \exp^{-eP_N:P_G})]$. Pearson correlation coefficients were determined for soil nitrate-N for the 0- to 1.2-m depth and SOM for the 0- to 0.2-m depth with yield and yield response to applied N.

RESULTS AND DISCUSSION

Grain Yield Levels and Weather Conditions

The highest treatment grain yield per trial ranged from 2.67 to 11.56 Mg ha^{-1} (Table 2). The highest treat-

Table 2. Weather conditions during 1 July to 15 August, maximum mean measured treatment yield, and functions for grain sorghum yield response to applied N for 39 trials conducted in southern Nebraska.

Year	County	Mean air temperature†	Total rainfall†	Maximum treatment yield‡	N rate (kg ha^{-1}) response function‡	R^2
		°C	mm	Mg ha^{-1}		
1993	Gage	23.3	406	2.67	$Y = 1.02 + 1.74 \times (1 - \exp^{-0.010N})$	81
1993	Saunders	23.3	305	2.98	Y = 2.62§	NS¶
1993	Buffalo	22.2	284	3.23	$Y = 1.56 + 1.29 \times (1 - \exp^{-0.020N})$	69
1993	Lancaster	23.9	372	3.61	Y = 3.42	NS
2005	Jefferson	25.6	168	3.95	Y = 3.78	NS
1993	Saline	23.3	318	4.52	Y = 4.11	NS
2002	Lancaster	26.1	57	5.33	Y = 4.69	NS
2002	Gage	26.1	127	5.55	Y = 5.25	NS
1995	Lancaster	25.6	132	5.70	$Y = 2.91 + 2.02 \times (1 - \exp^{-0.010N})$	57
2005	Jefferson	25.6	168	5.78	Y = 5.49	NS
2004	Gage	22.2	79	5.87	Y = 5.39	NS
1995	Cass	25.0	74	6.08	Y = 5.12	NS
1993	Cass	23.1	432	6.18	$Y = 4.70 + 1.19 \times (1 - \exp^{-0.030N})$	85
2001	Gage	26.1	227	6.27	Y = 5.42	NS
2005	Jefferson	25.6	168	6.58	Y = 6.32	NS
2002	Gage	26.1	127	6.59	Y = 6.50	NS
1994	Saline	22.8	170	7.00	$Y = 6.05 + 0.78 \times (1 - \exp^{-0.060N})$	90
1994	Gage	22.8	150	7.03	Y = 6.77	NS
1994	Cass	22.2	152	7.40	Y = 7.12	NS
1994	Saunders	22.2	127	7.48	$Y = 5.33 + 1.74 \times (1 - \exp^{-0.034N})$	89
2005	Saunders	24.8	119	7.49	$Y = 6.52 + 0.93 \times (1 - \exp^{-0.028N})$	92
2005	Lancaster	25.0	142	7.56	$Y = 5.44 + 2.02 \times (1 - \exp^{-0.016N})$	87
2005	Saunders	24.8	119	7.81	$Y = 5.86 + 2.16 \times (1 - \exp^{-0.016N})$	96
1994	Otoe	22.2	142	8.01	Y = 7.79	NS
2005	Lancaster	25.0	142	8.25	$Y = 5.32 + 3.60 \times (1 - \exp^{-0.010N})$	95
1994	Gage	22.8	175	8.41	$Y = 5.96 + 2.22 \times (1 - \exp^{-0.037N})$	95
2004	Gage	22.2	79	8.54	Y = 8.20	NS
2004	Saunders	21.7	76	8.82	$Y = 6.67 + 1.81 \times (1 - \exp^{-0.097N})$	81
2005	Nuckolls	25.0	168	8.94	Y = 8.65	NS
2005	Nuckolls	25.9	168	8.99	Y = 8.40	NS
2005	Lancaster	25.0	142	9.11	$Y = 6.79 + 2.838 \times (1 - \exp^{-0.010N})$	93
2004	Gage	22.2	79	9.19	$Y = 5.32 + 3.605 \times (1 - \exp^{-0.010N})$	78
2004	Lancaster	22.2	79	9.21	$Y = 5.68 + 3.750 \times (1 - \exp^{-0.018N})$	98
2004	Saunders	21.7	76	9.46	$Y = 8.37 + 1.061 \times (1 - \exp^{-0.028N})$	98
2004	Saunders	21.7	76	9.89	$Y = 7.94 + 2.298 \times (1 - \exp^{-0.01N})$	87
2004	Lancaster	21.7	94	10.63	Y = 10.63	NS
2004	Lancaster	21.7	79	10.82	$Y = 5.93 + 4.194 \times (1 - \exp^{-0.035N})$	90
2004	Lancaster	21.7	94	10.87	Y = 10.56	NS
2004	Lancaster	21.7	79	11.56	$Y = 9.83 + 1.290 \times (1 - \exp^{-0.049N})$	80

† Mean temperature and total rainfall are for the period of 1 July 1 to 15 August.
‡ Maximum treatment yield is the mean measured yield for the treatment with the highest yield in the trial while yield (Y) in the response functions is the yield predicted from the function.
§ When the response function was not significant at $P = 0.05$, the trial mean is presented.
¶ NS, not significant.

Table 3. Yield response to applied N for grain sorghum following soybean, and the difference of yield at EONR minus 95% of maximum yield for N rates up to 140 kg ha^{-1} at five N price–grain price ratios.

			P_N:P_G									
			4		6		8		10		12	
Yield level	No. of trials	Frequency of response	*a*†	*b*‡	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*
Mg ha^{-1}		%	%	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}
<6	11	27	27	−34	27	−210	27	−494	27	−494	27	−494
6–8	12	50	0	235	8	77	25	−77	33	−230	50	−384
>8	16	62	0	458	25	335	25	246	25	129	37	19
Overall	39	46	7.6	251	20	102	26	−62	28	−157	38	−250

† *a*, Trials needing a higher N rate than EONR to achieve 95% of maximum yield.
‡ *b*, Yield difference for yield at EONR minus 95% of maximum yield.

ment yield was negatively related to mean air temperature (T, $r = -0.47$), the amount of rainfall (R, $r = -0.64$), and the temperature by rainfall interaction (T × R, $r = -0.67$) during July 1 to August 15. This period normally includes the late vegetative, boot, and soft dough stages (Vanderlip and Reeves, 1972). This weather effect on grain yield (Y, Mg ha^{-1}) was represented by the function in which the main effect of rainfall was not significant: Y = 20.62 − 0.467 T − 0.000593 T × R, $R^2 = 0.56$. In 1993, rainfall during this period was more than usual and yields were relatively low. The exclusion of the 1993 data from the correlation analysis did not improve the correlation coefficients for rainfall, although the negative coefficient for temperature was increased. The mean temperatures were not high relative to the estimated optimum mean temperature of 29°C for sorghum (Martin and Leonard, 1967) but temperatures in excess of this were common during July and August. The negative relationship with rainfall demonstrates the tolerance of grain sorghum to water deficits and the crop's capacity for water use efficiency.

Yield Response to Applied Nitrogen and Agronomic Efficiency

For the 11 of the 39 trials with the highest treatment yield of <6 Mg ha^{-1}, 27% had a significant yield response

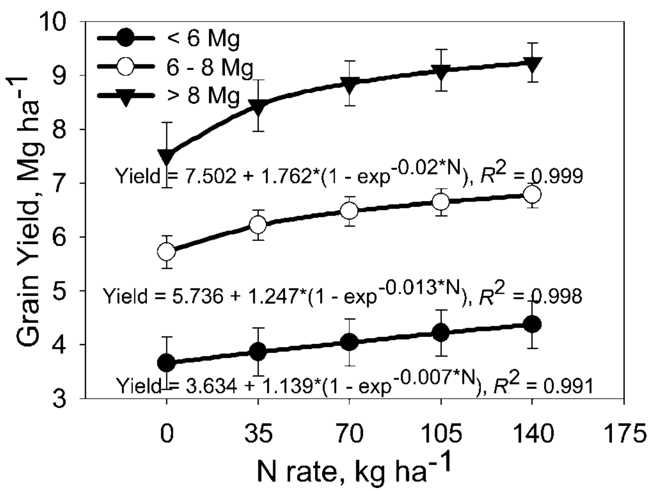

Fig. 1. Nitrogen response curves for grain sorghum following soybean determined from 11, 12, and 16 trials for yield levels <6, 6 to 8, and >8 Mg ha^{-1}, respectively. Y-bars represent the standard error of the means.

to applied N (Tables 2 and 3), while 53% of the trials with >6 Mg ha^{-1} yield had a significant yield response. When treatment effects were significant, the exponential function accounted for a mean of 86% of the variation among treatments. The response rate was similar to results reported by Varvel and Wilhelm (2003), where 43% of the 21 trials conducted at one location between 1983 and 2002 had significant responses to applied N.

The best-fit exponential yield response equations across all trials and for categories of trials grouped by the maximum treatment yield are presented in Fig. 1. Grain yield with no N applied increased as the maximum treatment yield of trials increased, presumably due to less severe biotic and abiotic constraints for the trials in the high-yield category. The shape of the response curve was near linear with little slope for the low-yield category, and became steeper and more curvilinear as the yield level increased.

The additional gain in grain yield due to added N (AE_N) was highest for the high-yield category and lowest for the low-yield category (Table 4). Agronomic N efficiencies of <6 kg grain kg N^{-1} were measured at all sites with <6 Mg ha^{-1} yield, indicating that yield response to fertilizer N was severely constrained by factors other than N. At the high-yielding sites (>8 Mg ha^{-1}), AE_N averaged 14 to 17 kg kg^{-1} for N rates ranging from 70 to 105 kg N ha^{-1}, suggesting fewer constraints to crop growth. The difference in AE_N due to yield level was greatest at the N rate of 35 kg ha^{-1} but the incremental AE_N was near 5 kg grain kg^{-1} N applied for all yield categories at the 105 kg ha^{-1} N rate and higher (Fig. 2).

Economically Optimal Nitrogen Rates

The EONRs were related to P_N:P_{GS} ratio by the respective functions, assuming a yield plateau at a N rate of 140 kg ha^{-1}:

EONR for <6 Mg ha^{-1} =

$$139.4 - 223.1\,[1 - \exp^{(-0.09\,P_N:P_G)}];\ R^2 = 0.880,$$

EONR for 6–8 Mg ha^{-1} =

$$144.1 - 315.5\,[1 - \exp^{(-0.04\,P_N:P_G)}];\ R^2 = 0.987,$$

EONR for >8 Mg ha^{-1} =

$$139.4 - 174.1\,[1 - \exp^{(-0.07\,P_N:P_G)}];\ R^2 = 0.995.$$

The EONRs increased with yield level (Fig. 3) and decreased as P_N:P_G ratios increased. As P_N:P_G ratios in-

Table 4. Average agronomic efficiency of applied N (AE_N)† by grain sorghum at four N rates and for three yield categories.

N rate	AE_N		
	<6 Mg ha^{-1}	6–8 Mg ha^{-1}	>8 Mg ha^{-1}
kg ha^{-1}	kg kg^{-1}		
35	5.91	14.19	24.43
70	5.50	10.86	17.57
105	5.34	8.85	13.69
140	5.14	7.56	11.26

† $AE_N = (Y_{+N} - Y_{0N})$/N rate, where Y_{+N} and Y_{0N} are yield with N applied for the given N rate and yield with no N applied, respectively.

creased, the response curve for the net financial returns to applied N became sharper with steeper increases and decreases, and less plateau, than for lower P_N:P_G ratios. As fertilizer N price increased relative to the price of grain sorghum, NRF decreased, the range of profitable N rates decreased, and the economic penalty of applying above-optimum N rate increased. Sawyer and Nafziger (2005) and Dobermann et al. (2006) found similar results for corn.

Nitrogen application was not profitable for the <6 Mg ha^{-1} category when P_N:P_G was >6 (Fig. 3a). The EONRs for the 6 to 8 Mg ha^{-1} category were 23 and 108 kg N ha^{-1}, and 51 and 106 kg N ha^{-1} for the >8 Mg ha^{-1} category, with P_N:P_G ratios of 12 and 4, respectively (Fig. 3b, 3c). These EONRs were higher than rates determined for the same P_N:P_G ratios using data reported by Varvel and Wilhelm (2003) from eastern Nebraska, but lower for the >8 Mg ha^{-1} category, than determined from 4 yr of results at another location (Binder et al., 2002).

The EONRs calculated with P_N:P_G ratios of 4 and 12 were adequate to achieve 95% or more of maximum yield for 92 and 62% of the trials, respectively (Table 3). Across all trials, the yield at EONR was 0.21 Mg ha^{-1} more and 0.27 Mg ha^{-1} less with P_N:P_G of 4 and 12, respectively, than 95% maximum yield for N rates up to 140 kg ha^{-1}. Yield at EONR for the high-yield category was >95% maximum yield for N rates up to 140 kg ha^{-1} for all five P_N:P_G ratios.

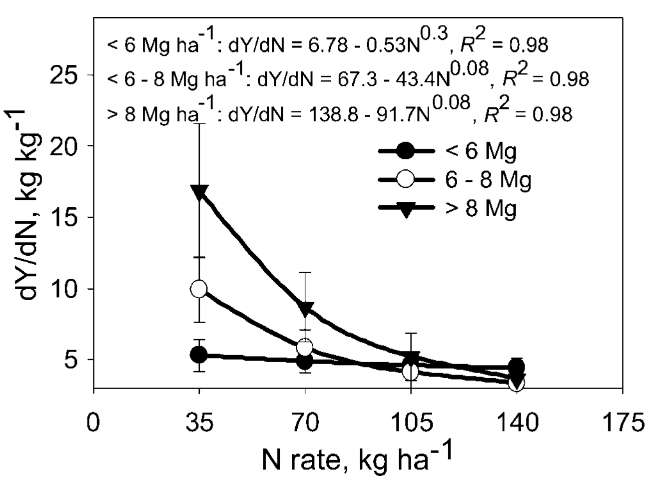

Fig. 2. Incremental agronomic efficiency of applied N (δY/δN), expressed as additional grain yield resulting from N application (kg kg^{-1}) for yield levels < 6, 6 to 8, and > 8 Mg ha^{-1}. Y-bars represent the standard error of the means.

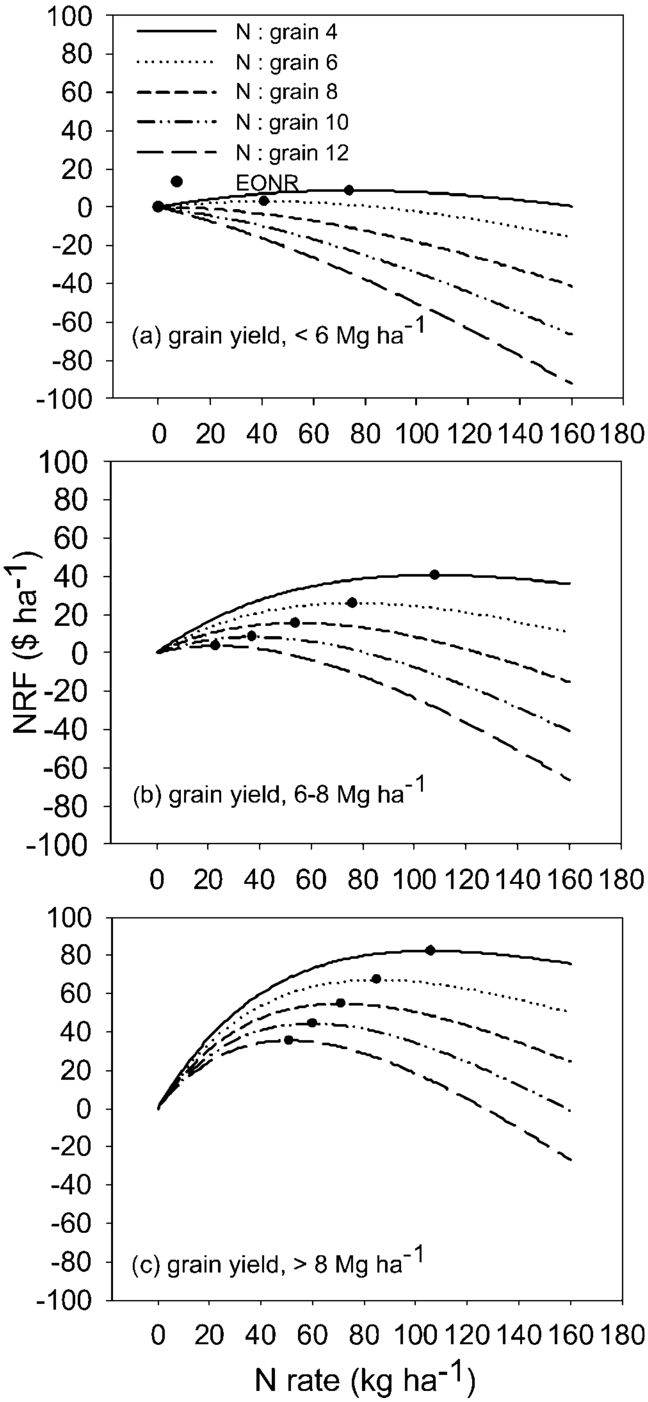

Fig. 3. Net returns to N fertilizer (NRF), and economically optimal N rates (EONR), for grain sorghum following soybean at five N price: grain price ratios ($ kg^{-1}) for yield categories of: (a) <6, (b) 6–8, and (c) >8 Mg ha^{-1}.

Soil Properties, Yield Goal, and EONR

Soil nitrate concentrations for the 1.2-m depth ranged from about 1 to 6 mg kg^{-1} for these 39 trials, with a median RSN concentration and amount of 3.7 mg kg^{-1} and 53 kg ha^{-1}, respectively, assuming a bulk density of 1.2 kg L^{-1} (Table 1). Soil organic matter for the 0.2-m depth ranged, in a normal distribution, from about 16 to 37 g kg^{-1} for these 39 trials, with a median of 28.6 g kg^{-1}

Table 5. Pearson coefficients of correlation for residual soil nitrate (mg kg^{-1}) to the 120-cm depth and soil organic matter (SOM, g kg^{-1}) to the 0.2-m depth with yield properties (Mg ha^{-1}) for 39 grain sorghum trials conducted in southern Nebraska.

	Yield, no N	Yield, maximum with N applied	Yield response to applied N	Soil nitrate-N
Yield, maximum	0.86***			
Yield response	−0.15 ns†	0.38*		
Soil nitrate-N	0.32‡	0.28‡	−0.03 ns	
SOM	0.47**	0.45**	0.12 ns	0.33*

* Significant at $P \leq 0.05$.
** Significant at $P \leq 0.01$.
*** Significant at $P \leq 0.001$.
† NS, not significant.
‡ Significant at $P \leq 0.1$.

(Table 1). As most of these trials were conducted on farmers' fields, RSN and SOM levels were probably representative of situations for sorghum produced in rotation with soybean. Both RSN and SOM concentration were positively correlated with maximum grain yield and yield without N application (Table 5), but these soil properties were not related to yield response resulting from fertilizer N.

The current University of Nebraska–Lincoln algorithm for grain sorghum credits both RSN and SOM as N sources (Ferguson, 2000). The RSN credit may be valid for greater amounts of nitrate-N carryover (Vanotti and Bundy, 1994), but the RSN credit is not supported by the results of these trials for RSN concentrations of >6 mg kg^{-1} when the estimate of EONR may be improved by giving a RSN credit (Ferguson, 2000). The RSN credit is probably more important for sorghum following a cereal, especially corn, in rotation when RSN is typically more than following soybean (Franzleubbers et al., 1994). The SOM credit also is not supported by the results of these trials. However, given the findings of others (Oberle and Keeney, 1990), it may be prudent to increase the N rate by 15 to 30 kg ha^{-1} when SOM is less than the range represented by these trials (Ferguson, 2000).

Yield level was related to yield response to applied N (Fig. 1; Table 5) and EONR changed with yield level. Therefore, YG should be considered in determination of EONR. The EONR is related to both P_N:P_G ratio and YG by

$$\text{EONR} = 139.8 + 248.1\,(1 - \exp^{(-0.06\,\text{YG})}) - 219.2\,[1 - \exp^{(-0.22\,P_N:P_G)}];\ R^2 = 0.939$$

where YG might be considered to be 105% of the producer's mean yield for the field. The determination of EONR for grain sorghum produced in rotation with soybean should consider YG and P_N:P_G.

CONCLUSIONS

Frequency and magnitude of grain sorghum yield response to applied N increased as yield increased. The EONR also increased as yield increased. Yield goal was, therefore, found to be more important for the determination EONRs than SOM and RSN. Soil organic matter and RSN, if in the ranges represented by these trials, do not need to be considered in determining the EONR for grain sorghum in rotation with soybean. The EONR can be most accurately determined considering YG and the P_N:P_G ratio.

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