

Cultivar and N Fertilizer Rate Affect Yield and N use Efficiency in Irrigated Durum Wheat

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ABSTRACT

Optimizing N management and using cultivars with high N use efficiency (NUE) are important for durum wheat (*Triticum durum* Desf.) producers in irrigated desert production systems. A field experiment with six durum wheat cultivars was conducted with five or six levels of N treatment for two growing seasons (2010–2011 and 2011–2012) to determine NUE and yield of durum wheat cultivars under irrigated desert conditions. Recovery efficiency of N fertilizer was very high, ranging from 63 to 79%. Durum wheat cultivars differed in grain N concentration (GNC) in both seasons. In the 2011 to 2012 growing season, cultivars differed in grain yield, agronomic efficiency (AE), NUE, and N harvest index (NHI). The N fertilizer rate had a highly significant, positive effect on nearly all variables in both seasons. As the N fertilizer rate increased, grain yield, GNC, and total N uptake increased and then plateaued, while AE and N utilization efficiency (NUE) decreased linearly. Nitrogen uptake efficiency (NUpE) and NUE decreased as a power function with increased N fertilizer rates. Durum wheat NUE was more closely related to NUpE than NUE. The N harvest index responded in a quadratic manner to N rate in both years. In summary, although there was variation in grain yield and NUE among durum wheat cultivars, N fertilizer effects were much more significant than cultivar effects. This indicates that grower decisions on optimal N rate will have more impact than cultivar selection.

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Abbreviations: AE, agronomic efficiency; GDD, growing degree days; GNC, grain N concentration; NHI, N harvest index; NUE, N use efficiency; NUpE, N utilization efficiency; NUpE, N uptake efficiency; RE, recovery efficiency.

NITROGEN is the most important nutrient for durum wheat (*Triticum durum* Desf.) production in Arizona's irrigated desert production systems (Ottman and Thompson, 2006). Large amounts of N fertilizer are often applied for higher yield and better grain quality (Giuliani et al., 2011b; López-Bellido et al., 2008). It is critical for durum wheat growers to achieve a GNC of 22.8 g kg⁻¹ at 120 g kg⁻¹ of grain moisture, or else a grain price discount is levied. Since N is one of the main inputs and the residual N fertilizer is a potential pollution source to groundwater (Raun and Johnson, 1999; Fageria et al., 2008), selecting durum wheat cultivars with high NUE and optimizing N management on the basis of agricultural practices could increase economic return and reduce environmental pollution.

Various definitions of NUE have been proposed and used (Kessel et al., 2012). In this study, NUE is defined as grain yield

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per unit of N available in the soil according to Moll et al. (1982). In practice, N supply from fertilizer is commonly used because nitrification in soil is difficult to estimate (Moll et al., 1982). Nitrogen use efficiency can be divided into two components: NUpE and NUtE. Nitrogen uptake efficiency accounts for the quantity of N extracted from the soil. Nitrogen utilization efficiency accounts for the quantity of N translocated to grain and used for grain production (Moll et al., 1982). Genotypes with high NUE can absorb more N from soil and can produce higher grain yield per unit of N absorbed (Fageria et al., 2008; Isfan, 1993).

Many indices have been proposed to calculate utilization efficiency of applied N (Fageria et al., 2008; Ladha et al., 2005). Among these methods, recovery efficiency (RE) and AE are commonly used because of their practicality. Recovery efficiency is the ratio of increase in total N uptake compared with the untreated control and N fertilizer rate, indicating plant N uptake per unit of N applied. Agronomic efficiency is the ratio of increase in grain yield from untreated control and the N fertilizer rate, indicating crop yield increase per unit of N applied (Fageria et al., 2008).

Crop cultivars differ significantly in NUE in both bread wheat (*Triticum aestivum* L.) and durum wheat (López-Bellido et al., 2008; Giambalvo et al., 2010; Giuliani et al., 2011a). Motzo et al. (2004) reported that durum wheat cultivars developed in different time periods differed in NUE, grain yield, and GNC. The higher yield of modern cultivars was mainly due to higher NHI with similar total N uptake compared with older cultivars, indicating that NUtE was more important than NUpE for increases in NUE over the last century. However, among modern bread wheat and among durum wheat cultivars, genetic variation in NUE and GNC was mainly due to NUpE, especially under low N supply (Ehdaie et al., 2001; Le Gouis et al., 2000; Ortiz-Monasterio et al., 1997).

Nitrogen fertilizer rate, application timing, and fertilizer formulation also affect NUE (López-Bellido et al., 2008). Although higher N fertilizer rates can increase durum wheat yield and GNC, NUE generally decreases at the same time, especially under low soil moisture conditions (López-Bellido et al., 2008; Giuliani et al., 2011a). Different N fertilizer rates are also critical to NUE studies because the amount of N supply affects the contribution of NUpE and NUtE to NUE (Ehdaie et al., 2001; Le Gouis et al., 2000; Kessel et al., 2012; Moll et al., 1982).

Although N fertilizer input is high in durum wheat, growers in the arid southwestern United States need sufficient information on the amount and timing of N application to produce desirable grain yield and GNC. Previous research on wheat response to N fertilizer has focused mainly on bread wheat, and limited information is available regarding the effects of cultivar and N fertilizer rate on durum wheat NUE (López-Bellido et al., 2008; Giuliani et al., 2011b). It was also found that durum wheat had smaller N uptake capacity and

was less efficient in using N for grain production although durum wheat cultivars had higher GNC than bread wheat (López-Bellido et al., 2008; Ehdaie et al., 2001). Furthermore, most studies on NUE of durum wheat have been conducted under rainfed Mediterranean conditions. Therefore, field experiments with six durum wheat cultivars and six N fertilizer rates were conducted at Maricopa, Arizona in the 2010 to 2011 and 2011 to 2012 growing seasons. The objectives of this study were to compare grain yield, N fertilizer response, and NUE among six durum wheat cultivars for irrigated desert conditions in Arizona.

MATERIALS AND METHODS

Experimental Site and Design

The study was conducted in the 2010 to 2011 and 2011 to 2012 growing seasons at the University of Arizona's Maricopa Agricultural Center at Maricopa, Arizona (33.067547°N, 111.97146°W). The soil texture at the site is a Casa Grande sandy loam and sandy clay loam (fine-loamy, mixed, superactive, hyperthermic Typic Natrargid). Mehlich 3-P and 1M ammonium acetate extractable K were 35 and 250 mg kg⁻¹, respectively, in the surface 15 cm of soil. One M KCl extractable-NO₃-N was 35 kg N ha⁻¹ for 0 to 90 cm soil profile. Fields were irrigated based on periodic soil moisture measurements and the AZSched irrigation scheduling software (Martin, 2007). Nine flood irrigations were applied in each season, from early December to the end of April. A total of 840 and 710 mm irrigation water were applied in the first and second season. Individual irrigations varied in amount from 40 to 100 mm. Precipitation amounted to 29 and 41 mm in the 2010 to 2011 and 2011 to 2012 growing seasons. The average air temperature was 16.9 and 16.0°C for the first and second growing seasons.

A split plot design with four replications was used with a plot size of 5 m wide and 8 m long. Durum wheat cultivars were the main plots and N fertilizer rates were the subplots. Durum wheat cultivars included Duraking, Topper, Kronos, Havasu, Orita, and Ocotillo. These cultivars are currently predominant in Arizona durum wheat production (Ottman, 2008). Five N levels (0, 73, 123, 185, and 269 kg ha⁻¹) were used in the 2010 to 2011 growing season, and six N levels (0, 73, 123, 185, 269, and 403 kg ha⁻¹) were used in the 2011 to 2012 growing season (Table 1). The 269 kg ha⁻¹ rate is similar to farmers' rate. The sixth 403 kg ha⁻¹ level was added in the second season because the high rate of 269 kg N ha⁻¹ in the first season was suboptimal. Nitrogen fertilizer in the form of urea was manually applied to each plot at five different growth stages. Arizona farmers usually apply N fertilizer in several splits. The fertilizer was incorporated into the soil with flood irrigation immediately after application. We assume little to no N fertilizer washed between plots.

Sudangrass [*Sorghum bicolor* (L.) Moench var. *sudanense*] cover crops were grown in the summer before durum wheat planting to remove excess N and reduce fertility variations in the soil. As a result, preplant soil samples showed that the field averaged <3 mg kg⁻¹ NO₃-N in the top 90 cm of the soil profile at the start of both seasons. The last cutting of sudangrass was taken in early September of each growing season, and fields were plowed, disked twice, and laser-leveled for durum wheat planting. To ensure N was the only limiting factor in the study, a maintenance

Table 1. N fertilizer rate at different growth stages in the 2010 to 2011 and 2011 to 2012 growing seasons.

Growth stage	Date		N rate					
	2010–2011	2011–2012	0	73	123	185	269	403 [†]
Preplant	N/A	8 Dec. 2011	0	0	0	0	0	90
Feekes 1–2	18 Jan. 2011	11 Jan. 2012	0	17	34	62	90	112
Feekes 5	9 Mar. 2011	28 Feb. 2012	0	11	22	34	45	56
Feekes 10	24 Mar. 2011	13 Mar. 2012	0	22	34	45	67	67
Feekes 10.5	11 Apr. 2011	9 Apr. 2012	0	22	34	45	67	78

[†] The rate was only used in 2011–2012 growth season.

application of 56 kg ha⁻¹ of phosphate in the form of 0–45–0 (N–P–K) fertilizer was applied before planting. Other nutrients were sufficient according to preplant soil analysis and guidelines on nutrient management for durum wheat in Arizona (Ottman and Thompson, 2006). Durum wheat was planted into dry soil on flat seed beds on December 15 in 2010 and December 9 in 2011, and flood irrigation was applied immediately after planting. The planting rate was 168 kg ha⁻¹ with a row spacing of 19.1 cm and a planting depth of 2.5 cm.

Plant Samplings and Measurements

Wheat plants were destructively sampled from the experimental plots on 18 Jan. (Feekes 2), 24 Feb. (Feekes 5), 22 Mar. (Feekes 10), 7 Apr. (Feekes 10.5), and 2 June (harvest) 2011 and 10 Jan. (Feekes 1), 16 Feb. (Feekes 5), 13 Mar. (Feekes 10), 4 Apr. (Feekes 10.5), and 24 May (harvest) 2012. Plants within two 0.5 m row lengths in each plot were cut at the soil surface and were separated into stems, leaves, and spikes (if any). All samples were oven-dried at 65°C with ventilation to constant weight. The dried biomass was finely ground and samples were prepared for analysis of N content by the Dumas combustion methods with a Carlo Erba elemental analyzer (model NA1500 N/C, Carlo Erba Instruments, Milan, Italy). At maturity, the middle eight rows in each plot were harvested with a small-plot combine harvester on 2 June 2011 and 24 May 2012. Grain yield was recorded, and a sample of grain from each plot was analyzed for GNC with the Carlo Erba analyzer. The last hand harvest was used to determine straw yield and N content for total N uptake. Heads were removed from the hand sample. Chaff was not included in total N uptake.

Data Analysis

The following parameters were calculated according to Moll et al. (1982) and Fageria et al. (2008):

$$\text{Total N uptake} \\ (N_t, \text{ kg ha}^{-1}) = \text{Above ground dry matter} \\ \times \text{N concentration in dry matter} \quad [1]$$

$$\text{Total grain N uptake} \\ (N_g, \text{ kg ha}^{-1}) = \text{Grain yield} \times \text{GNC} \quad [2]$$

$$\text{NUpE, kg N}_{\text{plant}} (\text{kg N}_{\text{fertilizer}})^{-1} = N_t / F_x \quad [3]$$

$$\text{NUtE, kg grain} (\text{kg N}_{\text{plant}})^{-1} = \text{Grain yield} / N_t \quad [4]$$

$$\text{NUE, kg grain} (\text{kg N}_{\text{fertilizer}})^{-1} = \text{NUpE} \cdot \text{NUtE} \quad [5]$$

$$\text{NHI, \%} = (N_g / N_t) \times 100 \quad [6]$$

$$\text{N RE, \%} = [(N_x - N_0) / F_x] \times 100 \quad [7]$$

$$\text{AE, kg grain} (\text{kg N}_{\text{fertilizer}})^{-1} = (G_x - G_0) / F_x \quad [8]$$

where N_t and N_g are total above ground plant N uptake and N uptake in durum wheat grain at maturity, N_0 and G_0 are N uptake and grain yield of unfertilized plot at maturity, and N_x and G_x are plant N uptake and grain yield under N fertilizer rate x (F_x).

Since the levels of N were different for the two seasons, analysis of variance (ANOVA) using PROC MIXED in SAS (SAS Institute, 2012) was performed for each year separately. Block and block \times cultivar were considered as random effects. Cultivar, N fertilizer rate, and cultivar \times N rate were fixed. Cultivar and N fertilizer rate means were separated using Fisher's protected least significant difference at the 0.05 probability level.

Linear functions were fitted to the total N uptake of durum wheat cultivars over growing seasons expressed by growing degree days (GDD). Growing degree days was calculated using the single sine methods using 0°C as base temperature and 30°C as ceiling temperature (Zalom et al., 1983). The linear functions among cultivars or the N fertilizer rate were compared using the extra of sum squares method (Ratkowsky, 1983). Linear or quadratic regression functions (depending on best fit) were estimated for GC, grain yield, total N uptake, NHI, AE, RE, NUpE, NUtE, and NUE vs. N fertilizer rate using PROC REG (SAS Institute, 2012). Single regression functions were fitted for both years' data (combined) in these cases. The economic optimum N fertilizer rate was calculated by setting the first derivative of the quadratic grain yield vs. N fertilizer rate function to a N fertilizer/grain price ratio of 3.8 (\$1.10 per kg N fertilizer⁻¹ and \$0.29 per kg durum wheat⁻¹), and solving for N fertilizer rate (Bronson et al., 2001).

RESULTS

Grain Yield and GNC

No cultivar \times N fertilizer rate interactions were found for grain yield, grain N uptake, total N uptake, RE, AE, NUpE, NUtE, and NUE (Table 2). Therefore, cultivar means (Table 3) and N fertilizer rate means of these variables are presented separately. Cultivar \times N rate interaction was only observed in season two for AE and GNC (Table 4). There were no differences in grain yield among the six durum wheat cultivars in the 2010 to 2011 growing season (Table 2, 3). In the 2011 to 2012 growing season, cultivars Duraking, Kronos, and Orita had a higher grain yield than Topper and Ocotillo. Grain yield of Duraking was 25% greater than that of Ocotillo in 2011 to 2012. Cultivar differences in grain yield in the second season were probably related to growing conditions, such as more favorable temperatures that contributed to greater yields than in the first season. In 2011 to 2012, Ocotillo and Havasu had the lowest grain yields (Table 3), but the highest GNC (Table 4) among the cultivars. Also, in the second season, Duraking,

Table 2. Analysis of variance for durum wheat grain yield, grain N uptake, total N uptake, N recovery efficiency (RE), agronomic efficiency (AE), N uptake efficiency (NUpE), N use efficiency (NUE), N harvest index (NHI), and grain N concentration (GNC).

	Grain yield	Grain N uptake	Total N uptake	RE	AE	NUpE	NUE	NUE	NHI	GNC
	Mg ha ⁻¹	— kg ha ⁻¹ —		%	kg grain kg N _{fertilizer} ⁻¹	kg N _{plant} kg N _{fertilizer} ⁻¹	kg grain kg N _{plant} ⁻¹	kg grain kg N _{fertilizer} ⁻¹	%	g kg ⁻¹
2011										
Cultivar	NS [†]	NS	*	NS	NS	NS	NS	NS	NS	*
N rate	**	**	**	**	**	**	**	**	**	**
Cultivar × N rate	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
2012										
Cultivar	**	*	NS	NS	*	NS	NS	**	**	**
N rate	**	**	**	*	**	**	NS	**	**	**
Cultivar × N rate	NS	NS	NS	NS	*	NS	NS	NS	NS	**

[†]NS, not significant at $P < 0.05$.

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

Table 3. Effects of durum wheat cultivar (averaged across N fertilizer rate) on grain yield, grain N uptake, total N uptake, N recovery efficiency (RE), agronomic efficiency (AE), N uptake efficiency (NUpE), N use efficiency (NUE), and N harvest index (NHI).

Cultivar	Grain yield	Grain N uptake	Total N uptake	RE	AE	NUpE	NUE	NUE	NHI	GNC
	Mg ha ⁻¹	— kg ha ⁻¹ —		%	kg grain kg N _{fertilizer} ⁻¹	kg N _{plant} kg N _{fertilizer} ⁻¹	kg grain kg N _{plant} ⁻¹	kg grain kg N _{fertilizer} ⁻¹	%	g kg ⁻¹
2011										
Ocotillo	4.66	115	134 a [†]	71.6	20.8	1.04	37.7	36.3	86.0	23.5 a
Orita	4.86	116	136 a	79.3	27.5	1.05	38.0	38.8	83.8	22.6 ab
Kronos	4.66	108	121 b	74.8	25.5	0.98	41.2	37.9	88.1	22.0 b
Havasus	4.90	116	136 a	75.9	23.5	1.04	39.7	38.6	85.5	22.3 b
Duraking	4.64	106	120 b	72.5	26.6	0.94	39.8	36.5	86.7	21.8 b
Topper	4.79	114	132 ab	74.0	23.7	1.03	39.0	38.0	86.5	22.7 b
2012										
Ocotillo	4.46 d	105 c	139	63.6	24.1 bc	0.83	37.6	29.4 c	73.1 c	23.3 a
Orita	5.33 ab	120 a	147	63.4	23.5 c	0.86	38.9	32.9 b	80.9 a	21.1 b
Kronos	5.39 ab	119 ab	140	67.6	23.8 bc	0.84	49.1	33.6 b	84.8 a	21.1 b
Havasus	5.12 bc	125 a	155	68.4	22.6 c	0.92	34.6	32.1 b	77.5 b	22.9 a
Duraking	5.57 a	122 a	148	70.2	27.0 ab	0.93	40.4	36.8 a	82.8 a	21.1 b
Topper	4.92 c	111 bc	135	70.4	27.0 a	0.85	40.8	32.0 bc	75.6 b	21.8 b

[†] Within columns in each growing season, means followed by the same letter are not significantly different according to LSD ($P = 0.05$). Means with no letter are not statistically different ($F > 0.05$). All cultivar × N interactions were not significant.

Kronos, and Havasu had the highest grain yield among the cultivars (Table 3) but the lowest GNC (Table 4).

Nitrogen fertilizer rate effects were highly significant for nearly all variables in both seasons (Table 2, Fig. 1–5). Averaged across varieties, both grain yield and GNC increased as N fertilizer rate increased ($P < 0.01$, Fig. 1a and 1b). Durum wheat grain yield increased from 1.75 Mg ha⁻¹ in the unfertilized treatment to 8.11 Mg ha⁻¹ at 403 kg ha⁻¹ N fertilizer rate, while GNC increased from 16.5 to 24.5 g kg⁻¹. Grain yield and GNC at 403 kg ha⁻¹ N fertilizer rate treatment were 460 and 50% higher than the unfertilized treatments, respectively. Both grain yield and GNC had a quadratic relationship with N fertilizer rates, with the estimated maximum grain yield occurring at 413 kg ha⁻¹. Using both years' data, the economic optimum N fertilizer rate was 365 kg N ha⁻¹. However, this rate needs to be

interpreted with caution, given that only in the second year were N rates used that were >365 kg N ha⁻¹.

Nitrogen Uptake and NHI

Nitrogen uptake by durum wheat cultivars had a linear relationship with GDD in both growing seasons. The extra sum of squares test showed that there were no significant differences among the six durum wheat cultivars for N uptake over growing seasons ($P = 0.76$, Fig. 2a). At harvest, the cultivars Ocotillo, Orita, and Havasu had the highest GNC and total N uptake in season one (Table 3).

As expected, N fertilizer rate treatments significantly affected N uptake over the growing seasons when averaged across cultivars ($P < 0.01$, Fig. 2b). Treatments with high N fertilizer rates had significantly higher total N uptake than the low N fertilizer rates. At the harvest stage,

Table 4. Effects of durum wheat cultivar and N fertilizer rate on agronomic N use efficiency (AE) grain N concentration (GNC), Maricopa, AZ, 2012.

N rate	Cultivar						Means
	Duraking	Havasu	Kronos	Ocotillo	Orita	Topper	
kg N ha ⁻¹	kg grain kg N _{fertilizer} ⁻¹						
73	37.2 a [‡]	25.3 b	23.5 b	32.3 ab	21.8 b	34.0 a	29.0 [†]
123	30.2 a	24.4 b	26.6 ab	27.2 ab	27.9 ab	31.3 a	27.9
185	27.3 a	23.9 b	28.0 a	25.0 ab	26.2 ab	27.7 a	26.3
269	23.1 a	22.5 a	23.1 a	21.0 a	23.1 a	24.4 a	22.8
403	17.2 a	16.7ab	17.9 a	14.8 b	18.5 a	17.6 a	17.1
	g kg ⁻¹						
0	17.0 b [‡]	16.8 b	17.6 b	23.4 a	16.9 b	18.8 b	18.4 [§]
73	19.1 a	21.7 a	20.0 a	20.3 a	19.4 a	21.2 a	20.3
123	20.0 b	21.9 a	20.6 ab	21.7 a	16.9 b	19.6 b	20.5
185	22.0 ab	23.6 a	20.5 b	22.6 ab	21.1 b	22.5 a	22.0
269	23.9 bc	26.5 a	23.2 c	25.6 a	24.3 b	24.5 b	24.7
403	25.2 b	27.0 a	25.0 bc	26.3 a	25.6 b	24.4 c	25.6

[†] Linear and quadratic N rate trend significant at $P < 0.01$.

[‡] Means in a row followed by the same letter are not significantly different at $P < 0.05$.

[§] Linear trend significant at $P < 0.01$.

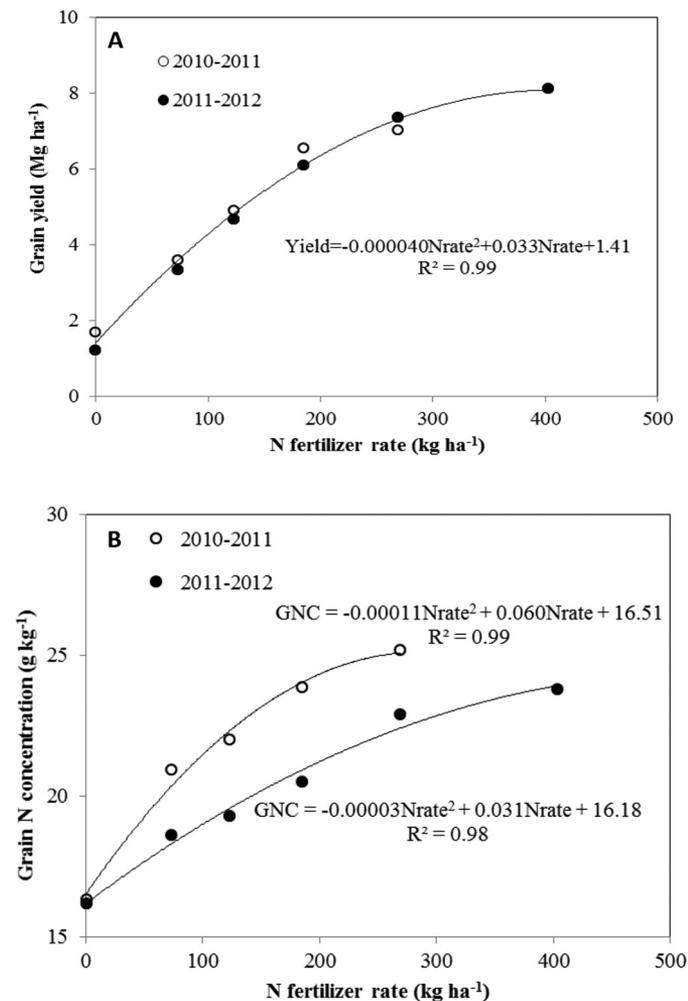


Figure 1. Relationship of durum wheat grain yield vs. N fertilizer rate (a) (2010 to 2011 and 2011 to 2012 seasons pooled regression), and grain N concentration vs. N fertilizer rate (b) (2010 to 2011 and 2011 to 2012 seasons separate regressions).

the total N uptake increased from 30 kg ha⁻¹ in the unfertilized treatment to 270 kg N ha⁻¹ in the 403 kg ha⁻¹ N fertilizer rate treatment (Fig. 2b). The relationship of total N uptake and N fertilizer rate can be described by a quadratic curve with an R^2 of 0.99.

Nitrogen harvest index was very high, ranging from 73 to 83% among the six durum wheat cultivars in the two growing seasons, but cultivar was only significant during the 2011 to 2012 season (Table 3). Averaged across varieties, the relationship of NHI and N fertilizer rate can be described by a quadratic equation with an R^2 of 0.55 (Fig. 3), indicating low efficiency in utilizing acquired N for grain N production at the two highest N fertilizer rates.

Recovery Efficiency and AE

The RE did not differ among durum wheat cultivars in either year (Table 2, 3), and ranged from 60 to 81%. Nitrogen fertilizer rate affected RE in both years (Table 2). This effect was quadratic in 2011 and linear, but negative in 2012. Across cultivars, the RE was 67 to 81% when the N fertilizer rate was ≤ 185 kg ha⁻¹ and then decreased to 60% when the N fertilizer rate was 403 kg ha⁻¹ (Fig. 4a).

Durum wheat cultivars differed significantly in AE in the second growing season only (Table 2, 3). In the 2011 to 2012 season, Duraking and Topper had higher AE than Havasu and Orita. The AE decreased linearly as the N fertilizer rate increased (Fig. 4b). It ranged from 28.7 kg grain kg N_{fertilizer}⁻¹ at the 73 kg ha⁻¹ N fertilizer rate to 16.9 kg grain kg N_{fertilizer}⁻¹ at 403 kg ha⁻¹ N fertilizer rate, indicating that the yield increase from each unit of N input decreased with increasing N fertilizer rate. For every 100 kg ha⁻¹ increase in N fertilizer rate, the AE decreased by 3.6 kg grain kg N_{fertilizer}⁻¹.

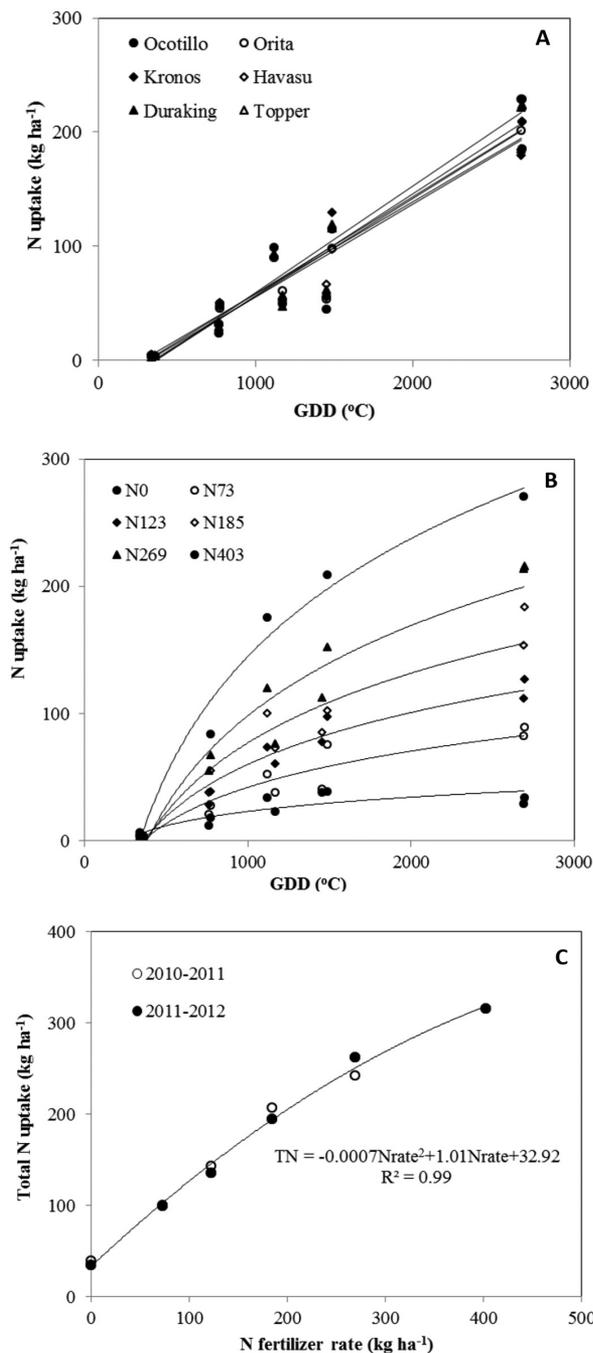


Figure 2. (a) Nitrogen uptake of durum wheat vs. growing degree days (GDD) in 2010 to 2011 and 2011 to 2012 season pooled by cultivar and (b) N uptake vs. GDD by fertilizer rate (2010 to 2011 and 2011 to 2012 seasons pooled regressions). (c) Total N uptake vs. N fertilizer rate (2010 to 2011 and 2011 to 2012 seasons pooled regression).

Nitrogen Uptake Efficiency and NUtE

There were no differences in NUpE or NUtE among durum wheat cultivars in either growing season (Table 2). The differences in NUE were not significant in the 2010 to 2011 growing season, while Duraking and Ocotillo had the highest and lowest NUE, respectively, in the 2011 to 2012 growing season.

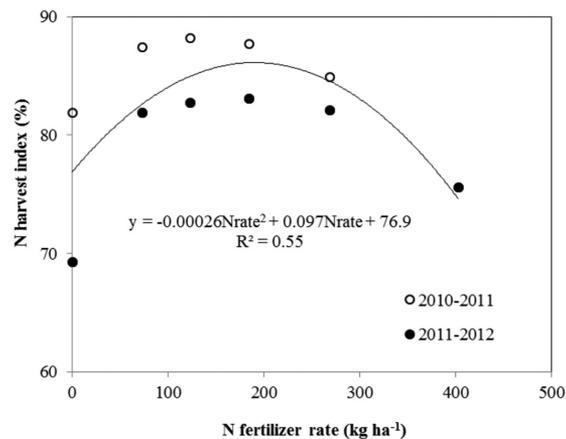


Figure 3. Nitrogen harvest index (NHI) of durum wheat vs. N fertilizer rate (2010 to 2011 and 2011 to 2012 seasons pooled regression).

The relationship of NUpE of durum wheat and N fertilizer rate was described by a power function (Fig. 5a). Nitrogen uptake efficiency cultivars varied significantly with N fertilizer rate, ranging from 1.52 kg N_{plant} kg N_{fertilizer}⁻¹ at the 73 kg ha⁻¹ N fertilizer rate to 0.91 kg N_{plant} kg N_{fertilizer}⁻¹ at the 403 kg ha⁻¹ N fertilizer rate. Nitrogen utilization efficiency decreased linearly as the N fertilizer rate increased, from 35.7 kg grain kg N_{plant}⁻¹ in the unfertilized treatment to 24.5 kg grain kg N_{plant}⁻¹ at the 403 kg ha⁻¹ N fertilizer rate. Decreases in both NUpE and NUtE with increased N fertilizer rate resulted in a negative correlation between NUE and N fertilizer rate. Nitrogen use efficiency decreased from 51.4 kg grain kg N_{fertilizer}⁻¹ at the 73 kg ha⁻¹ N fertilizer rate to 23.9 kg grain kg N_{fertilizer}⁻¹ at the 403 kg ha⁻¹ N fertilizer rate, with a faster rate of decrease at the lower range of the N fertilizer rate.

Compared with NUtE, NUpE had an overall higher correlation with NUE ($r = 0.82$ for NUtE and NUE vs. $r = 0.94$ for NUpE and NUE). When the N fertilizer rate was lower than 123 kg ha⁻¹, the differences between the correlation coefficients were more significant ($r = 0.36$ for NUtE and NUE vs. $r = 0.88$ for NUpE and NUE), indicating that NUpE was more influential on NUE under low N supply. The correlation coefficients were 0.66 for NUtE and NUE and 0.85 for NUpE and NUE when the N fertilizer rate was 185 kg ha⁻¹ or higher.

DISCUSSION

Many studies have shown that crop production can be improved by selecting cultivars with higher NUE in conjunction with improved management of N fertilizer, irrigation water, and tillage (Hirel et al., 2007; Raun and Johnson, 1999). The NUE in this study was 27.2 to 32.7 kg grain kg N_{fertilizer}⁻¹ with 200 to 300 kg ha⁻¹ of N fertilizer, which most Arizona durum wheat farmers use in their fields. Nitrogen is used more efficiently in the irrigated desert production systems than in many other regions because the durum wheat crop is fertilized with multiple

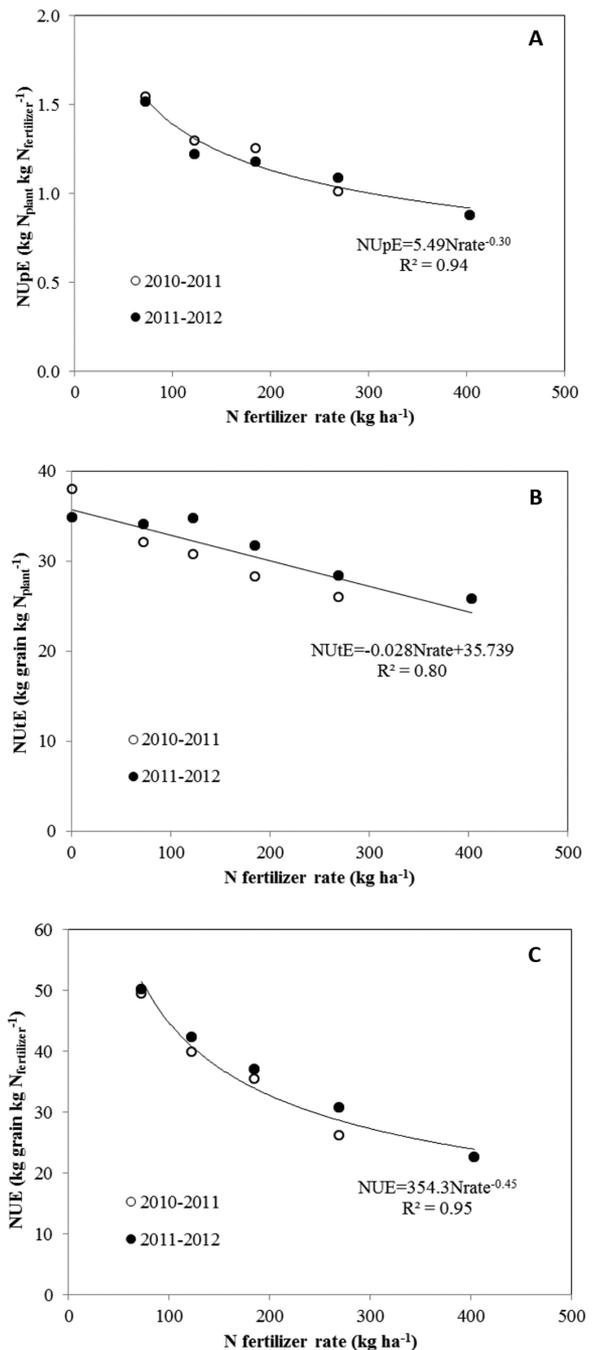
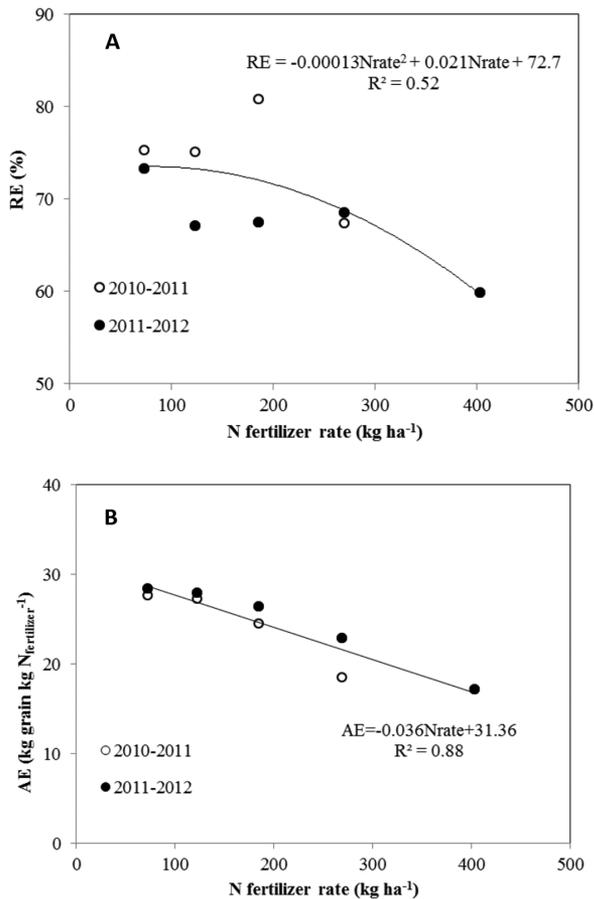


Figure 4. (a) Nitrogen recovery efficiency (RE) vs. N fertilizer rate (2010 to 2011 and 2011 to 2012 seasons pooled regression) and (b) agronomic efficiency (AE) of durum wheat vs. N fertilizer rate (2010 to 2011 and 2011 to 2012 seasons pooled regressions).

N applications and has frequent irrigations (López-Bellido et al., 2008; Giambalvo et al., 2010). However, our study showed minimal variation in durum wheat cultivars for grain yield, total N uptake, and grain N. These variations indicate modest potential for improvement of modern durum wheat cultivars for higher grain yield and higher NUE in irrigated conditions (Raun and Johnson, 1999).

In our study, durum wheat GNC was negatively related to grain yield, which is consistent with other studies on wheat and other cereals (Feil, 1992; Motzo et al., 2004; Stewart and Dwyer, 1990; Ehdaie and Waines, 2001). Studies on the relationship of grain yield and GNC among durum wheat and bread wheat cultivars from different eras of breeding showed that grain yield and GNC were inversely related and that the lower GNC of modern cultivars was mainly due to the dilution effect caused by higher yield (Motzo et al., 2004; Stewart and Dwyer, 1990). This is likely the case for the negative correlations between grain yield and GNC among the modern cultivars (Ehdaie and Waines, 2001). The inverse relationship between grain yield and protein concentration makes it difficult to improve these two traits simultaneously. To maintain GNC, the increase in grain N uptake needs to keep pace with the increase of grain yield

Figure 5. (a) Nitrogen uptake efficiency (NUpE) vs. N fertilizer rate (2010 to 2011 and 2011 to 2012 seasons pooled regressions), (b) N utilization efficiency (NUE) vs. N fertilizer rate (2010 to 2011 and 2011 to 2012 seasons pooled regressions), and (c) N use efficiency (NUE) vs. N fertilizer rate (2010 to 2011 and 2011 to 2012 seasons pooled regressions).

through genetic improvement or management practices (Martre et al., 2003). This can be done by increasing both total N uptake and NHI (Guarda et al., 2004; Motzo et al., 2004). Variations in total N uptake and NHI among durum wheat cultivars in this study indicate potentials of this proposed method to improve both grain yield and GNC.

Nitrogen harvest index is an indicator of the capacity for cultivars to utilize the acquired N to increase grain N

production. Higher NHI is related to higher grain yield and quality (Giuliani et al., 2011b). In this study, NHI was significantly different among six cultivars in the second season, indicating that there is potential to improve NHI in durum wheat. The response of NHI to N fertilizer rates was described by a quadratic curve, which is different from the inverse linear relationship in previous reports (López-Bellido et al., 2008). However, the high NHI levels in our study were similar to the levels found in López-Bellido et al. (2008), despite the lower yields and RE in that rainfed study in Spain. When the N fertilizer was $<186 \text{ kg ha}^{-1}$ (first derivative of function in Fig. 3), NHI increased as the N fertilizer rate increased. This, combined with decreased NUtE (less grain yield per unit of N uptake), resulted in a faster rate of increase in GNC at low N fertilizer rates. However, when the N fertilizer rate was $>186 \text{ kg ha}^{-1}$, NHI decreased as the N fertilizer rate increased, resulting in a slower rate of GNC increase with increased N fertilizer rate. The negative relationship of NHI and N fertilizer rate makes it less efficient to improve GNC by increasing N supply, especially when N fertilizer rates are already high.

Recovery efficiency of N fertilizer in wheat is generally $<50\%$ (Guarda et al., 2004; Giambalvo et al., 2010; Giuliani et al., 2011a). However, in this study, RE for the six durum wheat cultivars ranged from 60 to 81%. Similarly, AE (the increase in grain yield from untreated control per unit of N fertilizer) in the study was also significantly higher than previous studies on durum and bread wheat (Guarda et al., 2004). The high RE and AE was probably due to the fact that sudangrass cover crop removed most of the available soil N, and low soil organic matter ($<10 \text{ g kg}^{-1}$) means lower N mineralization in these soils. Split N application with irrigation, which is a common practice in the desert production system with low precipitation, probably reduced N loss by leaching and volatilization, which further influenced RE and AE. Finally, it must be emphasized that frequent, sizeable irrigations in our study resulted in rapid biomass production and much greater grain yields than the 2 to 3 Mg ha^{-1} in the wheat studies with RE $<50\%$ (Guarda et al., 2004; Giambalvo et al., 2010; Giuliani et al., 2011a). The only wheat study we know of with REs similar to ours is Wuest and Cassman (1992) who reported RE of 55 to 80% when N fertilizer was applied at preplant and at anthesis in irrigated durum wheat in California.

The relative contributions of NU_pE and NU_tE to NUE have been compared in previous studies (Moll et al., 1982; Kessel et al., 2012; Berry et al., 2010; Ortiz-Monasterio et al., 1997). Moll et al. (1982) studied eight maize hybrids and found that the genetic variation of NUE was due largely to variation in NU_tE with low N supply and NU_pE with high N supply. The relationship was confirmed in genetic studies on quantitative trait loci associated with NUE in maize (Hirel et al., 2007). Contrary to Moll et al. (1982), studies on oilseed rape revealed that NU_pE was more important with

low N supply and that NU_tE was more important with high N supply (Berry et al., 2010; Kessel et al., 2012). In our study, NU_pE was the more important contributor to NUE for all N fertilizer rates but especially when N fertilizer rate was low. This is consistent with NUE studies on durum wheat, bread wheat, rice (*Oryza sativa* L.), and oilseed rape (Ehdaie et al., 2001; Le Gouis et al., 2000; Singh et al., 1998; Schulte auf'm Erley et al., 2011; Ortiz-Monasterio et al., 1997; Dhugga and Waines, 1989). The differences between maize and other crops could be caused by the fact that oilseed rape has an indeterminate growth habit and that wheat and rice can increase tillers from higher NU_pE. These properties confer to oilseed rape, wheat, and rice a better ability to increase sink capacity from higher NU_pE and improve NUE.

CONCLUSIONS

The six durum wheat cultivars that are common in Arizona systems differed significantly only in GNC in both growing seasons. Grain yield, AE, NUE, and NHI varied among the durum wheat cultivars only in the 2011 to 2012 growing season. Second season differences in NUE suggest that there is potential to improve durum wheat grain yield and NUE by breeding for N efficient cultivars. The cultivar rankings in 2011 to 2012 for grain yield and NUE were the same. Recovery efficiency of added N by durum wheat was greater in this irrigated desert system than in rainfed Mediterranean studies. This may have been due to the high number of split applications and the well-irrigated conditions that resulted in high yields. Nitrogen uptake efficiency was better correlated with NUE than NU_tE, indicating the importance of NU_pE, especially when N fertilizer rates were low. Grain yield, GNC, and total N uptake responded to N fertilizer rate with a single quadratic response in both seasons. Interactions between cultivar and N were almost absent in this study. Nitrogen fertilizer effects were greater and more consistent than cultivar effects and should therefore be given the most attention by growers.

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