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Evaluation of the yield and nitrogen use efficiency of the dominant maize hybrids grown in North and Northeast China

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Breeding high-yielding and nutrient-efficient cultivars is one strategy to simultaneously resolve the problems of food security, resource shortage, and environmental pollution. However, the potential increased yield and reduction in fertilizer input achievable by using high-yielding and nutrient-efficient cultivars is unclear. In the present study, we evaluated the yield and nitrogen use efficiency (NUE) of 40 commercial maize hybrids at five locations in North and Northeast China in 2008 and 2009. The effect of interaction between genotype and nitrogen (N) input on maize yield was significant when the yield reduction under low-N treatment was 25%–60%. Based on the average yields achieved with high or low N application, the tested cultivars were classified into four types based on their NUE: efficient-efficient (EE) were efficient under both low and high N inputs, high-N efficient (HNE) under only high N input, low-N efficient (LNE) under only low N input, and nonefficient-nonefficient under neither low nor high N inputs. Under high N application, EE and HNE cultivars could potentially increase maize yield by 8%–10% and reduce N input by 16%–21%. Under low N application, LNE cultivars could potentially increase maize yield by 12%. We concluded that breeding for N-efficient cultivars is a feasible strategy to increase maize yield and/or reduce N input.

maize, genotype×nitrogen interaction, low nitrogen stress, nitrogen use efficiency, yield

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Food security is among the most important concerns in China. In 2011, the Food Security Risk Index of China was predicted as ‘medium risk’ by the FAO and Maplecroft in the United Kingdom [1]. To meet the food requirements of China’s increasing population, estimates indicate that the crop yield per unit area should be increased to as high as 5250 kg hm^{-2} by 2020 [2]. However, fertilizer application is increasing rapidly in China and has reached a total of 50 million tons per annum [3]. Overuse of fertilizer not only reduces fertilizer efficiency, but also increases soil nutrient loss and results in environmental pollution. Methods to reduce fertilizer input while maintaining or even increasing crop yield are a major goal of crop research [4,5].

Among crops in China, maize has the highest total yield and growing area. The partial fertilizer productivity (PFP) of nitrogen (N) in China is only 21–38 kg kg^{-1} for maize [6–11], whereas the average PFP worldwide is as high as 57 kg kg^{-1} [11]. Therefore, there is substantial potential to in-

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*Corresponding author (email: miguohua@cau.edu.cn) crease nitrogen use efficiency (NUE) in maize production in China. Breeding for N-efficient cultivars may contribute to higher NUE in addition to higher yield. Variation in NUE among maize genotypes is well documented [6,12–14], providing opportunities for genetic improvement of this trait. Breeding for low-N-tolerant maize has long been a target of International Maize and Wheat Improvement Center (CIMMYT) [15]. Some major maize-breeding companies, such as Pioneer, also rate NUE among the highest priorities of their breeding programs [16]. As one example of success, N-efficient maize cultivars bred in a low-N environment showed increased yield of 10.5% under high-N conditions and 14% under low-N conditions. Therefore, increasing maize NUE under low-N supply while maintaining the yield potential under high-N conditions is feasible [17].

The targets for NUE improvement are to (i) increase yield potential without additional N input, (ii) reduce N input without affecting yield significantly, or (iii) increase low-N tolerance with very low N input [18]. In Africa, where the population is less dense than in China and where N fertilizer supply is limited, low-N-tolerant cultivars are highly desirable [19]. In China, where the population is large and where food shortages and environmental pollution are urgent problems, cultivars must be bred with higher yields and low N-input requirements. Liu et al. [20] classified cultivars into four different NUE classes based on the conditions under which they are efficient: efficient-efficient (EE) cultivars are efficient under both low and high nitrogen inputs; high-nitrogen efficient (HNE) cultivars under only high nitrogen input; low-nitrogen efficient (LNE) cultivars under only low nitrogen input; and nonefficient–nonefficient (NN) cultivars under neither. The extent of variation in NUE among the dominant Chinese hybrids in cultivation and the potential to increase yield and reduce N fertilizer input through high-yielding, N-efficient cultivars is unclear. In the present study, we evaluated the yield and NUE of 15 commercial maize hybrids at five locations in North and Northeast China. The results are important for maize breeders to set targets for increasing NUE.

1 Materials and methods

1.1 Experimental locations

Ten to 15 maize hybrids comprising the dominant cultivars grown in North and/or Northeast China were grown in each of the eight environments at five locations in China in 2008 and 2009: Changping, Beijing; Changchun, Jilin Province; Qingdao, Shangdong Province; Xuchang, Henan Province; and Hengshui, Hebei Province (Tables 1 and 2). The growth period was from early May to the end of September in Beijing and Changchun, and from mid-June to mid-October in Qingdao, Xuchang, and Hengshui. The soil physicochemical characteristics at the onset of the experiment are shown in Table 2. The experimental field at Changping has been part of a long-term N fertilizer experiment since 1984 [21].

1.2 Experimental design

The experimental design was a split-plot with three replicates, with N fertilizer treatments in the main plots and the cultivars in the subplots. The plots were 12–20 m^2 in area. The rows were 6 m long and spaced 50–60 cm apart. Seeds were hand-sown at a density of 60000 seeds hm^{-2}. The distance between plants within a row was 0.28–0.33 m. For the high N (HN), medium N (MN), and low N (LN) treatments, 240, 120, and 0 kg N hm^{-2} (as urea), respectively, were applied, half at sowing and half at the V12 stage. Potassium (as K_2SO_4) and phosphorus (as superphosphate) were applied before sowing at 30–45 kg K_2O hm^{-2} and 60–90 kg

Table 1 Maize cultivars tested at each location in China

Location				
Xuchang, Henan	Hengshui, Hebei	Changchun, Jilin	Changping, Beijing	Qingdao, Shandong
ZD958	ZD958	ZD958	ZD958	ZD958
XY335	XY335	XY335	XY335	XY335
XD20	XD20	XD20	XD20	XD20
XF32D22	XF32D22	XF32D22	XF32D22	XF32D22
LY13	LY13	LY13	LY13	LY13
ND108	ND108	JD137	ND108	ND108
XD18	JH5	NY309	JH5	JH5
YH988	XQ73-1	ND588	XQ73-1	LD981
HY14	LY16	PQ13	LY16	LD9032
YF335	LD981	SY103	DH661	LiaoYu22
XD29	LY18	DF77		LY35
ZK11	LD9002	XY508		LN14
LY4	H6272	YF29		XF1
LD9	H311	YQ281		ZJ3
		JD26		

Table 2 Location, precipitation, and soil physicochemical characteristics at the maize study sites in China[a)]

Experiment No.	Year	Location	Latitude and longitude	Precipitation during growth season (mm)	Soil type	NaOH-N (mg kg^{-1})		Olsen-P (mg kg^{-1})		NH_4Ac-K (mg kg^{-1})		Organic matter (g kg^{-1})		pH	
						HN	LN	HN	LN	HN	LN	HN	LN	HN	LN
1	2008	Xuchang, Henan	34°07′N, 113°77′E	397	Alluvial soil	5.23		10.7		80.0		15.4		7.90	
2		Hengshui, Hebei	37°45′N, 115°30′E	400	Alluvial soil	15.6		33.7		106.4		14.5		8.45	
3		Changchun, Jilin	43°78′N, 125°38′E	502	Black soil	5.9		31.8		110.1		22.5		6.67	
4		Changping, Beijing	40°09′N, 116°36′E	520	Alluvial soil	20.0	5.64	16.9	22.4	139	115	12.9	12.6	8.27	8.20
5		Qingdao, Shandong	36°38′N, 120°45′E	501	Brown soil	20.2		42.9		94		13.0		5.69	
6	2009	Qingdao, Shandong	36°38′N, 120°45′E	416	Brown soil										
7		Changchun, Jilin	43°78′N, 125°38′E	367	Black soil										
8		Changping, Beijing	40°09′N, 116°36′E	360	Alluvial soil										

a) HN, high nitrogen; LN, low nitrogen. Data of precipitation were from the local meteorological bureaus. Experimental numbers are designated according to the experimental years.

P_2O_5 hm^{-2} in all plots.

1.3 Statistical analysis

On the basis of the average yield under LN and HN, the tested cultivars were classified as either EE, HNE, LNE, or NN. The potential of a cultivar to reduce N fertilizer input was estimated according to the method of Chen et al. [22] as the reduction in N fertilizer at which the yield of the cultivar equaled the average of all tested cultivars under HN. The calculations were as follows:

Agronomical N efficiency (AE)=(yield with N input −yield without N input)/N input level, (1)

Reduction in N fertilizer requirement=N inputlevel −(average yield of all tested cultivars−yield of individual cultivar without N input)/AE of the cultivar, (2)

Potential fertilizer reduction (%)=reduction in N fertilizer requirement/N input level×100, (3)

Potential yield increase (%)=(yield of a cultivar −average yield of all tested cultivars)/ average yield of all tested cultivars×100, (4)

NUE=yield/N input level [13], (5)

Yield reduction at LN or MN (%)=(yield at HN −yield at LN or MN)/yield at HN×100. (6)

Heritability (h^2) was estimated following Hallauer and Miranda [23]:

$$h^2\% = \frac{\sigma_g^2}{\sigma_g^2 + \sigma_e^2 / r} \times 100, \tag{7}$$

where σ_g^2 is the genetic variance, σ_e^2 is the random error, and r is the number of repeats.

Phenotypic correlation (r_p) and genetic correlation (r_g) were calculated as follows [24]:

$$r_p(xixj) = \mathrm{COV}_p(xixj) / \sqrt{\delta_p^2(xi)\delta_p^2(xj)}, \tag{8}$$

$$r_g(xixj) = \mathrm{COV}_g(xixj) / \sqrt{\delta_g^2(xi)\delta_g^2(xj)}. \tag{9}$$

The experimental data were analyzed using two-way analysis of variance (ANOVA) with SAS software (SAS Institute, Cary, NC, USA) and differences were compared using the least significant difference (LSD) test at the 0.05 level of significance.

2 Results

2.1 Variance analysis of yield

Among the eight environments, the average heritability of yield was 75.8% and was unaffected by N-supply treatments (Table 3). The genotype×N (G×N) interaction was significant in Experiments (Exps) 5–8, but not in Exps 1–4. The effect of N was also significant in Exps 5–8 (Table 4). In Exps 1–4, there was a significant correlation between yield at any two N levels. The only exception was in yield between LN and HN in Exp 4. In Exps 6–8, phenotypic and genetic correlations in yield were non-significant between LN and HN and between LN and MN.

2.2 Variation in yield in response to N treatments in different environments

In Exps 1–4, in which the G×N interaction was not significant, LN slightly reduced yield by an average of 8.8% compared with that of HN (Table 5). The percentage reduction was highest at Xuchang, Henan (by 13.4%) and lowest at Hengshui, Hebei (by 1.68%). The coefficient of variation (7.98%–8.74%) was similar among the three N treatments. The yield under MN was not significantly different from that under HN, but NUE increased from 38.2 kg kg^{-1} under LN to 75.9 kg kg^{-1} under MN.

In Exps 5–8, in which the G×N interaction was significant, the yield under LN was 39% lower than that under HN, with a difference of 3788 kg hm^{-2}. The percentage reduc-

Table 3 Heritability of yield and correlation with nitrogen (N) level in maize[a)]

Experiment No.	LN	MN	HN	LN vs. MN		LN vs. HN		MN vs. –HN	
	h^2	h^2	h^2	r_p	r_g	r_p	r_g	r_p	r_g
1	72.4	64.7	85.1	0.567*	0.801**	0.664**	0.843**	0.558*	0.68**
2	81.5	86.0	82.6	0.775**	0.95***	0.779**	0.893***	0.884***	0.974***
3	37.1	63.6	50.7	0.812***	1.07***	0.683**	1.06***	0.721**	1.02***
4	56.9	84.2	69.1	0.615	0.891***	0.757*	1.020***	0.721*	0.979***
5	87.2	62.0	82.7	0.553*	0.814**	0.489	0.573*	0.724**	1.05***
6	86.2	87.7	77.3	0.041	0.0302	–0.175	–0.240	0.796**	1.08***
7	81.4	74.4	86.2	0.163	0.196	–0.309	0.160	0.365	1.01***
8	96.3	80.6	83.8	0.161	0.184	–0.185	–0.254	0.683*	0.731**

a) Experiment numbers are described in Table 2. LN, low-N treatment; MN, medium-N treatment; HN, high-N treatment; h^2, heritability; r_p, phenotypic correlation; r_g, genetic correlation. *, **, and *** indicate significance at P<0.01, P<0.05, and P<0.001 level, respectively.

Table 4 Analysis of variance in yield in the eight nitrogen (N) experiments on maize[a)]

Experiment No.	Block	N treatment	Genotype (G)	G×N	Error
1	1191934	14369263***	4281028***	814321	533120
2	2450277***	417789	4278164***	341711	288733
3	118756	17421263***	3340509***	354562	681735
4	568841	13517231***	4490705***	686626	526279
5	8488851***	176654000***	5128346***	1008196*	617205
6	2003330*	2003330***	3380001***	1754041***	395034
7	416202	137214683***	3179078***	3057113***	692245
8	652956	90530388***	3832923***	2114208***	357040

a) Experiment numbers are described in Table 2. *, P<0.05; ***, P<0.001.

Table 5 Variation in yield in response to nitrogen (N) treatments in eight fertilization experiments on maize[a)]

Experiment No.	LN				MN					HN			
	Yield (kg hm^{-2})	Variation coefficient (%)	Yield reduction (%)	LSD$_{0.05}$	Yield (kg hm^{-2})	Variation coefficient (%)	Yield reduction (%)	NUE (kg kg^{-1})	LSD$_{0.05}$	Yield (kg hm^{-2})	Variation coefficient (%)	NUE (kg kg^{-1})	LSD$_{0.05}$
Experiments in which G×N interaction was non-significant													
1	7260	10.1	13.4	1354	8101	9.18	3.38	67.5	1281	8384	11.2	34.9	1064
2	8260	8.90	1.68	916	8453	10.0	–0.61	70.4	1186	8402	7.45	35.0	780
3	9181	7.04	11.7	1479	10034	6.77	3.45	83.6	1205	10393	6.61	43.3	1392
4	9752	5.90	8.55	1239	11061	9.02	–3.73	81.9	1170	10663	7.43	39.5	1299
Mean	8613	7.98	8.82		9412	8.74	0.62	75.9		9460	8.17	38.2	
SE	546	0.94	2.58		692	0.69	1.73	4.04		619	1.03	2.01	
Experiments in which G×N interaction was significant													
5	4906	19.0	42.5	1395	8371	9.31	1.96	69.8	1628	8538	11.2	35.6	1469
6	4198	20.0	56.1	1053	8924	10.7	6.61	74.4	1109	9556	8.63	39.8	1139
7	8198	14.4	27.0	1717	11212	6.59	0.18	93.4	1162	11233	9.62	46.8	1193
8	7200	13.3	30.3	661	10076	9.08	2.43	74.6	1187	10327	9.35	38.2	1161
Mean	6126	16.7**	39.0		9646	8.92	2.80	78.0		9914	9.70	40.1	
SE	942	1.66	6.60		631	0.86	1.36	5.25		572	0.54	2.40	

a) LN, low-N treatment; MN, medium-N treatment; HN, high-N treatment; LSD, least significant difference; NUE, nitrogen use efficiency; G×N, genotype×nitrogen treatment interaction ; SE, standard error. **, P<0.01 by analysis of variance.

tion was highest at Qingdao, Shandong (by 42.5% and 56.1%, in 2008 and 2009, respectively). The variation coefficients for LN and MN were significantly higher than for HN, suggesting large differences in the responses to N treatment among cultivars. The yield under MN was not significantly different from that under HN, but NUE increased from 40.1 kg kg^{-1} under LN to 78 kg kg^{-1} under MN.

2.3 Potential fertilizer reduction and yield increase by N-efficient cultivars

On the basis of average yield in the LN and HN treatments, the cultivars were classified into four NUE classes using the data obtained in Exps 5–8. For each NUE class, the average yield, percentage reduction, NUE, reduction in N fertilizer requirement, potential fertilizer input reduction, and potential yield increase were calculated (Tables 6–9).

Fifteen cultivars (28% of the total cultivar numbers used in Exps 5–8) were classified as LNE (Table 6). Under LN, the yield of LNE cultivars was 11.8% higher than the average yield of all tested cultivars and average yield reduction was 26.3%. Under MN and HN, the yields of LNE cultivars were 3.25% and 7.76% lower, respectively, than the average yield of all tested cultivars. No potential N savings were observed for this class of cultivars. The yield performance of LNE cultivars was variable, with only XD20 and ND108 showing the same performance.

Ten cultivars (19% of the total cultivar numbers used in Exps 5–8) were classified as HNE (Table 7). Under LN, the yield of HNE cultivars was 15.4% lower than the average yield of all tested cultivars, and under HN, it was 9.46% higher. The average yield reduction was 52.6%. The potential N fertilizer savings was 20.7%. XY335 was a typical HNE cultivar in which yield performance was identical in.

Thirteen cultivars (25% of the total cultivar numbers used in Exps 5–8) were classified as EE (Table 8). Under LN, MN, and HN, the yields of EE cultivars were 15%, 6.62%, and 7.57% higher, respectively, than the average yields of all tested cultivars. The average yield reduction was 34.7%. The potential N fertilizer savings was 25.2%–15.9%. ZD958 was a typical HNE cultivar in which yield performance was identical.

Fifteen cultivars (28% of the total cultivar numbers used in Exps 5–8) were classified as NN (Table 9). Under LN, MN, and HN, the yields of NN cultivars were 13.5%, 4.26%, and 4.74% lower than the average yield of all tested cultivars. The average yield reduction was 44.6%. No potential N fertilizer savings was observed for this class of cultivars.

The yields of cultivars within a NUE class were averaged and compared for each N treatment (Figure 1). The yield of EE cultivars was significantly higher than that of HNE cultivars under LN but not under MN and HN. Thus, HNE cultivars (such as XY335) were more sensitive to low N than were EE cultivars (such as ZD958). The yield of LNE cultivars (such as ND108 and XD20) was significantly higher than that of NN cultivars under LN but not under HN and MN. For most of the tested cultivars, the NUE varied among environments.

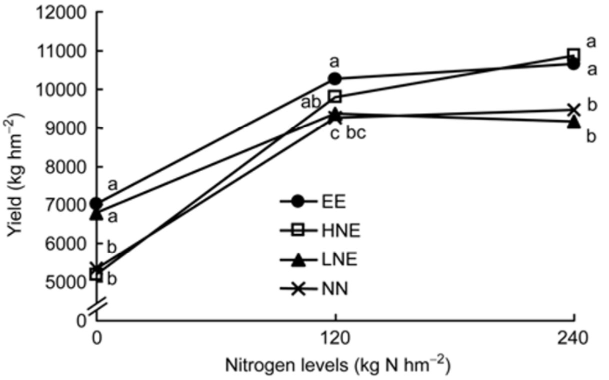

Figure 1 Yield of cultivars in each nitrogen use efficiency (NUE) class in response to three N application levels. Data are derived from Tables 6–9. The yield of the cultivars in each NUE class was averaged and compared for each N treatment. Points at the same nitrogen level with different lowercase letters were significantly different at the $P<0.05$ level by the LSD test.

Table 6 Yield and nitrogen (N) responsiveness of low-nitrogen-efficient cultivars$^{a)}$

N treatment	Parameter	Experiment No. 5	Experiment No. 6	Experiment No. 7	Experiment No. 8	Mean	SE
LN	Cultivars	XD20, LY22, LN14	ND108, LD9032, LD981, ZJ3	ND588, JD26, XD20, YF29, YQ281	LY13, DH3719, ND108		
	Average yield (kg hm^{-2})	5662	4881	8858	7731	6783	917
	Yield reduction compared with HN (%)	27.6	46.2	15.2	16.3	26.3	7.20
	Yield increase compared with the average yield of all tested cultivars (kg hm^{-2})	756	683	660	531	657	46.8
	Percentage yield increase (%)	15.4	16.3	8.06	7.38	11.8	2.35
MN	Average yield (kg hm^{-2})	8081	8647	11076	9548	9338	653
	Yield reduction compared with HN (%)	−3.27	4.67	−6.05	−3.42	−2.02	2.32
	Average NUE (kg kg^{-1})	67.3	72.1	92.3	79.6	77.8	5.44
	Reduction in N fertilizer requirement (kg hm^{-2})	−10.9	−7.47	−5.67	−30.3	−13.6	5.69
	Potential N fertilizer input reduction (%)	−9.12	−6.22	−4.72	−22.5	−10.6	4.05
	Yield increase compared with the average yield of all tested cultivars (kg hm^{-2})	−290	−277	−136	−528	−308	81.2
	Percentage yield increase (%)	−3.46	−3.10	−1.21	−5.24	−3.25	0.83
HN	Average yield (kg hm^{-2})	7825	9071	10444	9233	9143	536
	Average NUE (kg kg^{-1})	32.6	37.8	43.5	34.2	37.0	2.42
	Reduction in N fertilizer requirement (kg hm^{-2})	−58.6	−23.9	−84.3	−145	−78.0	25.6
	Potential N fertilizer input reduction (%)	−24.4	−9.95	−35.1	−53.8	−30.8	9.24
	Yield increase compared with the average yield of all tested cultivars (kg hm^{-2})	−713	−485	−789	−1094	−770	126
	Percentage yield increase (%)	−8.35	−5.07	−7.02	−10.6	−7.76	1.16

a) LN, low-N treatment; MN, medium-N treatment; HN, high-N treatment; SE, standard error.

Table 7 Yield and nitrogen (N) responsiveness of high-nitrogen-efficient cultivars[a)]

N treatment	Parameter	Experiment No. 5	Experiment No. 6	Experiment No. 7	Experiment No. 8	Mean	SE
LN	Cultivars	LD9032, XY335	LY13, XF32D22, XY335	DF77, XY335, XY508	XY335, JH5		
	Average yield (kg hm^{-2})	4550	3183	6737	6309	5195	821
	Yield reduction compared with HN (%)	50.8	69.5	46.3	43.9	52.6	5.79
	Yield increase compared with the average yield of all tested cultivars (kg hm^{-2})	−356	−1015	−1461	−891	−931	227
	Percentage yield increase (%)	−7.25	−24.2	−17.8	−12.4	−15.4	3.63
MN	Average yield (kg hm^{-2})	8143	9449.6	11085	10475	9788	644
	Yield reduction compared with HN (%)	11.9	9.32	11.6	6.88	9.92	1.16
	Average NUE (kg kg^{-1})	67.9	78.7	92.4	77.6	79.1	5.04
	Reduction in N fertilizer requirement (kg hm^{-2})	−8.45	12.0	−5.26	16.5	3.69	6.19
	Potential N fertilizer input reduction (%)	−7.04	10.0	−4.39	12.2	2.69	4.90
	Yield increase compared with the average yield of all tested cultivars (kg hm^{-2})	−228	526	−127	399	143	188
	Percentage yield increase (%)	−2.72	5.89	−1.13	3.96	1.50	2.04
HN	Average yield (kg hm^{-2})	9243	10421	12537	11249	10863	694
	Average NUE (kg kg^{-1})	38.5	43.4	52.2	41.7	44.0	2.94
	Reduction in N fertilizer requirement (kg hm^{-2})	39.0	33.4	72.1	61.5	51.5	9.18
	Potential N fertilizer input reduction (%)	16.3	13.9	30.1	22.8	20.7	3.63
	Yield increase compared with the average yield of all tested cultivars (kg hm^{-2})	705	865	1304	922	949	127
	Percentage yield increase (%)	8.25	9.05	11.6	8.93	9.46	0.74

a) LN, low-N treatment; MN, medium-N treatment; HN, high-N treatment; SE, standard error.

Table 8 Yield and nitrogen (N) responsiveness of efficient-efficient cultivars[a)]

N treatment	Parameter	Experiment No. 5	Experiment No. 6	Experiment No. 7	Experiment No. 8	Mean	SE
LN	Cultivars	ZD958, LY13, LY35	XD20, ZD958, LY35, QD1	PQ13, JD137, XF32D22	XF32D22, XQ73-1, ZD958		
	Average yield (kg hm^{-2})	6007	4742	9266	8038	7013	1012
	Yield reduction compared with HN (%)	39.4	52.6	21.2	25.7	34.7	7.12
	Yield increase compared with the average yield of all tested cultivars (kg hm^{-2})	1101	544	1068	838	888	129
	Percentage yield increase (%)	22.4	13.0	13.0	11.6	15.0	2.50
MN	Average yield (kg hm^{-2})	9287	9443	11749	10572	10263	572
	Yield reduction compared with HN (%)	6.32	5.67	0.03	2.32	3.59	1.47
	Average NUE (kg kg^{-1})	77.4	78.7	97.9	78.3	83.1	4.95
	Reduction in N fertilizer requirement (kg hm^{-2})	25.1	11.9	18.2	19.8	18.7	2.72
	Potential N fertilizer input reduction (%)	20.9	9.89	15.1	14.7	15.2	2.25
	Yield increase compared with the average yield of all tested cultivars (kg hm^{-2})	916	519	537	496	617	100
	Percentage yield increase (%)	10.9	5.81	4.79	4.92	6.62	1.46
HN	Average yield (kg hm^{-2})	9913	10011	11752	10823	10625	428
	Average NUE (kg kg^{-1})	41.3	41.7	49.0	40.1	43.0	2.01
	Reduction in N fertilizer requirement (kg hm^{-2})	65.9	18.8	35.1	37.0	39.2	9.80
	Potential N fertilizer input reduction (%)	27.5	7.82	14.6	13.7	15.9	4.14
	Yield increase compared with the average yield of all tested cultivars (kg hm^{-2})	1375	455	519	496	711	222
	Percentage yield increase (%)	16.1	4.76	4.62	4.80	7.57	2.85

a) LN, low-N treatment; MN, medium-N treatment; HN, high-N treatment; SE, standard error.

Table 9 Yield and nitrogen (N) responsiveness of nonefficient-nonefficient cultivars[a)]

N treatment	Parameter	Experiment No. 5	Experiment No. 6	Experiment No. 7	Experiment No. 8	Mean	SE
LN	Cultivars	XF1, ZJ3, JH5, XF32D22, ND108, LD981	JH5, LN14, LiaoY22	ZD958, SY103, NY309, LY13	XD20, LY16		
	Average yield (kg hm^{-2})	4096	3578	7666	6039	5345	938
	Yield reduction compared with HN (%)	48.6	59.0	29.3	41.4	44.6	6.24
	Yield increase compared with the average yield of all tested cultivars (kg hm^{-2})	−810	−620	−532	−1161	−781	140
	Percentage yield increase (%)	−16.5	−14.8	−6.48	−16.1	−13.5	2.36
MN	Average yield (kg hm^{-2})	8135	8076	11074	9725	9253	717
	Yield reduction compared with HN (%)	−2.03	7.48	−2.07	5.59	2.24	2.51
	Average NUE (kg kg^{-1})	121	112	120	122	119	2.28
	Reduction in N fertilizer requirement (kg hm^{-2})	−8.77	−26.2	−5.75	−18.8	−14.9	4.70
	Potential N fertilizer input reduction (%)	−7.31	−21.9	−4.79	−13.9	−12.0	3.82
	Yield increase compared with the average yield of all tested cultivars (kg hm^{-2})	−236	−848	−138	−351	−393	158
	Percentage yield increase (%)	−2.82	−9.50	−1.23	−3.49	−4.26	1.81
HN	Average yield (kg hm^{-2})	7973	8729	10850	10300	9463	670
	Average NUE (kg kg^{-1})	33.2	36.4	45.2	38.1	38.2	2.54
	Reduction in N fertilizer requirement (kg hm^{-2})	−44.2	−43.8	−34.7	−2.36	−31.3	9.88
	Potential N fertilizer input reduction (%)	−18.4	−18.2	−14.5	−0.87	−13.0	4.14
	Yield increase compared with the average yield of all tested cultivars (kg hm^{-2})	−565	−827	−383	−27.1	−451	168
	Percentage yield increase (%)	−6.62	−8.65	−3.41	−0.26	−4.74	1.84

a) LN, low-N treatment; MN, medium-N treatment; HN, high-N treatment; SE, standard error.

3 Discussion

3.1 Genotype×nitrogen interaction and the pressure for NUE selection

Bänzinger et al. [19] suggested that selection of N-efficient genotypes should (i) include adequate sources of genetic variation and strong selection pressures for the important traits at all stages of the breeding program, (ii) use experimental procedures to achieve high levels of heritability in the breeding trials, and (iii) employ tests that achieve a high genetic correlation between germplasm performance in breeding trials and under farm conditions. Yield in the field is the most important nutrient efficiency parameter. Soil N availability is the key selection pressure that determines selection efficiency. In the present study, coefficients of variation were significantly different among N treatments only in the experiments in which the G×N interaction was significant. Therefore, only under sufficiently low-N stress could the maximum genetic variation be observed. According to studies by CIMMYT, selection for LN tolerance should be conducted in fields in which LN yields are 25%–35% of those in N-sufficient plots. However, others have suggested that yield in LN plots should be 60%–65% of those in N-sufficient plot [25], in which case the N level may be too high for selection of LNE-type genotypes [15]. The present results suggested that when the yield of LN plots was 25%–60% of that of HN plots, the G×N interaction on yield was significant and yield heritability remained about 75%. Under LN stress, the variation in yield among genotypes was sufficiently high to classify them into different NUE classes. If yield reduction is less than 15%, a significant G×N interaction will be difficult to obtain.

A correlation between yields under HN and LN is frequently observed. If LN stress in the target area is not serious (yield reduction is less than 10%, for example), selection for high yield in multiple environments can also increase yield performance under LN [26]. Nevertheless, with increasing LN stress, the correlation between yield under HN and LN decreases [27,28]. In the present study, when yield reduction was as high as 27.0%–56.1%, the correlation between the yields under HN and LN was no longer significant (Table 5). To obtain LNE and EE genotypes, selection in both LN and HN environments is necessary [15]. Selection in a LN environment can increase selection efficiency by 30%. If the correlation between yields under LN and HN is about 0.65, LN-tolerant genotypes selected in LN environments often achieve a higher yield under HN [28]. Therefore, breeding for NUE in maize should be conducted in both low and high N environment and the yield reduction under low N plots should be 25% to 60%.

3.2 Potential reduction in N fertilizer input and/or increased yield with N-efficient cultivars

The standard for NUE classification depends on the aim of the study. With reference to Liu et al. [20] and Mi et al. [18], the cultivars tested in the present study were classified as HNE, LNE, EE, or NN. By comparing each yield performance with the average yield of all tested cultivars, the potential reduction in N fertilizer input and/or increased yield via use of N-efficient cultivars were estimated. The current commercially grown HNE and EE cultivars have the potential to achieve an increased yield of 8%–10% and/or reduce N fertilizer input by 16%–21%. The HNE cultivars were highly responsive to N fertilizer, but suffered a high loss in yield (by 52.6%) under LN stress. These cultivars can only achieve high yields under HN input [29]. The EE cultivars achieve high yields under both LN and HN conditions and should be used for breeding in the future. Both HNE (such as XY335) and EE cultivars (such as ZD958) should be treated as N-efficient cultivars in an intensive cropping system (Tables 7 and 8). The present results are compatible with those of previous studies. Worku et al. [30] reported that EE cultivars had the potential for a 10.7% increase in yield and 12.7% reduction in N fertilizer input. In contrast, HNE cultivars could achieve 15.1% increased yield and 17% reduction in N fertilizer input. In France, Coque and Gallais [31] reported that variation in the yield of current commercial cultivars was small. However, the results of the present study suggested that, in North and Northeast China, maize yield can be increased by 10%–15% and N fertilizer input could be reduced by 10%–20% if EE and/or HNE cultivars were used.

Nitrogen deficiency is a worldwide problem in crop production. In India, 2.5 million hm^2 of arable land suffers from N deficiency, which results in a 50% reduction in yield [32]. In South China, the area of N-deficient land is 1.15 million hm^2, which results in a yield reduction of 10%–20%. In Brazil, more than 80% of arable land has low fertility, and maize yield is only 1–2 tons hm^{-2} [33]. The maize yield in Africa is only 1.3 tons hm^{-2} because of LN and drought stress. Therefore, LNE cultivars are crucial to address the food security problem worldwide [15,34]. In the present study, LNE cultivars showed a potential increase in yield of 12% (Table 7). XD20 and ND108 were typical LNE cultivars and were LN tolerant. ND108 was found to be LN tolerant in previous studies [35,36]. LNE cultivars bred by CIMMYT have shown excellent performance in Africa, producing yields of 2–5 ton hm^{-2}, which is 11%–20% higher than the local cultivars [34]. At Hohenheim University, Germany, cultivars developed under LN stress produce 12% higher yield than those developed under HN conditions when grown in a LN environment [37]. Worku et al. [30] reported that the potential to increase yield of LNE cultivars was 14.5%. Collectively, these studies indicate that LNE cultivars may increase maize yield by 10%–20%.

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