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Full Length Article

Differential Responses of Maize Hybrids for Growth and Nitrogen Utilization to Applied Nitrogen

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Abstract

The present study investigated the effects of nitrogen (N) application on the maize cultivars Xianyu 508 (XY 508) and Zhenghong 311 (ZH 311) at two experimental sites for a three-year field study. Six N levels applied were 0, 90, 180, 270, 360 and 450 kg N ha^{-1}. ZH 311 had comparatively greater plant height, leaf area index (LAI), dry matter and N accumulation, N partial factor efficiency, recovery efficiency, uptake efficiency and agronomic efficiency. However, it had relatively lower N grain production efficiency, harvest index (HI) and N harvest index (NHI). The response of these variables to increasing N levels was greater in XY 508 than ZH 311. In contrast, yield and its components were higher in ZH 311 than XY 508. The optimal N levels required for maximum dry matter accumulation, N accumulation and yield were greater in XY 508 (450.00, 453.73 and 450.00 kg N ha^{-1}) than in ZH 311 (330.14, 331.37 and 297.57 kg N ha^{-1}). Maize cultivar XY 508 was sensitive to low N levels should be planted in fertile plain regions or receive adequate N fertilization to ensure higher yield. On the other land, maize cultivars like ZH 311 which tolerate low N levels could be sown on barren hills and in mountainous regions to maintain high and stable yields while reducing N fertilizer application.

Keywords: Maize; Nitrogen application; Growth; Nitrogen utilization; Cultivar differences

Introduction

Maize (*Zea mays* L.) is the most important cereal crops in the world and accounts for more than one-third of the cereal production in China (Chen *et al.*, 2015). With rapidly increasing global demands for food, livestock feed and renewable bioenergy, the need for maize is increasing (Cassman and Liska, 2007; Ning *et al.*, 2012). However, the availability of cultivated land for maize production has been decreased with increasing land degradation, environmental disruption, and urbanization (Zhang *et al.*, 2014). Therefore, the most efficient method to meet the consistent global requirement for maize is to increase its yield per unit area.

Nitrogen (N) is essential plant macronutrients and has significant effects on plant development, photosynthesis, and yield (Guo *et al.*, 2014; Zhang *et al.*, 2015). High-yield cereal crops like maize, rice, and wheat require large amounts of N fertilizer and application that substantially increases maize yield (Montemurro *et al.*, 2006; D'Andrea *et al.*, 2008; Motta and Maggiore, 2013). To obtain high yields, farmers often use excessively high N fertilizer levels which, in fact, lowers N utilization efficiency (Jin *et al.*, 2012; Sui *et al.*, 2013), wastes N resources (Blicher-Mathiesen *et al.*, 2014), aggravates environmental pollution (Bhattacharyya *et al.*, 2012; Bechmann *et al.*, 2014) and causes other serious problems. Dry matter accumulation, N uptake, N utilization and yield are all affected by the genetic background of the maize crop (Ciampitti and Vyn, 2012), ecological conditions (Cirilo *et al.*, 2009), cultivation and agricultural management practices (Nyakudya and Stroosnijder, 2015).

Many reports show that the N fertilizer requirements vary significantly among maize cultivars. Certain varieties strongly tolerate low N, whereas others are sensitive to it (Li *et al.*, 2010; Cui *et al.*, 2013; Xie *et al.*, 2015). Dry matter production, N absorption and yield of maize cultivars which tolerate low N are significantly higher than low N sensitive cultivars. Moreover, the differences in these maize cultivars responds to N application are affected by ecology and soil fertility (Chen *et al.*, 2013; Cui *et al.*, 2013). Southwest China is one of the main maize producing areas in China and the maize yield of this region accounts for 20% of the national maize crop. Southwest China is a vast territory with very wide local variations in ecological conditions and soil

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physicochemical properties. Previous studies investigating maize cultivars with different tolerances to low N have mainly focused on their relative differences in growth characteristics, N uptake and yield at a single N level. Furthermore, most of these trials were performed on the Northeast China Plain. However, reports on differences between maize cultivars that vary in low N tolerance in response to N fertilizer in Southwest China are limited. Investigating the differences among maize cultivars with contrasting tolerances to low-N in terms of response to N fertilization, dry matter production, N absorption and utilization and yield is of great practical importance. Depending on the individual N fertilizer requirements of these maize cultivars, N fertilization can be optimized to improve N utilization efficiency, conserve N resources, reduce environmental pollution, and maximize crop yield potential under the various ecological conditions in Southwest China.

Xianyu 508 (XY 508) and Zhenghong 311 (ZH 311) are the main cultivars sown in the Southwest China, nevertheless, with contrasting tolerance for low N (Li *et al.*, 2014; Li *et al.*, 2015a). Their relative differences in dry matter accumulation, N absorption and utilization and yield in response to N fertilizer are unknown. In this study, the differences between XY 508 and ZH 311 in terms of dry matter accumulation, translocation, N accumulation, translocation, yield formation and N utilization efficiency in response to increasing N level were analyzed. The objective of this study, then, was to establish a plan for the rational fertilization of maize cultivars in southwest China with contrasting tolerances for low N levels.

Materials and Methods

Study Sites and Materials

The field trials were conducted at Jianyang (30°38´N, 104°53´E, 429 m above sea level, hilly area, previously planted with wheat) during the 2011–2013 growing seasons, and at Shuangliu (30°57´N, 104°94´E, 495 m above sea level, plain area, previously planted with vegetables) in 2011. Both are located in Sichuan province. These regions have a warm and subtropical humid monsoon climate. At Jianyang, the soil was a heavy loam. The topsoil (0–30 cm) contained 25.22 mg kg^{-1} alkali hydrolyzable N, 13.54 mg kg^{-1} Olsen-P, 138.75 mg kg^{-1} exchangeable K, 1.24 g kg^{-1} total N, 0.73 g kg^{-1} total P, 12.54 g kg^{-1} total K, 16.60 g kg^{-1} organic matter and pH 8.63. At Shuangliu, the soil was a medium loam with a topsoil containing 152.92 mg kg^{-1} alkali hydrolyzable N, 97.53 mg kg^{-1} Olsen-P, 94.25 mg kg^{-1} exchangeable K, 2.10 g kg^{-1} total N, 0.93 g kg^{-1} total P, 28.41 g kg^{-1} total K, 23.18 g kg^{-1} organic matter and pH 6.11, respectively. Temperature, precipitation and sunlight hours were recorded, and the mean monthly data for the four growing seasons were reported for the duration of the experiment (Table 1).

Based on experiments conducted in 2010 and 2011, XY 508 and ZH 311 were selected to represent the low N-tolerant and low N-sensitive maize cultivars, respectively. Seeds of both cultivars were obtained from Sichuan Nongda Zhenghong Seed Co. Ltd. and Pioneer Technology Co., Tieling, respectively. Both cultivars had a growth cycle of ~120 d.

Experimental Design

The experimental design was a split-plot with two maize hybrids as the main plots and six N levels as the subplots. There were three replicates. Each plot was 4 × 8 m and consisted of eight 5 m rows, 1.5 + 0.5 m apart. The planting density was 50,000 plants ha^{-1}. Before sowing, the soil was plowed, cleansed of residues from the previous crops, fertilized, irrigated and mulched with film. The subplot treatments consisted of urea (46.7-0-0) at 0, 90, 180, 270, 360 and 450 kg N ha^{-1} in two equal split plots at the sowing and pre-silking stages. Prior to sowing, superphosphate (0-12.0-0; 72 kg ha^{-1}) and potassium chloride (0-0-63.1; 90 kg ha^{-1}) were applied, respectively. Maize sowing and harvesting dates were April 12 and August 14, 2011 in Shuangliu (2011S), March 31 and July 31, 2011 in Jianyang (2011J), March 31 and August 2, 2012 in Jianyang (2012J), and April 4 and August 1, 2013 in Jianyang (2013J). The maize cultivation practices used in the present study, including the control of pests, diseases and weeds, were comparable to those used for high-yield cultivation in this region.

Plant Sampling and Measurements

Plant height was defined from the caudex to the uppermost visible ligules. Leaf area was determined using the length-to-width coefficient method. The coefficient was determined to be 0.75. Total shoot dry matter accumulation was measured at silking and maturity. Five representative plants were sampled and separated into leaves, stems + sheath and panicles at silking and maturity. Samples were desiccated at 105°C for 45 min, oven dried at 85°C to a constant weight, weighed, powdered and passed through a 60-mesh sieve. Maize plant materials were ground and each sample was digested with 10 mL H_2SO_4-H_2O_2. Nitrogen was determined by the Kjeldahl method. Yield and 1000-kernel weight were determined using all except the border plants in a 10-m^2 area within each plot. Moisture content was adjusted to 14.0%. Panicle characteristics (length, diameter and length of barren) and yield components (row numbers, grains per row and grains per panicle) were determined from 20 continuous plants per plot.

Growth and yield parameters were determined as follows:

Leaf area index (LAI, m^2 m^{-2}) = Green leaf area/land area [1]

Dry matter translocation (DMT, t ha^{-1}) = dry matter in vegetative organ at silking - dry matter in vegetative organ at maturity [2]

Dry matter translocation efficiency (DMTE, %) = (DMT/dry matter at silking) × 100 [3]

Pre-silking dry matter accumulation (SDMA, t ha^{-1}) = dry matter accumulation at silking [4]

Post-silking dry matter accumulation (PDMA, t ha^{-1}) = dry matter accumulation at maturity - dry matter accumulation at silking [5]

Nitrogen uptake and assimilation parameters were calculated as follows:

N translocation (NT, kg ha^{-1}) = N accumulation by vegetative organs at silking-N accumulation by vegetative organs at maturity [6]

N translocation efficiency (NTE, %) = (NT/N accumulation at silking) × 100 [7]

Pre-silking N accumulation (SNA, kg ha^{-1}) = N accumulation at silking [8]

Post-silking N accumulation (PNA, kg ha^{-1}) = total N accumulation – SNA [9]

N grain production efficiency (NGPE, kg kg^{-1}) = grain yield/N accumulation [10]

N uptake efficiency (NUE, %) = N accumulation by the fertilized treatment / (total amount of N fertilizer applied + N accumulation by the control) × 100 [11]

N recovery efficiency (NRE, %) = [(N accumulation by the fertilized treatment - N accumulation by the control)/total amount of N fertilizer applied] × 100 [12]

N agronomic efficiency (NAE, kg kg^{-1}) = [grain yield in the fertilized treatment - grain yield in the control]/N fertilizer applied [13]

N partial factor productivity (NPFP, kg kg^{-1}) = grain yield in the fertilized treatment/N fertilizer applied [14]

Harvest index (HI) and N harvest index (NHI) were calculated as the ratios of dry matter by grain to the total dry matter and N accumulation in grain to the total N accumulation at maturity, respectively (Abbasi *et al.*, 2013; Ju *et al.*, 2015; Gaju *et al.*, 2016).

Statistical Analysis

Data were analyzed by one way analysis of variance using the least significant difference test with three replicates of each treatment combination using SPSS 20.0 for windows 2010. Means were tested by the least significant difference at P=0.05 (LSD≤0.05).

Results

The weather conditions during the 2011–2013 growing seasons varied among experimental locations (Table 1). Temperatures were high during the growth period of the 2011J season. Precipitation levels were lowest (562.8 mm) and the number of sunshine hours was highest (671.3 h) during this time. In contrast, there were significantly fewer sunshine hours (498.9 h) during the growth period of 2012J. During of growth period of 2013J, conditions were mild; precipitation and sunshine hours were adequate (743.0 mm and 637.9 h, respectively) (Table 1). Consequently, the effects of N fertilization on maize varied over the three years of the experiment in part because of seasonal differences in weather conditions.

Plant Height and Leaf Area Index

Experimental site and cultivar significantly influenced maize plant height (Fig. 1). The average plant height of the two cultivars in 2011S was 14.9% greater than that in 2011J. At the two experimental sites over three years, the average plant height of ZH 311 was 9.6% greater than XY 508. In addition, N application substantially increased maize plant height at both experimental sites. These improvements were significantly influenced by both experimental site and cultivar. Compared to the 0 N treatments, the average height of plants subjected to N application increased by 1.1% in 2011S and by 7.2% in 2011J. Therefore, N application more effectively increased plant height in Jianyang than it did at Shuangliu. ZH 311 plant height initially increased then decreased with increasing N rates. The highest values were observed with 270 N in 2011S, 360 N in 2011J, 270 N in 2012J and 360 N in 2013J. XY 508 plant height increased with N application rates. The highest values were observed with 450 N at both experimental sites over three years. Relative to the 0 N treatments, ZH 311 plant height increased by 0.2, 5.7, 6.9, and 4.4% in 2011S, 2011J, 2012J and 2013J, respectively, in response to the average N treatment. Compared to the control, XY 508 plant height increased by 2.6, 4.6, 16.8 and 5.7% in response to the average N dosage during the same respective seasons. Therefore, the plant height of the low N-tolerant cultivar was significantly greater than the low N-sensitive cultivar. However, the relative increase in plant height observed with N application in the low N-sensitive cultivar was significantly greater than observed for the low N-tolerant cultivar. Moreover, plant height improvement in the barren areas of Jianyang was significantly greater than observed for the fertile regions of Shuangliu.

Fig. 2 shows that leaf area index (LAI) significantly differed between Shuangliu and Jianyang. The average LAI of the two cultivars in 2011S was 96.3% higher than that measured in 2011J. Nitrogen application significantly increased LAI at Jianyang. In contrast, it only slightly influenced LAI at Shuangliu. Relative to XY 508, the LAI of ZH 311 was 21.9% higher in 2011S, 28.3% higher in 2011J, 48.1% higher in 2012J and 40.6% higher in 2013J. The relative differences in LAI between the two cultivars were significantly higher at Jianyang than they were at Shuangliu. Nitrogen application significantly increased the LAI of ZH 311 at Jianyang and the LAI of XY 508 at both Jiangyang and Shuangliu. The LAI of ZH 311 first increased then decreased with increasing N

Table 1: Monthly precipitation, hours of sunlight and mean temperature in different growth seasons

Month	Temperature (°C)				Precipitation (mm)				Sunlight (h)			
	2011 S	2011 J	2012 J	2013 J	2011 S	2011 J	2012 J	2013 J	2011 S	2011 J	2012 J	2013 J
January	3.3	3.5	5.9	7.1	19.6	27.2	14.3	4.0	22.0	38.6	63.2	99.2
February	8.2	8.7	7.1	11.0	10.3	28.8	17.3	3.8	54.3	90.8	77.5	58.1
March	10.2	10.9	13.1	18.1	37.8	35.3	29.4	0.60	72.4	92.7	113.7	182.0
April	18.2	19.0	19.9	20.0	10.9	21.4	30.0	47.0	119.0	157.3	159.3	189.9
May	21.3	22.2	22.4	22.3	203.1	115.1	107.5	172.9	123.2	187.0	123.3	147.5
June	24.9	25.6	23.4	26.0	40.7	79.8	184.3	254.7	143.5	188.6	93.6	145.4
July	25.2	26.2	25.8	27.1	390.6	346.5	328.0	268.4	107.4	138.4	122.7	155.1
August	26.5	28.0	27.8	27.6	82.4	45.4	118.3	164.7	179.1	244.0	213.0	202.3
September	21.3	21.8	22.0	21.5	164.4	143.3	101.8	113.8	63.0	92.0	94.8	70.0
October	17.4	18.0	18.1	18.5	27.6	25.1	49.4	25.3	41.5	63.5	82.1	100.1
November	14.9	15.2	12.1	13.3	11.3	11.5	5.3	28.2	37.1	62.3	59.1	79.7
December	7.9	8.0	7.8	7.8	12.5	13.1	4.1	2.7	31.5	34.8	58.3	78.4
WHP	2847.6	2836.8	2793.4	2913.6	667.6	562.8	649.8	743.0	545.6	671.3	498.9	637.9
Mean in WHP	23.0	23.1	22.3	24.7	5.4	4.6	5.2	6.3	4.4	5.5	4.0	5.4

WHP: Whole growth period

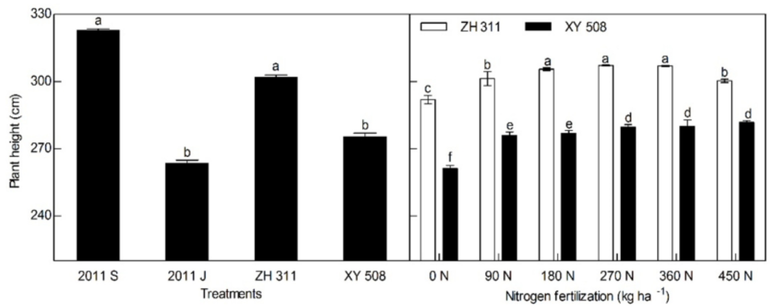

Fig. 1: Plant height of maize under different N applications at silking stage
Vertical bars represent S.E of the mean. The S.E was calculated across three replicates for each year. Different lowercase letters in columns represent significant (P < 0.05) differences among treatments. 0 N, 90 N, 180 N, 270 N, 360 N, and 450 N represent N application levels of 0, 90, 180, 270, 360, and 450 kg ha^{-1}

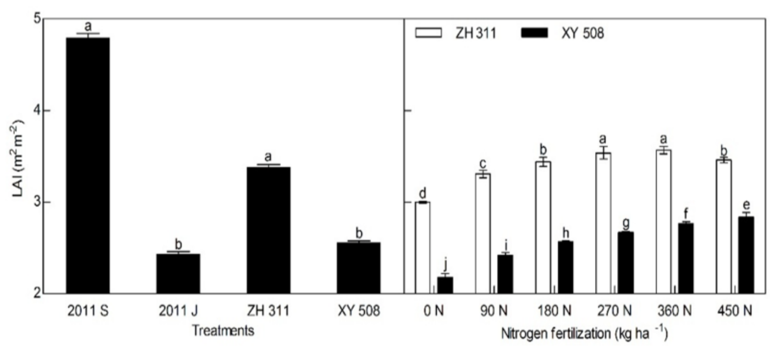

Fig. 2: Leaf area index of maize under different N applications at silking stage
Vertical bars represent S.E of the mean. The S.E was calculated across three replicates for each year. Different lowercase letters in columns represent significant (P < 0.05) differences among treatments. 0 N, 90 N, 180 N, 270 N, 360 N, and 450 N represent N application levels of 0, 90, 180, 270, 360, and 450 kg ha^{-1}

rate at Jianyang. On the other hand, the LAI of XY 508 increased with N rate at both Shuangliu and Jianyang. The highest LAI values were observed for ZH 311 at medium N levels whereas those for XY 508 were observed at high N levels. Therefore, the relative differences in LAI between the two genotype cultivars were greatest at medium N levels. Nitrogen fertilizer increased the LAI of ZH 311 by 2.2% in 2011S, 32.7% in 2011J, 18.0% in 2012J, and 27.0% in 2013J. It increased the LAI of XY 508 by 4.4, 39.8, 35.6 and 39.9%, respectively, in the same seasons. Nitrogen application significantly increased the LAI of maize at the silking stage, while the increases for the low N-sensitive cultivar were substantially higher than for the low N-tolerant cultivar.

Dry Matter Accumulation and Distribution

Stover, grain, and total dry matter accumulation and harvest index (HI) were significantly different between the maize in Shuangliu and Jianyang. The average stover,

Table 2: Dry matter accumulation (DMA) at maturity of two maize cultivars under six N levels

Cultivar	N rate	Stover dry matter accumulation (t ha^{-1})				Grain dry matter accumulation (t ha^{-1})				Total dry matter accumulation (t ha^{-1})				Harvest index			
ZH 311		2011 S	2011 J	2012 J	2013 J	2011 S	2011 J	2012 J	2013 J	2011 S	2011 J	2012 J	2013 J	2011 S	2011 J	2012 J	2013 J
	0 N	9.6 b	5.3 d	5.8 d	6.2 b	7.5 c	5.7 c	5.2 b	5.7 b	17.2 d	11.0 d	11.0 c	11.9 d	0.44 a	0.52 ab	0.47 a	0.48 a
	90 N	10.0 b	6.3 c	6.5 c	7.1 b	7.9 bc	6.7 b	5.7 ab	6.5 a	17.9 c	13.0 c	12.2 b	13.6 c	0.44 a	0.52 ab	0.47 a	0.48 a
	180 N	11.1 c	6.7 bc	7.1 b	8.1 b	8.0 abc	7.4 a	5.9 a	6.8 a	19.0 b	14.1 b	13.0 ab	14.9 b	0.42 ab	0.52 ab	0.45 a	0.46 ab
	270 N	12.4 a	7.6 a	7.6 a	10.0 a	8.0 abc	7.4 a	5.8 ab	6.9 a	20.3 a	15.0 a	13.3 a	16.9 a	0.39 b	0.49 b	0.43 b	0.41 bc
	360 N	12.0ab	6.9 b	7.8 a	10.1 a	8.4 a	7.8 a	5.7 ab	6.7 a	20.3 a	14.8 a	13.5 a	16.8 a	0.41 ab	0.53 a	0.42 b	0.40 c
	450 N	11.6bc	6.4 c	7.6 a	9.9 a	8.2 ab	6.7 b	5.6 ab	6.6 a	19.8 b	13.1 c	13.2 a	16.5 a	0.42 ab	0.51 ab	0.42 b	0.40 c
	Average	11.1 A	6.5 A	7.1 A	8.6 A	8.0 A	7.0 A	5.6 A	6.5 A	19.1 A	13.5 A	12.7 A	15.1 A	0.42 B	0.52 B	0.45 B	0.44 B
XY 508																	
	0 N	6.5 c	3.1 c	3.1 c	4.6 c	6.7 a	4.0 c	3.9 c	5.3 b	13.2 c	7.1 e	7.0 c	9.9 e	0.51 a	0.56 a	0.56 a	0.54 ab
	90 N	6.9 c	4.5 b	4.6 b	4.7 c	7.1 a	5.4 b	4.3 c	6.0 a	14.0 bc	9.9 d	8.8 b	10.6 d	0.51 a	0.54 a	0.48 b	0.56 a
	180 N	6.8 c	4.9 ab	4.9 ab	6.0 b	7.3 a	5.2 b	4.7 b	6.0 a	14.0 bc	10.2 c	9.6 a	12.0 c	0.52 a	0.52 a	0.49 b	0.50 bc
	270 N	7.5 b	4.9 ab	4.5 b	6.5 b	7.0 a	5.6 ab	5.2 a	6.0 a	14.4 b	10.5 b	9.7 a	12.4 b	0.48 ab	0.54 a	0.54 a	0.48 cd
	360 N	7.6 b	5.0 a	4.6 b	6.7 ab	7.1 a	5.7 ab	5.3 a	6.0 a	14.6 b	10.7 b	9.9 a	12.6 b	0.48 ab	0.53 a	0.54 a	0.47 cd
	450 N	7.8 a	5.3 a	5.0 a	7.3 a	7.0 a	6.0 a	5.1 a	5.9 a	14.9 a	11.3 a	10.1 a	13.2 a	0.44 b	0.53 a	0.50 b	0.45 d
	Average	7.1 B	4.6 B	4.4 B	6.0 B	7.0 B	5.3 B	4.7 B	5.8 B	14.2 B	9.9 B	9.2 B	11.8 B	0.49 A	0.54 A	0.52 A	0.50 A
Significance	Cultivar (C)	921.0**	443.6**	1231.0**	271.7**	39.7**	305.0**	98.0**	49.1**	877.3**	2569.5**	610.3**	2396.3**	90.5**	6.0**	322.2**	38.8**
	N rate (N)	33.5**	45.6**	57.4**	51.1**	1.3^{ns}	34.7**	10.7**	7.1**	27.89**	263.6**	35.9**	384.7**	4.8**	0.82^{ns}	13.4**	11.6**
	C × N	8.1**	6.5**	7.7**	3.6*	0.44^{ns}	5.2**	4.5**	0.56^{ns}	5.6**	31.8**	0.78^{ns}	28.0**	1.8^{ns}	1.29^{ns}	16.2**	0.45^{ns}

Data are means of three replicates. Different lowercase letters within the same column represent significant ($P < 0.05$) differences between different N rates; within cultivars, averages with different uppercase letters are significantly different at $P < 0.05$ according to the LSD test. ns: not significant. * $P < 0.05$. ** $P < 0.01$

grain and total dry matter accumulation for the two cultivars in 2011S were higher than in 2011J by 65.4, 21.2 and 42.2%, respectively. The HI in 2011J was 16.0% higher than in 2011S (Table 2). At Jianyang, dry matter accumulation was highest in 2013J and lowest in 2012J. Nitrogen application obviously increased stover and total dry matter accumulation in Shuangliu and Jianyang and grain dry matter accumulation in Jianyang. However, it decreased maize HI at both Shuangliu and Jianyang except in 2011J. Compared to the 0 N treatments, the average N treatment increased stover, grain and total dry matter accumulation by 17.6, 6.1 and 12.2% in 2011S, 38.9, 33.8 and 36.2% in 2011J, 35.1, 16.6 and 25.8% in 2012J and 42.4, 14.2 and 28.1% in 2013J. Meanwhile, HI decreased by 5.4, 2.6, 8.6 and 11.1% in each of those seasons, respectively. Therefore, the effects of incremental N application on stover, grain and total dry matter accumulation in barren regions (Jianyang) were significantly greater than in fertile regions (Shuangliu). Furthermore, N application improved stover dry matter accumulation significantly more than it did grain dry matter accumulation.

Cultivar type significantly affected dry matter accumulation and HI in maize. For both experimental sites over three years, the average stover, grain and total dry matter accumulation of ZH 311 were 33.6, 18.9 and 48.8% higher, respectively, than those of XY 508. There were significant differences between cultivars in terms of the effects of N rate on dry matter accumulation and HI. The mean variations in stover, grain and total dry matter accumulation and HI at both experimental sites over three years were 22.1, 15.0, 28.5 and 6.1% for ZH 311 and 26.2, 18.0, 35.5 and 7.4% for XY 508. Nitrogen application had a stronger influence on dry matter accumulation and HI in the low N-sensitive cultivar than it did in the low N-tolerant cultivar. Increasing N fertilizer level improved dry matter production in the low N-sensitive cultivar more than it did the low N-tolerant variety. Total dry matter accumulation (*y*) of ZH 311 first increased then decreased with increasing N rate (*x*). A quadratic convex relationship was observed between *y* and *x* for both experimental sites and over three years (Table 8). The relationship between total dry matter accumulation in XY 508 and N rate was linear and positively correlated in 2011S and 2013J. The highest accumulation of dry matter was measured for the 450 kg N ha^{-1} treatment in both growing seasons. In the 2011J and 2012J seasons, the optimal N rate (the highest dry matter accumulation) for XY 508 was significantly higher than that for ZH 311 even though the relationship between total dry matter accumulation and N rate for XY 508 followed a quadratic convex function.

Post-silking dry matter accumulation (PDMA) was significantly higher than pre-silking dry matter accumulation (SDMA). On average for both cultivars, PDMA was greater than SDMA by 103.1% in 2011S, 68.8% in 2011J, 62.7% in 2012J and 30.0% in 2013J. Therefore, PDMA was the main determinant of maize yield formation (Table 3). In addition, there were significant ($P < 0.01$) differences between both cultivars in terms of SDMA, PDMA, dry matter translocation (DMT) and dry matter translocation efficiency (DMTE). The SDMA and PDMA for ZH 311 were higher than those for XY 508 by 10.6 and 45.8% in 2011S, 13.5 and 53.3% in 2011J, 49.2 and 32.0% in 2012J and 19.9 and 35.0% in 2013J. The DMT and DMTE of XY 508 were higher than those for ZH 311 by 84.4 and 84.0% in 2011S, 56.0 and 83.7% in 2011J, 56.7 and 135.2% in 2012J and 130.9 and 174.6% in 2013J.

Table 3: Pre-silking dry matter accumulation (SDMA), post-silking dry matter accumulation (PDMA), dry matter translocation (DMT), and dry matter translocation efficiency (DMTE)

Cultivar	N rate	SDMA (t ha^{-1})				PDMA (t ha^{-1})				DMT (t ha^{-1})				DMTE (%)			
		2011 S	2011 J	2012 J	2013 J	2011 S	2011 J	2012 J	2013 J	2011 S	2011 J	2012 J	2013 J	2011 S	2011 J	2012 J	2013 J
ZH 311	0 N	5.4 b	3.7 e	4.3 d	5.7 c	11.7 d	7.3 f	6.7 c	6.2 d	-1.5 a	0.41 d	0.13 c	0.53 b	-28.2 ab	10.9 c	3.0 c	9.3 b
	90 N	5.5 b	4.7 cd	5.2 ab	6.0 c	12.4 c	9.0 d	7.0 c	7.7 c	-2.0 ab	0.76 bc	0.52 b	0.61 b	-35.9 bc	16.1 ab	9.9 b	10.2 b
	180 N	5.6 b	4.8 bc	5.2 ab	6.4 b	13.4 b	9.3 c	7.8 b	8.5 b	-2.5 c	0.89 ab	0.61 b	0.65 b	-45.4 d	18.4 a	11.7 ab	10.1 b
	270 N	5.7 b	5.0 ab	5.0 bc	6.8 a	14.6 a	10.0 a	8.3 ab	10.1 a	-2.3 bc	0.94 a	0.58 b	0.96 a	-39.7 cd	18.8 a	11.6 ab	14.2 a
	360 N	6.2 a	5.1 a	5.0 c	6.8 a	14.1 ab	9.6 b	8.6 a	10.1 a	-2.4 bc	0.92 a	0.63 b	0.21 c	-39.1 cd	17.9 a	12.8 ab	3.2 c
	450 N	6.3 a	4.5 d	5.3 a	6.6 ab	13.6 b	8.5 e	7.9 b	9.9 a	-1.6 a	0.66 c	0.86 a	0.26 c	-26.0 a	14.5 b	16.5 a	4.0 c
	Average	5.8 A	4.7 A	5.0 A	6.4 A	13.3 A	8.9 A	7.7 A	8.7 A	-2.1 B	0.76 B	0.56 B	0.54 B	-35.7 B	16.1 B	10.9 B	8.5 B
XY 508																	
	0 N	4.9 b	2.8 d	2.4 d	4.5 b	8.3 c	4.2 e	4.6 c	5.4 e	-0.51 a	1.1 bc	0.58 d	0.95 c	-10.4 a	40.3 a	24.2 ab	21.3b
	90 N	5.0 b	4.1 c	3.2 c	5.2 a	9.0 b	5.8 d	5.7 b	5.4 e	-0.47 a	1.2 ab	0.68 cd	1.2 b	-10.1 a	30.2 b	21.6 b	23.1ab
	180 N	5.0 b	4.2 c	3.4 bc	5.5 a	9.0 b	6.0 cd	6.2 ab	6.5 d	-0.55 a	1.0 c	0.76bcd	1.4 a	-10.9 a	25.0 c	22.7 b	25.7 a
	270 N	5.4 a	4.2 bc	3.8 a	5.6 a	9.0 b	6.3 ab	5.9 ab	6.8 c	-0.08 a	1.1 bc	1.2 a	1.4 a	-1.5 a	25.6 c	31.4 a	24.9ab
	360 N	5.4 a	4.6 ab	3.7 a	5.5 a	9.3 b	6.2 bc	6.2 a	7.2 b	-0.00 a	1.2 ab	1.1 ab	1.2 b	-0.17 a	27.2 bc	28.3 ab	22.5ab
	450 N	5.7 a	4.7 a	3.6 ab	5.7 a	10.1 a	6.6 a	6.5 a	7.5 a	-0.07 a	1.4 a	0.94abc	1.3 ab	-1.4 a	29.3 bc	26.1 ab	22.4ab
	Average	5.2 B	4.1 B	3.3 B	5.3 B	9.1 B	5.8 B	5.8 B	6.5 B	-0.28 A	1.2 A	0.87 A	1.2 A	-5.7 A	29.6 A	25.7 A	23.3 A
Significance	Cultivar (C)	65.6**	104.5**	955.3**	205.0**	1208.8**	3145.1**	278.6**	1435.5**	261.9**	196.7**	34.0**	568.8**	213.2**	368.5**	132.6**	553.5**
	N rate (N)	16.8**	69.9**	41.0**	22.2**	24.8**	154.6**	22.7**	276.0**	2.9*	7.9**	10.4**	25.6**	3.6*	2.8*	4.4**	11.82**
	C × N	1.1^{ns}	7.4**	7.1**	1.3^{ns}	9.9**	20.2**	3.1*	31.8**	3.7*	12.8**	2.5^{ns}	14.0**	2.9*	24.5**	2.4^{ns}	5.2**

SDMA: pre-silking dry matter accumulation; PDMA: post-silking dry matter accumulation; DMT: dry matter translocation; DMTE: dry matter translocation efficiency. Data are means of three replicates. Different lowercase letters within the same column represent significant ($P < 0.05$) differences between different N rates; within cultivars, averages with different uppercase letters are significantly different at $P < 0.05$ according to the LSD test. ns: not significant. * $P < 0.05$. ** $P < 0.01$

Therefore, dry matter productivity in the low N-tolerant cultivar was significantly higher than in the low N-sensitive cultivar. N fertilizer significantly ($P < 0.05$) affected SDMA, PDMA, DMT, and DMTE. These effects were influenced by both experimental site and cultivar. Compared to the 0 N treatments, the average SDMA, PDMA, DMT, and DMTE at both experimental sites over three years increased by 16.8, 26.4, 25.6 and 23.9%, respectively in ZH 311 and by 27.4, 22.6, 25.5 and 28.0%, respectively, in XY 508. Therefore, in response to N application rate, the increase in DMTE in the low N-sensitive cultivar was higher than that observed in the low N-tolerant cultivar. In contrast, the PDMA of the low N-tolerant cultivar was higher than of the low N-sensitive cultivar. The PDMA in 2011S was 54.1% higher than in 2011J whereas the DMT and DMTE in 2011J were 198.1% and 232.9% higher, respectively, than in 2011S.

Nitrogen Accumulation and Distribution

Stover, grain and total N accumulation were higher in 2011S than they were in 2011J but the opposite was true for N harvest index (NHI) (Table 4). Stover N accumulation was substantially higher than grain N accumulation at Shuangliu whereas at Jianyang the opposite was true. The stover, grain and total N accumulation in ZH 311 were remarkably ($P < 0.05$) higher than in XY 508 by 42.2, 20.2 and 32.8% in 2011S, 59.7, 22.8 and 38.5% in 2011J, 65.7, 31.7 and 46.6% in 2012J and 31.6, 17.0 and 22.6% in 2013J. The NHI of XY 508 were obviously higher than ZH 311 by 10.3, 13.7, 12.0 and 5.0%, respectively, in 2011S–2013J. The differences between the two cultivars in terms of stover N accumulation were significantly higher than for grain and total N accumulation. Therefore, the vegetative organs of the low N-tolerant cultivar maintained a relatively higher N distribution ratio which delayed senescence and increased dry matter productivity in the late growth stage. Nitrogen application significantly increased stover, grain, and total N accumulation in both cultivars and apparently decreased the NHI of XY 508. However, except for 2013J, N application only slightly affected the NHI of ZH 311. Compared to the 0 N treatments, the average N dosages increased the stover, grain, and total N accumulation and NHI by 17.6, 10.7, 14.7 and 3.5% in 2011S whereas they increased these parameters in 2011J by 72.3, 36.5, 51.3 and 13.5%, respectively. Therefore, N application had significantly stronger effects on N accumulation and NHI at Jianyang than it did at Shuangliu. In addition, N application improved N accumulation more effectively at Jianyang than at Shuangliu and the relative yield increase was higher at the former than the latter. The stover and grain N accumulation and the NHI of ZH 311 first increased then decreased with increasing N rates. The highest values of all three parameters were observed with 360 N. These parameters all increased in XY 508 with increasing N levels and their highest values were observed with 450 N at both experimental sites over three years. Therefore, although N application substantially increased N accumulation in maize, excess N fertilizer (450 N) inhibited N accumulation in the low N-tolerant cultivar. Furthermore, N application increased stover N accumulation and NHI in XY 508 more than it did in ZH 311 but the opposite was true for grain N accumulation.

There were obvious differences in pre-silking N accumulation (SNA), post-silking N accumulation (PNA), N translocation (NT), and N translocation efficiency (NTE) between the two cultivars (Table 5). In

Table 4: N accumulation in different organs at maturity and N harvest index (NHI)

Cultivar	N rate	Stover N accumulation (kg ha^{-1})				Grain N accumulation (kg ha^{-1})				Total N accumulation (kg ha^{-1})				N harvest index			
		2011 S	2011 J	2012 J	2013 J	2011 S	2011 J	2012 J	2013 J	2011 S	2011 J	2012 J	2013 J	2011 S	2011 J	2012 J	2013 J
ZH 311	0 N	131.1 c	64.6 c	57.4 d	31.1 d	85.6 c	66.3 b	82.9 d	70.9 c	216.7 d	130.9 c	140.3 d	102.0 d	0.40 a	0.51 a	0.59 a	0.70 a
	90 N	137.2 c	83.8bc	68.1 c	44.5 c	88.9bc	85.0 a	90.8 c	81.0 b	226.1 cd	168.8 b	158.9 c	125.5 c	0.39 a	0.50 a	0.57ab	0.65 b
	180 N	148.7abc	83.8bc	72.9 bc	55.2 b	96.3 a	92.0 a	98.9 a	90.3 a	245.0abc	175.9ab	171.8 b	145.5 b	0.39 a	0.53 a	0.58ab	0.62 b
	270 N	145.1bc	104.0 a	76.7 b	56.0 b	95.2ab	91.3 a	94.3 b	91.8 a	240.4 bc	195.2 a	171.0 b	147.8 b	0.40 a	0.47 a	0.55 bc	0.62 b
	360 N	164.8 a	85.1ab	84.9 a	85.3 a	101.1 a	97.3 a	95.2 b	89.1 a	265.8 a	182.4ab	180.0 a	174.4 a	0.38 a	0.53 a	0.53 c	0.51 c
	450 N	160.7ab	78.1 c	77.7 b	80.6 a	98.7 a	83.7 a	89.7 c	88.7 a	259.5 ab	161.9 b	167.4 b	169.3 a	0.38 a	0.52 a	0.54 c	0.52 c
	Average	147.9 A	83.2 A	73.0 A	58.8 A	94.3 A	86.0 A	91.9 A	85.3 A	242.3 A	169.2 A	164.9 A	144.1 A	0.39 B	0.51 B	0.56B	0.60 B
XY 508																	
	0 N	88.6 d	19.9 c	26.1 c	27.8 c	73.1 a	53.2 c	59.9 e	62.7 b	161.6 d	73.1 d	86.0 d	90.5 e	0.45 a	0.73 a	0.70 a	0.70 a
	90 N	97.7 c	50.0 b	56.2 a	26.7 c	77.6 a	69.8 b	64.6 d	74.0 a	175.3 c	119.8 c	120.8 c	100.6 d	0.44 ab	0.58 b	0.54 d	0.73 a
	180 N	96.6cd	56.7ab	55.4 a	45.8 b	81.8 a	66.4 b	69.2 c	75.4 a	178.4 c	123.1 c	124.6 b	121.2 c	0.46 a	0.54 b	0.56 cd	0.62 b
	270 N	101.7 c	57.3ab	52.5 a	59.2 a	77.1 a	74.2ab	74.5 b	73.2 a	178.8 c	131.5bc	127.0 b	132.4ab	0.43 ab	0.56 b	0.59 c	0.55 b
	360 N	111.2 b	64.6 a	53.6 a	48.9 b	80.1 a	73.8ab	77.3 b	75.6 a	191.3 b	138.4ab	130.9 a	124.5bc	0.42 ab	0.53 b	0.59 c	0.61 b
	450 N	128.2 a	64.1 a	43.6 b	59.6 a	80.9 a	82.7 a	81.9 a	76.5 a	209.1 a	146.8 a	125.5 b	136.1 a	0.39 b	0.56 b	0.65b	0.56 b
	Average	104.0 B	52.1 B	47.9 B	44.7 B	78.4 B	70.0 B	71.2 B	72.9 B	182.4 B	122.1 B	119.1 B	117.6 B	0.43 A	0.58 A	0.60A	0.63 A
Significance	Cultivar (C)	272.6**	124.9**	481.8**	59.0**	59.6**	38.5**	1078.3**	125.5**	375.8**	190.8**	4349.3**	152.6**	19.6**	30.4**	51.4**	5.3*
	N rate (N)	15.8**	15.2**	47.2**	54.1**	3.0*	8.9**	58.0**	21.9**	20.0**	29.0**	312.4**	70.2**	2.2^{ns}	4.6**	20.4**	23.2**
	C × N	1.5^{ns}	3.7*	10.0**	9.8**	0.54^{ns}	1.9^{ns}	24.5**	2.5^{ns}	1.6^{ns}	4.2**	11.3**	6.8**	0.81^{ns}	5.8**	18.0**	5.1**

Data are means of three replicates. Different lowercase letters within the same column represent significant (P < 0.05) differences between different N rates; within cultivars, averages with different uppercase letters are significantly different at P < 0.05 according to the LSD test. ns: not significant. * P < 0.05. ** P < 0.01

Table 5: Pre-silking N accumulation (SNA), post-silking N accumulation (PNA), N translocation (NT), and N translocation efficiency (NTE)

Cultivar	N rate	SNA (t ha^{-1})				PNA (t ha^{-1})				NT (t ha^{-1})				NTE (%)			
		2011 S	2011 J	2012 J	2013 J	2011 S	2011 J	2012 J	2013 J	2011 S	2011 J	2012 J	2013 J	2011 S	2011 J	2012 J	2013 J
ZH 311	0 N	91.9 d	50.0 d	53.5 c	58.6 e	124.8 a	81.0 c	64.1 d	43.4 b	40.8 d	19.1 c	27.1 d	33.2 d	44.5 c	38.1 b	50.7 bc	56.7 d
	90 N	109.1 c	73.5 c	66.1 b	80.8 d	117.0 a	95.3 abc	66.0 d	44.7 b	57.0 c	34.6 b	35.4 b	52.1 c	52.3 ab	47.1 a	53.6 a	64.6 ab
	180 N	118.5 b	75.6 c	65.9 b	97.6 c	126.6 a	100.3 ab	74.7 b	48.0 b	60.8 bc	34.2 b	31.7 c	64.5 b	51.3 ab	45.1 ab	48.0 cd	66.1 a
	270 N	119.4 b	86.9 b	66.0 b	105.4 c	120.9 a	110.3 a	71.0 c	42.6 b	61.2 bc	36.7 b	34.9 b	67.4 a	51.3 ab	42.2 ab	52.8 ab	64.0 bc
	360 N	133.9 a	93.7 a	65.4 b	114.7 a	132.0 a	88.6 bc	79.4 a	59.7 a	64.2 b	46.0 a	29.9 cd	66.6 ab	48.0 bc	49.0 a	45.6 d	58.1 d
	450 N	133.0 a	77.1 c	74.8 a	108.4 b	126.4 a	84.8 bc	64.6 d	60.9 a	70.7 a	38.1 b	40.8 a	68.2 a	53.2 a	49.5 a	54.5 a	62.9 bc
	Average	117.6 A	76.1 A	65.3 A	94.2 A	124.6 A	93.4 A	70.0 A	49.9 A	59.1 A	34.8 B	33.3 B	58.7 A	50.1 B	45.2 B	50.9 B	62.1 B
XY 508																	
	0 N	75.0 e	41.4 e	36.2 d	45.6 d	86.6 b	31.8 b	36.4 bc	44.9 a	46.0 d	28.2 c	24.6 d	27.9 d	61.2 a	68.1 a	68.2 c	61.0 c
	90 N	90.8 d	63.6 d	51.2 c	66.8 c	84.5 bc	56.2 a	45.5 a	33.8 b	56.2 c	39.9 b	33.5 c	45.6 c	61.9 a	62.8 b	65.3 d	68.2 ab
	180 N	96.2 cd	67.2 d	58.1 b	81.0 b	82.2 c	55.9 a	43.8 ab	40.1 ab	59.8 bc	42.1 b	37.0 b	56.6 b	62.2 a	62.7 b	63.7 d	69.8 ab
	270 N	102.3 bc	71.9 c	63.1 a	88.0 ab	76.6 d	59.6 a	31.1 c	44.4 a	65.0 ab	44.5 b	44.3 a	59.6 ab	63.6 a	61.8 b	70.2 bc	67.8 b
	360 N	106.7 ab	77.2 b	62.2 a	90.6 a	84.6 bc	61.2 a	30.3 c	33.9 b	68.7 a	49.7 a	45.9 a	63.8 a	64.3 a	64.3 ab	73.8 a	70.4 a
	450 N	111.8 a	82.4 a	64.0 a	89.2 a	97.3 a	64.4 a	31.6 c	46.9 a	69.8 a	52.9 a	46.2 a	60.4 ab	62.4 a	64.2 ab	72.2 ab	67.8 b
	Average	97.1 B	67.3 B	55.8 B	76.9 B	85.3 B	54.9 B	36.4 B	40.7 B	60.9 A	42.9 A	38.6 A	52.3 B	62.6 A	64.0 A	68.9 A	67.5 A
Significance	Cultivar (C)	169.7**	82.5**	251.2**	233.3**	344.7**	151.9**	868.5**	24.9**	2.6^{ns}	52.0**	115.1**	50.6**	236.8**	256.1**	1324.0**	174.9**
	N rate (N)	55.5**	140.4**	132.6**	192.8**	3.5*	6.2**	8.8**	4.7**	48.5**	38.1**	98.7**	155.0**	3.3*	1.8^{ns}	17.1**	38.9**
	C × N	1.0^{ns}	10.4**	16.5**	2.1^{ns}	2.0^{ns}	2.6^{ns}	12.7**	5.3**	1.2^{ns}	1.9^{ns}	33.6**	0.83^{ns}	2.8*	4.0**	20.4**	11.3**

SNA: pre-silking N accumulation; PNA: post-silking N accumulation; NT: N translocation; NTE: N translocation efficiency. Data are means of three replicates. Different lowercase letters within the same column represent significant (P < 0.05) differences between different N rates; within cultivars, averages with different uppercase letters are significantly different at P < 0.05 according to the LSD test. ns: not significant. * P < 0.05. ** P < 0.01

ZH 311, the mean values for SNA and PNA were higher than those for XY 508 by 21.1 and 46.1% in 2011S, 13.2 and 70.2% in 2011J, 17.0 and 92.0% in 2012J, and 22.5 and 28.7% in 2013J. However, NTE was 20.0, 29.4, 26.1 and 8.0% lower in ZH 311 than in XY 508 in 2011S, 2011J, 2012J and 2013J, respectively. Therefore, it was mainly PNA which accounted for the differences between ZH 311 and XY 508 in terms of N accumulation.

The comparatively lower NTE of the low N-tolerant cultivar increased the proportion of N in the vegetative organs in the late growth stage. Except for 2011S, N application had significant (P < 0.05) effects on the SNA of both cultivars and the PNA of ZH 311. The effects of XY 508 on N accumulation were influenced by experimental site and year. Compared to the 0 N treatments, the mean N treatments increased SNA by 33.6, 62.9, 26.4 and 72.9% in ZH 311 and by 35.4, 75.1, 65.2 and 82.2% in XY 508 in 2011S, 2011J, 2012J and 2013J, respectively. The PNA of ZH 311 increased by

Table 6: Grains per panicle (GP), 1000-kernel weight, grain yield and N grain production efficiency in different growth seasons

Cultivar	N rate	Grains per panicle				1000-kernel weight (g)				Grain yield (t ha^{-1})				N grain production efficiency (%)			
		2011 S	2011 J	2012 J	2013 J	2011 S	2011 J	2012 J	2013 J	2011 S	2011 J	2012 J	2013 J	2011 S	2011 J	2012 J	2013 J
ZH 311	0 N	555.8 c	421.0 b	425.2 b	464.8 b	327.5 c	308.1 d	293.3 b	290.9 c	7.2 c	5.0 b	5.2 b	6.5 b	33.3 ab	38.5 ab	44.2 abc	57.7 a
	90 N	565.5 bc	508.1 a	451.4 a	512.4 a	327.1 c	309.6 cd	308.4 a	308.9 b	7.8 b	6.9 a	6.0 a	7.2 a	34.3 a	40.6 a	47.3 a	57.7 a
	180 N	561.4 c	512.7 a	461.1 a	514.9 a	340.1 ab	322.2 ab	312.8 a	315.6 b	8.2 ab	7.0 a	6.2 a	7.3 a	33.3 ab	40.1 a	44.7 ab	50.4 ab
	270 N	566.4 bc	513.5 a	459.5 a	516.1 a	333.3 bc	317.1 b	314.2 a	315.2 b	8.4 a	7.2 a	6.3 a	7.4 a	34.0 a	34.8 b	43.9 bc	48.1 ab
	360 N	583.1 a	513.4 a	456.2 a	516.5 a	340.8 a	325.7 a	311.0 a	324.6 a	8.4 a	7.2 a	5.9 a	7.4 a	31.7 c	39.4 a	40.6 d	42.2 b
	450 N	573.2 ab	487.4 a	468.9 a	509.9 a	341.1 a	315.3 bc	308.4 a	309.8 b	8.5 a	6.8 a	5.8 a	7.2 a	32.7 bc	42.5 a	41.5 cd	42.8 b
	Average	567.6 A	492.7 A	453.7 A	505.8 A	335.0 A	316.3 A	308.0 B	310.8 A	8.1 A	6.7 A	5.9 A	7.1 A	33.2 B	39.3 B	43.7 B	49.8 B
XY 508	0 N	535.2 b	358.4 b	344.5 c	448.3 b	303.0 b	300.9 b	319.7 a	285.5 ab	6.4 b	4.5 c	3.9 c	5.9 b	39.7 a	61.8 a	53.4 a	71.8 a
	90 N	562.3 a	464.8 a	407.0 a	515.8 a	304.4 b	314.4 ab	321.6 a	275.6 b	6.8 ab	5.9 b	5.0 a	6.6 a	38.8 a	48.9 b	51.7 a	68.4 a
	180 N	543.0 ab	473.0 a	368.2 bc	515.0 a	309.3 ab	319.4 a	321.7 a	277.7 ab	7.0 a	5.9 b	4.8 ab	6.7 a	39.5 a	48.0 b	47.1 a	55.4 b
	270 N	568.4 a	476.7 a	397.4 ab	522.8 a	316.1 a	321.2 a	320.7 a	276.5 ab	7.1 a	6.0 b	5.0 a	6.7 a	39.8 a	45.6 b	53.2 a	49.7 cd
	360 N	569.4 a	466.4 a	364.9 bc	489.5 ab	315.4 a	319.1 a	318.7 a	287.7 ab	7.2 a	6.3 ab	5.0 a	6.7 a	38.3 a	45.2 b	54.5 a	51.9 bc
	450 N	551.9 a	477.8 a	368.2 bc	504.4 a	318.2 a	318.3 a	315.9 a	289.6 a	7.3 a	7.1 a	4.6 b	6.7 a	34.7 b	48.3 b	48.1 a	47.6 d
	Average	555.0 A	452.9 B	375.0 B	499.3 A	311.0 B	315.6 A	319.7 A	282.1 B	7.0 B	5.9 B	4.7 B	6.5 B	38.5 A	49.6 A	51.3 A	57.4 A
Significance	Cultivar (C)	2.9^{ns}	67.4**	196.6**	0.71^{ns}	191.2**	0.12^{ns}	39.1**	208.7**	109.7**	16.8**	169.6**	16.3**	227.6**	118.0**	43.6**	29.7**
	N rate (N)	1.5^{ns}	17.0**	5.6**	6.1**	8.4**	5.6**	3.2*	6.5**	9.7**	12.3**	13.3**	3.5*	8.3**	8.3**	1.7^{ns}	23.7**
	C × N	0.29^{ns}	0.62^{ns}	2.4^{ns}	0.47^{ns}	1.1^{ns}	0.94^{ns}	2.7*	7.5**	0.52^{ns}	1.4^{ns}	1.1^{ns}	0.02^{ns}	4.4**	8.1**	2.1^{ns}	1.8^{ns}

Data are means of three replicates. Different lowercase letters within the same column represent significant ($P < 0.05$) differences between different N rates; within cultivars, averages with different uppercase letters are significantly different at $P < 0.05$ according to the LSD test. ns: not significant. * $P < 0.05$. ** $P < 0.01$

Table 7: N uptake efficiency (NUE), N recovery efficiency (NRE), N agronomic efficiency (NAE) and N partial factor productivity (NPFP) during different growth seasons

Cultivar	N rate	NUE (%)				NRE (%)				NAE (kg kg^{-1})				NPFPP (kg kg^{-1})			
		2011 S	2011 J	2012 J	2013 J	2011 S	2011 J	2012 J	2013 J	2011 S	2011 J	2012 J	2013 J	2011 S	2011 J	2012 J	2013 J
ZH 311	0 N	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	90 N	74.2 a	76.4 a	63.6 a	65.4 a	12.3 a	42.2 a	27.2a	26.1 a	6.7 a	20.3 a	13.1a	14.8 a	86.8 a	76.4 a	69.4 a	80.4 a
	180 N	61.8 b	56.5 b	47.2 b	51.6 b	15.7 a	25.0 b	18.4 b	24.2 a	5.3 b	11.0 b	6.0 b	8.0 b	45.3 b	39.0 b	34.9 b	40.8 b
	270 N	50.7 c	51.6 c	35.3 c	39.7 c	11.2 a	28.2 b	10.9 c	17.0 b	4.4 bc	7.9 bc	3.0 c	4.4 c	31.2 c	26.6 c	21.8 c	27.3 c
	360 N	46.1 d	37.2 d	30.3 d	37.7 c	13.6 a	14.3 c	10.3 cd	20.1 ab	3.4 cd	6.0 cd	1.9 d	4.1 cd	23.4 d	20.0 d	16.3 d	20.5 d
	450 N	38.9 e	27.8 e	24.6 e	30.7 d	9.5 a	6.9 c	7.1 d	15.0 b	2.9 d	4.0 d	1.3 d	3.0 d	18.9 e	15.2 d	12.9 d	16.1 d
	Average	54.4 A	49.9 A	40.2 A	45.0 A	12.5 A	23.3 B	14.8 A	20.5 A	4.5 A	9.8 A	5.1 A	6.9 A	41.1 A	35.4 A	31.1 A	37.0 A
XY 508	0 N	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	90 N	57.2 a	54.2 a	46.6 a	52.4 a	15.2 a	51.8 a	26.8 a	20.5 a	4.3 a	15.1a	12.4 a	11.0 a	75.6 a	65.2 a	55.5 a	76.5 a
	180 N	45.0 b	39.6 b	34.2 b	43.0 b	9.3 b	27.7 b	16.2 b	21.7 a	3.5 ab	7.8 b	5.1 b	4.6 b	39.2 b	32.8 b	26.7 b	37.3 b
	270 N	36.7 c	32.8 c	24.3 c	35.6 c	6.4 c	21.6 c	8.0 c	18.6 a	2.6 bc	5.6 c	4.2 b	2.6 c	26.4 c	22.3 c	18.6 c	24.4 c
	360 N	33.2 d	28.2 d	19.4 d	27.0 e	8.2 bc	18.1 c	5.5 c	11.8 b	2.5 bc	4.9 c	3.2 bc	1.6 cd	20.4 d	17.4 c	14.0 d	18.0 d
	450 N	31.4 e	25.3 e	16.8 e	24.7 e	10.6 b	16.4 c	5.1 c	12.0 b	1.9 c	5.7 c	1.6 c	1.3 d	16.1 e	15.8 c	10.2 d	14.4 d
	Average	40.7 B	36.0 B	28.3 B	36.5 B	9.9 B	27.1 A	12.3 B	16.9 B	3.0 B	7.8 B	5.3 A	4.2 B	35.5 B	30.7 B	25.0 B	34.1 B
Significance	Cultivar (C)	718.4**	210.9**	1112.8**	188.8**	5.0*	7.9*	10.0**	11.5**	50.8**	11.2**	0.50^{ns}	121.3**	89.5**	12.2**	49.1**	11.1**
	N rate (N)	457.1**	197.2**	1194.4**	325.4**	2.4^{ns}	79.1**	101.4**	13.6**	25.2**	61.0**	137.4**	271.8**	1511.9**	218.9**	453.8**	697.0**
	C × N	11.5**	13.9**	18.3**	6.5**	2.8^{ns}	4.7**	0.87^{ns}	2.5^{ns}	1.6^{ns}	3.7*	1.9^{ns}	3.0*	6.6**	2.1^{ns}	6.7**	0.19^{ns}

Data are means of three replicates. Different lowercase letters within the same column represent significant ($P < 0.05$) differences between different N rates; within cultivars, averages with different uppercase letters are significantly different at $P < 0.05$ according to the LSD test. ns: not significant. * $P < 0.05$. ** $P < 0.01$

18.4% in 2011J, 11.1% in 2012J and 17.9% in 2013J. Therefore, the increase in SNA was higher in the low N-sensitive cultivar than it was in the low N-tolerant cultivar. In contrast, the increase in PNA was higher in the low N-tolerant cultivar than the low N-sensitive cultivar. N application significantly increased NT in both cultivars but had significantly different effects on them in terms of NTE. Compared with the 0 N treatments, the mean N treatments increased the NTE of ZH 311 by 15.2% in 2011S, 22.2% in 2011J and 11.3% in 2013J. In contrast, the NTE of XY 508 decreased by 7.3% in 2011J and increased by 12.7% in 2013J. Therefore, N application significantly increased NT in both cultivars but the increments in NTE for the low N-tolerant cultivar were higher than those for the low N-sensitive cultivar.

Yield and its Components

The mean number of grains per panicle, mean 1,000-kernel weight and yield in 2011S were 14.1, 2.2 and 19.2% higher, respectively, than those in 2011J (Table 6). N fertilizer did not significantly ($P > 0.05$) influence the number of grains per panicle in Shuangliu. However, it did significantly ($P < 0.05$) affected the 1000-kernel weight and the grain yield at both experimental sites and the number of grains per panicle in Jianyang over three years.

N fertilizer application remarkably ($P < 0.05$) increased grain yield at both experimental sites by increasing the number of grains per panicle and the 1000-kernel weight. Compared to the 0 N treatments, the yield in 2011S increased by 12.8% while in 2011J it increased by 39.6%. Therefore, N fertilization caused significantly greater increases in grain yield at Jianyang than at Shuangliu. Moreover, the yield of ZH 311 was obviously ($P < 0.01$) higher than XY 508 at two sites. There were inter-annual variations between ZH 311 and XY 508 in terms of the number of grains per panicle and the 1000-kernel weight. For this reason, the combination of the number of grains per panicle and the 1000-kernel weight accounted for the difference in grain yield between the two type cultivars.

Table 8: Regression analysis between different index (y) and N application level (x)

Index	Cultivar	Year	Regression equation	R^2	F-value	Sig.	The optimal N application (kg ha^{-1})
Total dry matter accumulation (t ha^{-1})	ZH 311	2011 S	$y = -0.000023x^2+0.017575x+16.8689$	0.940	23.50*	0.015	382.07
		2011 J	$y = -0.000054x^2+0.028696x+11.1161$	0.957	33.09**	0.009	265.70
		2012 J	$y = -0.000022x^2+0.014912x+11.0079$	0.998	616.07**	0.000	338.91
		2013 J	$y = -0.000034x^2+0.026180x+11.7189$	0.973	54.23**	0.004	385.00
		Average	$y = -0.000033x^2+0.021789x+12.6843$	0.982	80.25**	0.003	330.14
	XY 508	2011 S	$y = 0.005006x+13.2252$	0.892	33.12**	0.005	450.00
		2011 J	$y = -0.000026x^2+0.019103x+7.5371$	0.883	11.34*	0.040	367.37
		2012 J	$y = -0.000023x^2+0.016316x+7.2229$	0.957	33.46**	0.009	354.70
		2013 J	$y =0.007298x+10.1395$	0.937	59.53**	0.002	450.00
		Average	$y = 0.006444x+9.8600$	0.891	32.54**	0.005	450.00
Total N accumulation (kg ha^{-1})	ZH 311	2011 S	$y = 0.104194x+218.8081$	0.867	25.96**	0.007	450.00
		2011 J	$y = -0.000819x^2+0.436808x+131.7189$	0.954	30.81**	0.010	266.67
		2012 J	$y = -0.000379x^2+0.233372x+140.5018$	0.949	27.74*	0.012	307.88
		2013 J	$y = -0.000506x^2+0.379597x+98.7429$	0.968	44.91**	0.006	375.10
		Average	$y = -0.000455x^2+0.301550x+146.6554$	0.984	93.54**	0.002	331.37
	XY 508	2011 S	$y = 0.090670x+162.0410$	0.895	34.09**	0.004	450.00
		2011 J	$y = -0.000390x^2+0.312727x+80.6871$	0.905	14.22*	0.030	400.93
		2012 J	$y = -0.000444x^2+0.272770x+90.6929$	0.902	13.79*	0.031	329.70
		2013 J	$y = 0.104003x+94.0343$	0.939	61.53**	0.001	450.00
		Average	$y = -0.000221x^2+0.200547x+106.5325$	0.954	31.01**	0.010	453.73
Grain yield (t ha^{-1})	ZH 311	2011 S	$y = -0.000009x^2+0.006766x+7.2321$	0.987	114.96**	0.002	375.89
		2011 J	$y = -0.000026x^2+0.015012x+5.2536$	0.891	12.24*	0.036	288.69
		2012 J	$y = -0.000015x^2+0.007734x+5.2893$	0.893	12.54*	0.035	257.80
		2013 J	$y = -0.000011x^2+0.006194x+6.5750$	0.938	22.72*	0.015	281.55
		Average	$y = -0.000015x^2+0.008927x+6.0875$	0.941	23.79*	0.014	297.57
	XY 508	2011 S	$y = -0.000004x^2+0.003726x+6.4393$	0.982	80.20**	0.003	465.75
		2011 J	$y = 0.004540x+4.9286$	0.822	18.44*	0.013	450.00
		2012 J	$y = x/(1.1212x-19.1255)+3.8998$	0.884	11.45*	0.039	450.00
		2013 J	$y = x/(1.1854x-19.5837)+5.8999$	0.998	660.87**	0.000	450.00
		Average	$y = x/(0.781717x+37.9877)+5.1785$	0.976	60.36**	0.004	450.00

There were significant differences between both cultivars in terms of the effects of N application rate on yield. The yield (y) of ZH 311 first increased then decreased with increasing N levels (x). The relationship between y and x was a quadratic convex. The optimal N levels ranged from 257.80 to 375.89 kg N ha^{-1} (Table 8). On the other hand, the relationship between grain yield and N application rate for XY 508 was either linear or it followed the fertility-yield model [$y = x / (a + bx) + c$]. The level of N required to obtain a high yield was greater than that required for ZH 311. Therefore, the low N-sensitive cultivar was more tolerant to excess N than the low N-tolerant variety.

For the average of both experimental sites over three years, the regression of the difference in grain yield between both cultivars (y) and the N application rate (x) was $y = -0.000007x^2 + 0.003150x + 0.726250$ ($R^2 = 0.9201$*). The differences in yield between two cultivars first increased then decreased with increasing N rate. The largest difference in grain yield between ZH 311 and XY 508 was 1.1 t ha^{-1} at 225.0 kg N ha^{-1}. There was, therefore, a significant difference in grain yield between the low N-tolerant and low N-sensitive cultivars. Under low-N conditions, the relative increases in grain yield were greater for the low N-tolerant cultivar than the low N-sensitive cultivar.

N Absorption and Utilization

NUE and NPFP were relatively higher in 2011S than the other seasons whereas NRE, NAE and N grain production efficiency were relatively lower in 2011S than in 2011J (Table 6 and 7). N fertilizer significantly decreased maize N uptake efficiency (NUE), N recovery efficiency (NRE), N agronomic efficiency (NAE) and N partial factor productivity (NPFP) at both sites. Moreover, these parameters decreased substantially more at Shuangliu than at Jianyang. Therefore, N application had a greater influence on N absorption and utilization at Jianyang than at Shuangliu. NUE, NRE (except for 2011J), NAE (except for 2012J) and NPFP for ZH 311 were higher than those for XY 508 significantly ($P < 0.01$). N grain production efficiency for XY 508 was higher than that for ZH 311 significantly ($P < 0.01$). The highest F values between ZH 311 and XY 508 were obtained for NUE. Moreover, NUE, NRE, NAE, NPFP and N grain production efficiency significantly decreased with increasing N application and these variables differed substantially between the two cultivars. The averages for both experimental sites over three years indicated that the relative differences in NUE, NAE and NPFP between ZH 311 and XY 508 decreased with increasing N level whereas those for NRE first increased then decreased with increasing N. N grain production efficiency first decreased then increased with N level. Increasing N, therefore, might be advantageous to the low N-sensitive cultivar whereas, in fact, the N level must be reduced for the low N-tolerant cultivar. Furthermore, N absorption and utilization in the low N-tolerant cultivar increased at both experimental sites, especially at low N application levels.

Discussion

N fertilizer application effectively increases grain yield per unit area and closes the "yield gap" between maize supply and demand (Abbasi *et al.*, 2013; Chen *et al.*, 2015). However, fertilizer must be dispensed according to the individual N requirements of each cultivar and with the environmental conditions to optimize N absorption and utilization, reduce N waste and environmental pollution and maximize the yield potential. In this study, the differences between low N-tolerant and low N-sensitive cultivars in Southwest China were investigated in terms of their responses to N application. Certain correlations were found between N fertilizer application rate and grain yield.

The N application rate had significant effects on maize plant height and LAI (Li *et al.*, 2015b). In this experiment, plant height and LAI significantly increased with N application. Nevertheless, there were obvious differences in these responses between ecological sites and cultivars (Fig. 1 and 2). Plant height and LAI were substantially higher at Shuangliu than at Jianyang. However, following N fertilizer application, the increases in plant height and LAI were greater at Jianyang than at Shuangliu. The former site had comparatively fertile soil and adequate precipitation. Plant height and LAI of ZH 311 were higher than XY 508 significantly at both sites but the ameliorative effects of N application on XY 508 were stronger than ZH 311. Moreover, the differences between the two cultivars in terms of plant height and LAI decreased with increasing N level. Overuse of N fertilizer decreased yield and grain quality (Abbasi *et al.*, 2013; Chen *et al.*, 2015). Therefore, the low N-sensitive cultivar can be grown in fertile soil (Shuangliu) for optimal plant height and LAI whereas the low N-tolerant cultivar can be raised in barren regions (Jianyang) to maintain ideal plant height and LAI under low-N conditions.

Biomass is due to distribution and accumulation of photosynthate in different parts and is the material basis of yield formation (Deng *et al.*, 2014; Mu *et al.*, 2015). In the present study, PDMA in both cultivars accounted for 60% of the total dry matter accumulation throughout the whole growth period. The differences between the two cultivars in terms of post-silking dry matter accumulation were significantly greater than pre-silking and total dry matter accumulation (Table 3). This finding corroborates those of other studies (Chen *et al.*, 2011; Cui *et al.*, 2013). The fertile soil and sufficient precipitation at Shuangliu significantly increased SDMA and PDMA compared with observed at Jianyang. The increases in dry matter accumulation realized by N fertilization were significantly greater at Jianyang than at Shuangliu (Table 2 and 3). PDMA at Jianyang was significantly higher than at Shuangliu. Consequently, pre-silking dry matter translocation was more strongly inhibited and DMT and DMTE were significantly greater at Jianyang than they were at Shuangliu. The relatively higher SDMA and lower PDMA in XY 508 resulted in its DMT and DMTE levels being significantly higher than in ZH 311. In XY 508, stover dry matter accumulation increased more with increasing N rates than did the grain dry matter accumulation. Therefore, the differences between the two cultivars in terms of HI increased with N rate. The differences between the two type cultivars in terms of dry matter accumulation decreased with increasing N rate. Low and moderate N application levels had the strongest positive effect on dry matter accumulation in ZH 311 at Jianyang. However, these benefits were substantially reduced at Shuangliu under all N levels and at Jianyang under high N levels (450 kg N ha^{-1}).

Biomass yield is an important indicator of grain yield and adequate biomass yield is the material basis of high grain yield (Chen *et al.*, 2015). On this basis, the maize yield at Shuangliu was higher than at Jianyang significantly and the yield of ZH 311 was higher than of XY 508 significantly (Table 6). Crop yield is determined by the coordination and integration of yield components. The number of grains per panicle and the 1000-kernel weight at Shuangliu were significantly higher than at Jianyang. The advantage of ZH 311 over XY 508 in terms of grain yield resulted from the combination of the number of grains per panicle and the 1000-kernel weight (D'Andrea *et al*., 2008). N fertilization significantly influenced crop yield formation but the magnitude of this effect significantly differed among cultivars (Chen *et al.*, 2015; Mu *et al.*, 2015).

Excess N fertilizer decreased grain yield. Regression of the average of both experimental sites over three years showed that the N rates producing the highest grain yield significantly differed between both cultivars (Table 8), these results are consistent with Chen *et al.* (2015). The optimal N rate for maximum yield potential in ZH 311 was 297.57 kg N ha^{-1} whereas for XY 508 was 450 kg N ha^{-1}. Furthermore, the yield of ZH 311 was higher than of XY 508 significantly at all N levels. The differences in grain yield between the two cultivars first increased then decreased with increasing N rate. The greatest difference in grain yield between ZH 311 and XY 508 was 1.1 t ha^{-1} at 225.0 kg N ha^{-1}. These results indicate that ZH 311 tolerates N deficiency whereas XY 508 tolerates excess N. Therefore, low N-sensitive cultivars should either be planted in fertile regions like Shuangliu or receive elevated N fertilizer doses to maximize their yield potential. In contrast, low N-tolerant cultivars can be sown in barren regions such as Jianyang to ensure high, stable grain yields while reducing N fertilization and increasing N utilization.

Grain accumulates N via SNA remobilization and PNA translocation. N fertilization has significant effects on pre- and post-silking N absorption and translocation (Mu *et al.*, 2015). In the study, accumulation, distribution, absorption and utilization of N in maize significantly differed under different ecological conditions and in cultivars with contrasting low N tolerances (Table 5 and 7). Stover, grain and total N accumulation, SNA, PNA, NT, NUE and NPFP at Shuangliu were significantly higher than at Jianyang. On the other hand, NHI, NRE, NAE and N grain production efficiency at Jianyang were significantly higher than at Shuangliu. N fertilization significantly increased stover, grain, and total N accumulation, SNA, PNA, NT and NTE but significantly decreased NHI, NUE, NRE, NAE and NPFP at both sites. Furthermore, the gains in stover, grain and total N accumulation, SNA, PNA, NT, NTE and the losses in NHI, NUE, NRE, NAE and NPFP were higher at Jianyang than at Shuangliu. These results indicate that maize N absorption at Shuangliu was significantly greater than at Jianyang. The soil at the former site is more fertile than at the latter. Relatively higher N absorption levels inhibited SNA remobilization and PNA translocation. The effects of N fertilization on N absorption and utilization at Jianyang were significantly stronger than at Shuangliu.

In this study, stover, grain, and total N accumulation, SNA and PNA in ZH 311 were significantly higher than in XY 508. Consequently, NUE, NAE and NPFP were remarkably higher in ZH 311 than in XY 508. In addition, NT and NTE in XY 508 were significantly higher than in ZH 311. As a result, NHI and N grain production efficiency in XY 508 were significantly greater than in ZH 311 (Table 5 and 7). N fertilization significantly affected N absorption and utilization in both maize cultivars. Increases in grain N accumulation, PNA and NTE were greater in ZH 311 than in XY 508. In contrast, the reductions in NUE, NRE, NAE and NPFP were larger in low N-sensitive cultivar than in low N-tolerant cultivar. Results indicate that N-tolerant cultivar had distinct advantages over N-sensitive cultivar in terms of N absorption and utilization especially under low-N supply (Li *et al.*, 2010).

Conclusion

In both the low N-sensitive and low N-tolerant cultivars, N fertilization significantly increased plant height, LAI, dry matter and N accumulation, yield, and significantly reduced HI, NHI, NUE, NRE, NAE and NPFP. Plant height, LAI, dry matter and N accumulation, yield and its components, NUE, NRE, NAE and NPFP were all higher in ZH 311 than in XY 508. On the other hand, HI, NHI and N grain production efficiency were lower in ZH 311 than in XY 508. Greater plant height, LAI and dry matter productivity of ZH 311 relative to XY 508 favor post-silking dry matter production and N absorption, significantly increase NUE, NRE, NAE and NPFP, and realize yield gains. This mechanism may explain the tolerance of ZH 311 to low N levels. Therefore, low N-sensitive cultivars should either be planted in fertile plain regions like Shuangliu or N fertilization should be increased to maximize grain yield. Low N-tolerant cultivars could be planted in barren hills and mountainous regions such as Jianyang to ensure high and stable yields while reducing N fertilizer application levels.

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