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Impact of Nitrogen Rate on Maize Yield and Nitrogen Use Efficiencies in Northeast China

S. J. Qiu, P. He,* S. C. Zhao, W. J. Li, J. G. Xie, Y. P Hou, C. A. Grant, W. Zhou, and J. Y. Jin

ABSTRACT

Optimizing N fertilization is important to improve both maize (*Zea mays* L.) yield and nitrogen use efficiencies (NUEs). A 3-yr maize field experiment (2008–2010) was conducted to evaluate the response of grain yield, aboveground biomass, plant N concentration, N uptake, and NUEs to fertilizer N rates from 0 to 280 kg N ha^{-1} at three different rain-fed Haplic Phaeozem soils (FAO classification) in Northeast China. When N application rate increased from 70 to 280 kg N ha^{-1} across all site-years, N recovery efficiency, N agronomic efficiency, N internal efficiency and N partial factor productivity decreased from 76.5 to 9.0%, 25.3 to 0.1 kg kg^{-1}, 70.7 to 40.8 kg kg^{-1}, and 145.6 to 22.8 kg kg^{-1}, respectively. Differences observed among the years and experimental sites were primarily caused by variability in rainfall and soil characteristics. The maximal grain yield of 11.0 Mg ha^{-1} was achieved at an N rate of 210 kg N ha^{-1} with normal rainfall. Nitrogen application beyond the optimal N rate did not consistently increase grain yield, and caused a decrease in NUEs. The range of optimal N rate for maize grain yield fell between 140 and 210 kg N ha^{-1} at the three sites from 2008 to 2010 in Northeast China based on the best fitted models (quadratic, linear plus plateau, and quadratic plus plateau). The results provide guidelines for selecting N application rates to optimize both maize yield and NUEs in Northeast China.

Nitrogen is the most limiting nutrient for agricultural production worldwide and application of N fertilizer is generally required for optimum yield of most non-legume crops. However, there is increasing concern about the negative effects of excess or unbalanced N fertilization on the environment. For example, excessive N causes an estimated environmental cost of 70 to 320 billion Euros per year in Europe (Sutton et al., 2011). Similarly, overuse of chemical N fertilizer in China leads to low NUE (He et al., 2009; Ju et al., 2009), resulting in enhanced soil acidification (Guo et al., 2010), aquatic eutrophication (Jin et al., 2005), and increased gaseous emissions of nitrous oxide and ammonia (Ju et al., 2009, 2011). The current priority for agricultural policy in China is high crop yield to meet the food demands of the large and growing population. However, sustainable agriculture must be developed to ensure long-term food security and environmental quality. Efficient N management based on application rates matched to crop demand is a critical step to produce high grain yields while avoiding environmental degradation.

Maize is an important crop for food, animal feed and forage, and bio-fuel (Chen et al., 2011; Grassini and Cassman, 2012). While it is theoretically possible to improve maize grain yield by increasing harvest index (HI), maize HI has been relatively stable over the past decades (Echarte and Andrade, 2003; Duvick, 2005). Therefore, improvements in maize grain yield are apt to be associated with increases in aboveground biomass (Duvick, 2005; Ciampitti and Vyn, 2011, 2012). Aboveground production can decrease if available N supply is limited (Kiniry et al., 2001). Aboveground biomass production also determines maize N uptake potential under optimum N application rates (Peng et al., 2010). Thus, high aboveground production not only requires adequate available N supply, but can also contribute to increased maize N uptake. Nitrogen accumulated by the maize biomass is partitioned into grain N and stover N, with luxury N uptake occurring when excess fertilizer N is applied. Therefore, grain and stover N concentration will reflect the maize N supply and can be used to provide an indication of N status of maize (Chen et al., 2010).

Nitrogen use efficiencies have two aspects: one is the efficiency of crop N uptake and the other is the conversion efficiency from total N uptake to grain yield (Moll et al., 1982). The components of NUEs include nitrogen recovery efficiency

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Abbreviations: AE_N, nitrogen agronomic efficiency; HI, harvest index; IE_N, nitrogen internal efficiency; LP, linear plus plateau model; NUEs, nitrogen use efficiencies; PFP_N, partial factor productivity; Q, quadratic model; QP, quadratic plus plateau model; RE_N, nitrogen recovery efficiency.

(RE_N), nitrogen agronomic efficiency (AE_N), nitrogen internal efficiency (IE_N), and partial factor productivity (PFP_N). Nitrogen recovery efficiency and AE_N reflect the aboveground N uptake and grain yield per unit of fertilizer N rate, respectively; IE_N indicates the conversion of aboveground N uptake to grain yield, PFP_N assesses the ratio of grain yield to applied N rate (Ciampitti and Vyn, 2011; 2012). The various assessments of NUEs are affected by the complex interaction of environment, management practices, and crop genotype (Ciampitti and Vyn, 2011) and are important to environmental sustainability and profitability. Excessive N application often reduces NUEs, because crop utilization of N will be limited by biotic and abiotic constraints other than N supply (Kaizzi et al., 2012). In contrast, low N applications may produce high NUEs, but result in poor yield and inefficient use of land, water, and other production inputs (Ciampitti and Vyn, 2011; Abbasi et al., 2012). Wortmann et al. (2011) reported values of 64%, 29 kg kg^{-1}, and 100 kg kg^{-1} for RE_N, AE_N, and PFP_N at economically optimum nitrogen rate (EONR) in irrigated maize in Nebraska, in the United States; Setiyono et al. (2010) summarized studies showing an average of 61 kg kg^{-1} for maize IE_N with balanced fertilization. In China, values of 31%, 11 kg kg^{-1}, and 72 kg kg^{-1} for RE_N, AE_N, and PFP_N were reported by Cui et al. (2008) in summer maize at EONR, calculated using linear plus plateau model simulation on the North China plain, and values of 59 kg kg^{-1} in spring maize and 49 kg kg^{-1} in summer maize for IE_N were documented in China (Xu et al., 2013). Based on the relatively low values reported for Chinese production systems (Chen et al., 2011; Liu et al., 2013), there appears to be substantial room for improvement in NUEs in cropping systems in China and a better understanding of NUEs could help to improve N management practices in the future.

The spring maize region in Jilin province in Northeast China comprises the "golden maize belt" and accounts for 12.6% of total maize production in China (Wang and Liu, 2009). The region is predominantly under rain-fed agriculture and contains highly fertile Haplic Phaeozem soil (FAO 2002). The soil organic C content in Northeast China has markedly decreased since the 1980s (Huang and Sun, 2006) and this decline has affected the soil N storage and buffering capacity. In this region, the average chemical fertilizer N application is about 180 kg ha^{-1} (Li et al., 2010), but N application by individual farmers varies greatly. For example, of 110 farmers surveyed in Jilin, only 21% applied N at the recommended level of 190 to 200 kg ha^{-1}, with the majority of the farmers applying either more or less than optimum rates (Liu et al., 2011). An improved understanding of the response of both maize grain yield and NUEs to N inputs is critical in the development of cropping systems that are both economically and environmentally sustainable for producers in regions with highly productive, but variable maize yields. The goal of the present study is therefore to evaluate the effect of increasing N application rates on aboveground biomass, grain yield, harvest index (HI), N partitioning in grain and stover, and NUEs of maize across a range of environments, with the goal of improving N recommendations for high production maize dryland cropping systems.

MATERIALS AND METHODS

Sites

The experiments were conducted in farmers' fields in the villages of Liufangzi, Taojia, and Yushu in Jilin province, Northeast China, from 2008 to 2010. Jilin Province belongs to a typical continental monsoon climate, and its annual precipitation is 500 to 900 mm with 60% of the rainfall occurring during the summer (July–September). Liufangzi and Taojia lie in Gongzhuling County and Yushu lies in Yushu County of Jilin province. The total precipitation from May to September in the 3-yr study period from 2008 to 2010 was 425, 249, and 493 mm and the average temperature was 20.1, 19.4, and 18.4°C in Gongzhuling County, with corresponding values of 490, 278, and 485 mm for precipitation and 17.5, 18.8, and 19.7°C for average temperature in Yushu County (weather data were accessed from China Meteorological Data Sharing Service System, http://cdc.cma.gov.cn/home.do). Precipitation and average temperature details for each month during this period are shown in Fig. 1.

Surface soil (0–20 cm) properties at the beginning of the experiment at the Liufangzi, Taojia, and Yushu sites from 2008 to 2010 are shown in Table 1. The Lifangzi site is representative of the thin layer Haplic Phaeozem soil (<5 cm), the Taojia site is the middle layer Haplic Phaeozem soil (5–20 cm), and the Yushu site is a thick layer Haplic Phaeozem soil (20–50 cm).

Experimental Design

Spring maize (variety Zhengdan 958) was ridge-tilled, sown at the beginning of May and harvested at the end of September. The rates of N as urea ranged from 0 (control treatment) to 280 kg N ha^{-1} in 70 kg N ha^{-1} increments resulting in five treatments, namely N0, N70, N140, N210, and N280, arranged in a completely randomized block design with three replications. One-quarter of the N in each treatment was broadcast as a basal application before the soil was plowed and the remaining three-fourths was top-dressed at the eight to nine leaf stage of maize. Plots were 10 m long and 4 m wide, with six maize rows spaced 65 cm apart and in-row plant spacing of 25 cm. The maize was over-seeded with hand planters and thinned to a stand of 61,000 plant ha^{-1} at the seedling stage (V3), to ensure the same plant density in each individual plot. The distance between replications was 1.5 m and the edge of each replication had three guard rows of maize. A basal broadcast fertilizer application of 26 kg P ha^{-1} as triple superphosphate and 75 kg K ha^{-1} as potassium chloride was used to avoid P and K deficiencies. Although lime application may have been warranted based on the soil pH, this is not the common practice for the region and so no lime applications were made. The other field management followed farmer's conventional practices.

Sample and Data Analysis

At harvest, plants were counted in three rows in each plot. The three rows were sampled to determine fresh ear and stalk yield (including leaves) together with ear number. Five plants were randomly selected from the harvested spring maize, separated into cob, stalk, and grain, and the weight of each component measured before and after oven-drying at 60°C. Grain yield was calculated based on the fresh ear weight in the three sampled rows with cob yield deducted and was adjusted using the proportional oven-dried grain yield and cob yield in the five-plant subsample. Stover yield was the sum of cob, husk, and stalk yield. Stalk yield was calculated based on the fresh stalk yield in the three sampled rows and the proportional oven-dried stalk yield in the five-plant subsample, while cob and husk yield were calculated based on ear number in the three sampled rows and the average weight of oven-dried cob and husk in the five-plant subsample. Grain and stover samples were ground and the digested with H_2SO_4–H_2O_2 (Jones and Case, 1990) and the N concentration measured using the Kjeldahl method (Bremner, 1996). Grain yield, aboveground biomass, plant N concentration, and plant N uptake were reported on oven-dried basis.

Surface soil in each site was sampled in five random locations in rows in the previous season's ridge using the 'S" sampling method at the end of April each year before the field was plowed. Soil organic C was determined using the H_2SO_4–$K_2Cr_2O_4$ wet combustion method, with organic matter calculated as 1.724 times soil organic C (Nelson and Sommers, 1996). Soil alkali-hydrolyzed N was determined with the mason-jar diffusion method (Bremner, 1996), soil Olsen-P was extracted with 0.5 M $NaHCO_3$ and determined at 880 nm (Kuo, 1996), soil NH_4OAc-extracted K was extracted with 1 M NH_4OAc and determined using atom absorption spectrophotography (Helmke and Sparks, 1996), and pH was measured in a 1:2.5 soil/water mixture (Thomas, 1996). Soil organic C was measured on soil ground to pass a 0.15-mm sieve and the other determinations were made on soil ground to pass a 2-mm sieve. All determination above reported on an oven-dried basis.

In each plot, HI was calculated as the ratio of grain to the total aboveground biomass. Aboveground N uptake, RE_N, AE_N, IE_N, and PFP_N values were calculated using the following equations:

Aboveground N uptake = (Grain N concentration × Grain yield) + (Stover N concentration × Stover biomass)

$$RE_N = (U_N – U_0)/N \text{ rate} \times 100\%$$

$$AE_N = (Y_N – Y_0)/N \text{ rate}$$

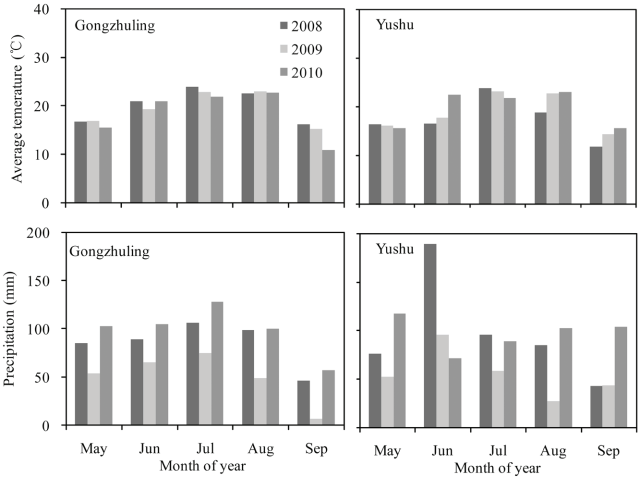

Fig. 1. Average temperature and precipitation from May to September in Gongzhuling (Liufangzi and Taojia sites) and Yushu (Yushu site) Counties in Jilin province, Northeast China from 2008 to 2010.

$$IE_N = Y_N/U_N$$

$$PFP_N = Y_N/N \text{ rate}$$

where U_N and Y_N represents the N uptake by aboveground biomass and grain yield in N application treatments, respectively; U_0 and Y_0 represent the N uptake by aboveground biomass and grain yield in the control treatment, respectively. The N rate is the total amount of N applied during maize growth.

Models

Quadratic (Q), quadratic plus plateau (QP), or linear plus plateau (LP) models were selected to describe maize grain yield response to N rate (Cerrato and Blackmer, 1990). The equations were as follows:

Q model:

$$Y = aX^2 + bX + c, \text{ and } X_{max} = –b/(2a),$$

$$Y_{max} = [–b + (b^2 – 4ac)^{0.5}]/(2a).$$

Table 1. Surface soil (0–20 cm) properties at the beginning of the experiment at three sites (Liufangzi, Taojia, Yushu) in Jilin province, Northeast China from 2008 to 2010.

Year	Latitude	Longitude	pH	Organic matter	Alkali-hydrolyzed N	Olsen-P	NH_4OAc-extracted K
				g kg^{-1}	mg kg^{-1}		
				Liufangzi			
2008	43°34′	124°53′	6.0	18.8	127.9	31.9	108.9
2009	43°45′	125°01′	4.9	20.4	118.2	75.7	122.4
2010	43°34′	124°53′	5.7	22.3	154.2	28.2	160.4
				Taojia			
2008	43°39′	124°39′	5.8	22.6	139.6	32.7	132.2
2009	44°39′	124°58′	5.2	22.6	124.2	16.1	199.6
2010	43°39′	125°00′	5.6	26.3	133.0	13.6	87.0
				Yushu			
2008	44°57′	126°17′	5.6	23.0	167.0	69.5	172.3
2009	44°48′	126°29′	5.6	26.6	130.3	31.8	179.9
2010	44°48′	126°28′	5.7	26.4	136.4	31.7	189.8

QP model:

$$Y = aX^2 + bX + c, \text{ if } X < X_{\text{opt}}; \text{ and}$$

$$Y = Y_{\max}, \text{ if } X \geq X_{\text{opt}}.$$

LP model:

$$Y = bX + c, \text{ if } X < X_{\text{opt}}; \text{ and}$$

$$Y = Y_{\max}, \text{ if } X \geq X_{\text{opt}}.$$

where Y is grain yield (Mg ha^{-1}), X is N rate (kg N ha^{-1}), a and b are quadratic and linear coefficients, respectively; c is intercept. $Y_{\max}$ is the maximum yield in Q model or plateau yield in QP and LP model; $X_{\max}$ is the maximum N rate in Q model; X_{opt} is the critical N rate that occurs at the intersection of two functions in QP or LP models.

Statistical Analysis

The yield, aboveground biomass, harvest index, grain N concentration, stover N concentration, aboveground N uptake, RE_N, AE_N, IE_N, and PFP_N were $\log_{10}$– or power-transformed to ensure that the data were distributed normally. Analysis of variance was then conducted on the transformed data using the general linear model procedure in SPSS 11.0 software. The statistical model treated N rate as fixed variable and considered year and site to be random variables, using a three-way randomized complete block design. With year and site designated as random variables, inferences regarding the N rate of spring maize can be extended to following years and to other similar regions of Jilin province. Unless otherwise specified, mean values of the above variables for each N treatment were compared using least significant difference at the 0.05 level. Mean values for untransformed data were reported. Yield response to N rate in each site-year was determined using Q, QP, or LP models including all individual plots values using PROC NLIN in SAS (version 9.0, SAS Institute, Cary, NC). The best fitted model for the data according to determined coefficient (R^2) and residual sum of squares was chosen for calculation of the response curve, optimum N rate, and grain yield at optimum N (Bélanger et al., 2000; Nyiraneza et al., 2010; Wang et al., 2012).

RESULTS AND DISCUSSION

At the three sites from 2008 to 2010 (Table 2), grain yield ranged from 4.3 to 11.0 Mg ha^{-1} with the lowest grain yields occurring in the unfertilized control treatments. Grain yields was maximized at an N rate of 140 kg N ha^{-1} in 6 of 9 site-years, and the other 3 site-years was maximized at an N rate of 0 (Taojia in 2008), 70 (Yushu in 2010) and 210 kg N ha^{-1} (Liufangzi in 2008), respectively (Table 2). Similarly, aboveground biomass ranged from 12.8 to 21.5 Mg ha^{-1} with lowest biomass yields associated with the control treatments (Table 2). The maximal aboveground biomasses were achieved under 70 to 140 kg N ha^{-1} in Liufangzi and Yushu depending on years (Table 2). However, aboveground biomass responses to fertilizer N levels differed greatly with years in Taojia. For example, no statistical differences were found among fertilizer N treatments on the aboveground biomass in 2008, but the maximal aboveground biomasses were under 210 and 140 kg N ha^{-1} in 2009 and 2010, respectively (Table 2). On the whole, increasing N applications beyond the optimal rates will lead to only small increases or even decreases in grain yield and aboveground biomass, increasing energy use and cost of production as well as the risk of negative environmental effects, such as nitrate leaching, soil acidification, and greenhouse gas emission (Ju et al., 2009; Guo et al., 2010; Ciampitti et al., 2013).

Table 2. Grain yield, aboveground biomass and harvest index at five N rates (0, 70 140, 210, 280 kg N ha^{-1}) at three sites (Liufangzi, Taojia, Yushu) in Jilin province, Northeast China from 2008 to 2010.

	Grain yield			Aboveground biomass			Harvest index		
Treatment†	2008	2009	2010	2008	2009	2010	2008	2009	2010
	Mg ha^{-1}								
				Liufangzi(n = 3)					
N0	9.5‡c§	5.8b	8.2c	17.1b	13.8b	15.8d	0.55a	0.42a	0.52c
N70	10.2b	6.3b	9.6b	20.8a	14.5b	17.5c	0.49a	0.43a	0.55ab
N140	10.0bc	6.9a	10.4ab	19.4a	17.0a	19.5ab	0.51a	0.41a	0.53bc
N210	11.0a	6.3ab	10.7a	20.0a	15.0b	20.0a	0.55a	0.42a	0.53bc
N280	10.3b	6.4ab	10.7a	19.1ab	14.9b	19.1b	0.54a	0.43a	0.56a
				Taojia(n = 3)					
N0	8.6a	4.3c	8.3c	15.7a	12.8c	16.0c	0.55a	0.34b	0.52ab
N70	8.6a	6.0b	9.2b	15.7a	15.4b	17.9b	0.55a	0.39a	0.51ab
N140	9.5a	6.4ab	9.6ab	17.2a	15.6b	19.0a	0.56a	0.41a	0.51ab
N210	9.0a	6.9a	9.7ab	17.6a	17.4a	18.8ab	0.51a	0.40a	0.51b
N280	9.4a	6.7a	9.9a	17.3a	16.3b	18.5ab	0.54a	0.41a	0.54a
				Yushu(n = 3)					
N0	7.0d	6.0c	7.8b	15.6d	15.3c	14.4b	0.45ab	0.39a	0.54ab
N70	7.3cd	7.4b	9.5a	16.8c	18.5b	17.3a	0.43b	0.40a	0.55ab
N140	9.2a	8.6a	9.7a	19.5a	20.8a	17.9a	0.47a	0.41a	0.54ab
N210	8.6ab	8.6a	10.2a	18.2b	21.5a	18.1a	0.47a	0.40a	0.56ab
N280	8.0bc	8.3a	9.1a	17.1c	20.4a	17.3a	0.47a	0.41a	0.52b

† Nx: N presents nitrogen, number “x” presents applied N rate.

‡ Value is mean of three replications.

§ Means followed by the same letter within a column at each site do not differ at $P < 0.05$.

At each N rate (Table 2), grain yield at Liufangzi and Taojia sites in 2009 was obviously lower than in the other 2 yr due to drought conditions, with a similar trend occurring in both aboveground biomass. Compared to yields obtained with the more normal precipitation of 2008 and 2010, grain yield at each N rate decreased more under the dry conditions of 2009 at Liufangzi and Taojia than at Yushu (Table 2). The Yushu soil has a deeper A horizon with slightly higher organic matter content than the Liufangzi and Taojia soils, which might increase its moisture-holding capacity (Dharmakeerthi et al., 2005). Timing of rainfall may have also played a role in the impact of drought stress, as rainfall in June of 2009 at Yushu was higher than at Gongzhuling (Fig. 1c–1d).

Nitrogen rate did not significantly affect HI at the Liufangzi and Taojia sites in 2008 or at Liufangzi and Yushu sites in 2009 (Table 2). The maximum value of HI in the study was 0.56 at Liufangzi and Yushu in 2010 and at Taojia in 2008, while the minimum value was 0.34 at Taojia in the N0 treatment in 2008. Moreover, HI at each N rate at the three sites in 2009 was obviously lower than in the other 2 yr. Damage from drought stress can occur through a restriction in sink size due to abortion of the kernels during the flowering stage (Earl and Davis, 2003; Roth et al., 2013). The reduced sink would lead to a decrease in HI. Earl and Davis (2003) also reported that lack of rainfall reduced HI and maize dry matter accumulation, as occurred in 2009 in our study (Table 2). Westgate (1994) reported that water stress during the grain-filling stage constrained kernel growth because of low available new photosynthate and therefore decreased HI.

Quadratic, QP or LP models were used to determine optimum N rate at each site-year based on the measured response of yield to N rate (Fig. 2). The optimum N rate ranged from 167 to 210 kg ha^{-1} at the Liufangzi site (Fig. 2a–2c), 140 to 196 kg ha^{-1} at the Taojia site (Fig. 2d–2f), and 162 to 194 kg ha^{-1} at the Yushu site (Fig. 2g–2i). Therefore, the range of optimum N rate predicted by the models fell in 140 to 210 kg ha^{-1} in three sites from 2008 to 2010 (Fig. 2). Correspondingly, the simulated yield (Fig. 2) at the predicted optimum N rate was only 0.1 to 0.4 kg ha^{-1} less than the actual maximum yield in each site-year (Table 2).

In the present study, the narrowed range of predicted optimum N rate between the lower and upper limits occurred because of the different models selected at each site-year. A wide range of predicted optimum N rates was reported by Nyiraneza et al. (2010) using quadratic plus plateau model, being 73 to 235 kg N ha^{-1} in 2007 and 48 to 200 kg N ha^{-1} in 2008. Derby et al. (2005) showed that a static yield response model for N recommendation did not well reflect the interannual variability induced by the adverse weather condition, resulting in overfertilization for the low attainable

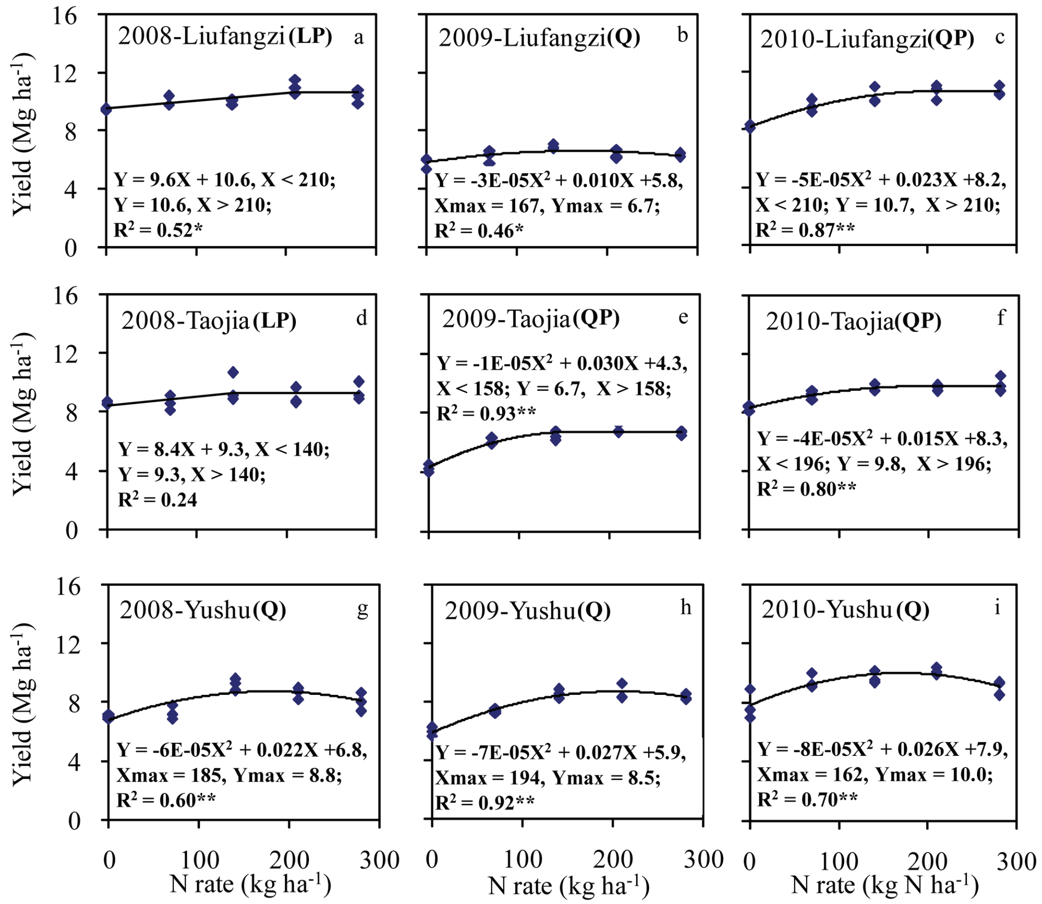

Fig. 2. Grain yield as a function of N fertilizer rate at three sites (Liufangzi, Taojia, Yushu) in Jilin province, Northeast China from 2008 to 2010. Predicted optimum N rate (kg ha^{-1}) and yield at optimum N rate were calculated using quadratic (Q), quadratic plus plateau (QP), or linear plus plateau (LP) models based on individual plot yield (Mg ha^{-1}) The best fitted model was selected based on the *R*^{2} value and residual sum of square from models above. * Denotes the significant difference at $P < 0.05$, ** Denotes the significant difference at $P < 0.01$. Letter in parentheses presents the predicted model.

yields in the adverse years. In 4 of 9 site-years in our study, the quadratic model was the best of the three models used in predicting the optimum N rate, based on its having the highest R^2 value and lowest residual sum of squares (data not shown), although the quadratic plus plateau or linear plus plateau models better described the yield response to N rate than did quadratic model (Alivelu et al., 2006; Chen et al., 2010; Nyiraneza et al., 2010; Wang et al., 2012). Bélanger et al. (2000) also reported that the quadratic model best predicted the potato (*Solanum turberosum* L.) yield response to N rate.

At the three sites from 2008 to 2010 (Table 3), the grain N concentration ranged from 7.3 to 13.3 g kg^{-1} and stover N concentration ranged from 3.4 to 9.2 g kg^{-1}. Grain N is derived from N that is remobilized from the N accumulated in the plant during the vegetative phase as well as N that is taken up during the reproductive phase. Nitrogen accumulation in the grain can be maintained by N mobilization from the older leaves and stems even when canopy photosynthesis is reduced by moisture stress (Ciampitti and Vyn, 2013). The remobilization of N may account for the larger variation in stover N concentration relative to that of grain N concentration and also for the difference in grain N concentration among the three sites in 2009 in our study (Table 3).

Aboveground N uptake ranged from 60.4 to 203.7 kg ha^{-1} at the three sites from 2008 to 2010 (Table 3). Aboveground N uptake was maximized at an N rate of 70 kg N ha^{-1} in 3 of 9 site-years, at 140 kg N ha^{-1} in 5 site-years, and at 210 kg N ha^{-1} in 1 site-year (Table 3). At each N rate, aboveground N uptake in 2009 at the Liufangzi and Taojia sites (Table 3) was lower than in the other 2 yr due to the lower aboveground biomass and yield (Table 2) caused by the 2009 drought. Aboveground N uptake has been closely linked with grain yield and aboveground biomass (Setiyono et al., 2010; Chuan et al., 2013). Abbasi et al. (2012) also reported that aboveground N uptake increased with N rate primarily due to the increased aboveground biomass. Aboveground N uptake can be divided into grain N and stover N accumulation. Therefore, the factors influencing aboveground N uptake were closely linked to grain yield, aboveground biomass, grain N concentration and stover N concentration. At the vegetative phase of maize in 2009, the month of June at the Yushu site had 30.3 mm greater rainfall (Fig. 1d) and a 1.5°C lower average month temperature (Fig. 1b) comparing to the Gongzhuling (Liufangzi and Taojia) site (Fig. 1c–1d). Correspondingly, soil moisture in the soil profile at Yushu site would increase because of the high precipitation, the high soil organic matter and the low temperature, and further benefiting maize growth during the critical period over the next months. The factors above might be responsible for the highest aboveground N uptake at the rate of 210 kg N ha^{-1} in 2009 at Yushu site.

Most of the grain N concentration (N_g) and aboveground N uptake (U_N) values (Table 3) in the present study were close to the average data in new era maize cultivars of N_g 11.9 g kg^{-1} and U_N 173 kg ha^{-1} reported by Ciampitti and Vyn (2013), respectively; but most of the stover N concentration were close to values of 8.1 g kg^{-1} reported by Setiyono et al. (2010). Differences among the studies were related to genotype (Ciampitti and Vyn, 2013), environment, management, and unbalanced mineral nutrient supply (Setiyono et al., 2010).

Improvements in NUEs can effectively decrease the potential negative impacts of fertilizer N on the environment (Ciampitti and Vyn, 2011; Abbasi et al., 2012). Fertilizer N rate relative to crop yield potential is the primary factor affecting NUEs. It is well accepted that NUEs are high at low N rates and decrease with increasing N rates (Ciampitti and Vyn, 2011). At the three sites from 2008 to 2010 (Table 4), as the N application rate increased RE_N and AE_N generally decreased, PFP_N consistently significantly ($P < 0.05$) decreased, and most

Table 3. Grain N, stover N concentrations and aboveground N uptake at five N rates (0, 70 140, 210, 280 kg N ha^{-1}) at three sites (Liufangzi, Taojia, Yushu) in Jilin province, Northeast China from 2008 to 2010.

Treatment†	Grain N concentration			Stover N concentration			Aboveground N uptake		
	2008	2009	2010	2008	2009	2010	2008	2009	2010
	g kg^{-1}						kg N ha^{-1}		
				Liufangzi (*n* = 3)					
N0	9.2‡a§	10.7b	8.2c	6.3c	4.2c	4.0b	135.3b	96.0c	98.2c
N70	9.2a	11.4b	9.7b	7.5b	5.7bc	5.4b	172.8a	118.2b	136.6b
N140	9.7a	13.2a	12.0a	8.2ab	5.0c	7.0a	174.7a	141.1a	188.6a
N210	9.7a	13.2a	11.9a	9.0a	7.1ab	7.2a	188.2a	145.5a	194.7a
N280	9.9a	13.3a	12.3a	7.7b	8.5a	7.4a	169.0a	156.9a	194.0a
				Taojia (*n* = 3)					
N0	10.3ab	7.4b	8.9b	5.9c	3.4c	5.5c	130.2b	60.4d	115.7c
N70	10.7ab	10.7a	9.3ab	7.8a	3.8bc	7.4ab	147.2ab	100.4c	150.1b
N140	9.5b	11.1a	10.5a	7.7a	4.8ab	8.8a	149.6ab	115.6bc	183.4a
N210	10.2ab	12.0a	10.1ab	7.2a	5.6a	7.0bc	152.8ab	140.7a	161.5ab
N280	10.8a	11.7a	10.5a	7.8a	5.3a	8.7ab	162.8a	129.6ab	178.7a
				Yushu (*n* = 3)					
N0	10.3b	7.3c	8.4b	7.8c	4.6c	5.0b	138.8c	86.3b	97.9b
N70	10.9ab	8.3bc	10.4a	8.4ab	5.5bc	6.8a	159.6bc	123.3b	151.4a
N140	11.9a	10.1ab	10.8a	8.7ab	6.8ab	6.9a	199.8a	169.9a	161.5a
N210	11.9a	10.8a	10.5a	9.2a	8.6a	7.4a	190.1a	203.7a	164.6a
N280	10.6ab	11.0a	11.0a	8.7ab	7.1ab	6.9a	164.0b	177.4a	156.6a

† Nx: N presents nitrogen, number “x” presents applied N rate.

‡ Value is mean of three replications.

§ Means followed by the same letter within a column at each site do not differ at $P < 0.05$.

of IE_N values in each site-year tended to remain stable with N rates between 140 and 280 kg N ha^{-1}. Values for RE_N fell from 76.5 to 9.0%, AE_N from 25.3 to 0.1 kg kg^{-1}, IE_N from 83.8 to 40.8 kg kg^{-1}, and PFP_N from 145.6 to 22.8 kg kg^{-1} with increasing N rate (Table 4). Ciampitti and Vyn (2012) reported that the mean values of RE_N, AE_N, IE_N, and PFP_N for new era hybrid maize were 44%, 22.9, 55.0, and 66.0 kg kg^{-1}, respectively. Comparing our study with the above data, most of the RE_N and all of the AE_N values were low, most of the IE_N were comparable with N applications from 140 to 210 kg ha^{-1} and the PFP_N values had a similar range at a rate of 140 kg ha^{-1} in the normal rainfall years (2008 and 2010).

The low RE_N in the present study may be because: (i) the maximum grain potential of modern cultivar,16.8 Mg ha^{-1} for our studied cultivar (Chen et al., 2011), was not attained because of biotic and abiotic stress, perhaps from moisture stress, low pH values, or unbalanced nutrient supply; (ii) RE_N is calculated by comparing the uptake in the fertilized treatment to the uptake in the unfertilized control treatment, thus high N uptake in the control treatments (Table 3) would lead to low RE_N values. Crop N uptake in the control treatments were higher than values observed between the 1980s and 2000s (Liu et al., 2013). The high N uptake in the control treatments may occur because the modern hybrid cultivars possess greater N stress tolerance and produce more grain yield when N supply is restricted (Ciampitti and Vyn, 2012). Alternatively, grain yield in control treatments in Northeast China may increase due to increased N supply resulting from N release from soil organic matter mineralization (Huang and Sun, 2006), residual available N from previous excessive N applications, and atmospheric N deposition (Ju et al., 2009; Liu et al., 2013). These factors would also contribute to the low AE_N (Table 4) in our study. Variation in environmental conditions and soil fertility (Table 1) can also affect grain yield (Table 2) and AE_N (Table 4). For example, the different depths of the Haplic Phaeozem soil at the three sites and differences in precipitation (Fig. 1c–1d) might be responsible for the higher AE_N values at the Taojia and Yushu sites compared to the Liufangzi site in 2009 (Table 4).

For IE_N, grain N concentration is the primary source of variability, producing 62% of the variation (Ciampitti and Vyn, 2012); the average variation was 57.5% in all site-years in our study (Table 4). Improving PFP_N will depend not only on decreasing the yield gap between yield potential and farmers' actual yields, but also on synchronizing crop N demand and fertilizer N supply by using the right fertilizer source, rate, time, and methods. Chen et al. (2011) reported that the PFP_N reached 57 kg kg^{-1} in North China plain under an integrated soil–crop management system. All three sites of each N rate had lower IE_N and PFP_N in 2009 than in 2008 and 2010 (Table 4) as the result of drought condition. Therefore, there is potential to improve NUEs (e.g., RE_N and AE_N) for sustainable agriculture in China if optimum practices for soil management, agronomy, ecology, and genetics are adopted (Chen et al., 2011; Ciampitti and Vyn, 2012, 2013).

Nitrogen application rate significantly affected variables related to N concentration and accumulation, but did not significantly ($P > 0.05$) affect grain yield, aboveground biomass, HI, and AE_N (Table 5) because of the large variation of soil fertility in the three sites (Table 1) and precipitation in the 3 yr (Fig. 1c–1d) of the study. The significant differences ($P < 0.05$) in grain yield or HI among years (Table 5) further indicated the important effect of precipitation on photosynthesis and carbohydrate transformation from source to sink. di Paolo and Rinaldi (2008) reported that sufficient available soil water led to better uptake and utilization of N in cell metabolic processes and increased crop biomass and yield. All aboveground parameters was significantly ($P < 0.05$

Table 4. N Recovery efficiency (RE_N), nitrogen agronomic efficiency (AE_N), nitrogen internal efficiency (IE_N) and nitrogen partial productivity (PFP_N) at five N rates (0, 70 140, 210, 280 kg N ha^{-1}) at three sites (Liufangzi, Taojia, Yushu) in Jilin province, Northeast China from 2008 to 2010.

	RE_N			AE_N			IE_N			PFP_N		
Treatment†	2008	2009	2010	2008	2009	2010	2008	2009	2010	2008	2009	2010
	%			kg kg^{-1}								
Liufangzi(n = 3)												
N0							70.1a	60.8a	83.8a			
N70	53.6‡a§	31.7a	54.9ab	10.5a	6.4ab	20.1a	59.0b	53.0b	70.7b	145.6a	89.6a	137.5a
N140	28.2b	32.2a	64.6a	3.9ab	7.8a	15.2ab	57.3b	49.2bc	54.9c	71.5b	49.4b	73.9b
N210	25.2b	23.6a	46.0bc	7.4b	2.4b	11.6b	58.7b	43.6cd	54.9c	52.4c	30.2c	50.7c
N280	12.1c	21.7a	34.2c	3.2b	2.0b	8.8b	61.8b	40.8d	55.2c	37.0d	22.8d	38.2d
Taojia(n = 3)												
N0							66.8a	71.1a	72.1a			
N70	24.2a	57.2a	49.1a	0.1a	25.3a	12.9a	58.7a	60.3b	61.8b	123.0a	86.4a	131.4a
N140	13.8a	39.5b	48.4a	6.7a	15.5b	9.5ab	63.9a	56.7bc	52.6c	68.1b	46.0b	68.8b
N210	10.8a	38.3b	21.8b	1.8a	12.5b	6.5bc	58.9a	49.2c	59.9bc	42.8c	32.8c	46.0c
N280	11.6a	24.7b	22.5b	2.7a	8.5b	5.8c	57.4a	51.5bc	55.6bc	33.4c	23.8d	35.4d
Yushu(n = 3)												
N0							50.7a	69.5a	80.1a			
N70	29.8a	52.8a	76.5a	3.5b	20.0a	23.4a	45.7a	60.5ab	62.5b	104.0a	105.2a	135.2a
N140	43.6a	59.7a	45.4b	15.7a	18.5a	13.5ab	46.5a	50.4bc	60.3b	66.0b	61.1b	69.4b
N210	24.4ab	55.9a	31.8bc	7.6ab	12.7ab	11.1ab	45.6a	42.7c	61.7b	41.1c	41.1c	48.3c
N280	9.0b	32.5a	21.0c	3.6b	8.4b	4.5c	49.0a	47.1c	58.0b	28.7d	29.7d	32.4d

† Nx: N presents nitrogen, number "x" presents applied N rate.

‡ Value is mean of three replications.

§ Means followed by the same letter within a column at each site do not differ at $P < 0.05$.

Table 5. Summary of ANOVA for grain yield, aboveground biomass, harvest index, and N related variables for rates (0, 70 140, 210, 280 kg ha^{-1}), sites (Liufangzi, Taojia, Yushu) and years (2008–2010) in Jilin province, Northeast China.

Sources of variation	Grain yield	Aboveground biomass	Harvest index	Grain N concentration	Stover N concentration	Aboveground N uptake	N use efficiencies			
							RE_N†	AE_N	IE_N	PFP_N
N	ns‡	ns	ns	$P < 0.05$	$P < 0.01$	$P < 0.01$	$P < 0.05$	$P > 0.05$	$P < 0.01$	$P < 0.01$
Site (S)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Year (Y)	$P < 0.05$	ns	$P < 0.05$	ns	ns	ns	ns	ns	$P < 0.05$	ns
N×S	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
N×Y	ns	ns	ns	ns	ns	ns	ns	ns	$P < 0.01$	$P < 0.01$
Y×S	$P < 0.01$	$P < 0.01$	$P < 0.01$	$P < 0.01$	$P < 0.01$	$P < 0.01$	ns	$P < 0.01$	$P < 0.01$	$P < 0.01$
N×S×Y	$P < 0.01$	$P < 0.01$	$P < 0.01$	$P < 0.01$	$P < 0.05$	$P < 0.05$	$P < 0.01$	$P < 0.05$	$P < 0.05$	$P < 0.01$

† RE_N: nitrogen recovery efficiency, AE_N: nitrogen agronomic efficiency, IE_N: nitrogen internal efficiency, PFP_N: nitrogen partial productivity.

‡ ns indicates that the effect is not significant at $P < 0.05$.

or $P < 0.01$) affected by the interaction of year and site (Table 5), because soil structure and soil moisture-holding capacity are closely linked with soil organic matter content and quality (Dharmakeerthi et al., 2005) Soil organic matter will further affect crop yield parameters as well as N accessed from the soil through effects on moisture supply, root distribution (Ribaut et al., 2008), microbial activity, organic matter mineralization, or immobilization (Cosentino et al., 2006) and micronutrient availability (Ciampitti et al., 2013). The above interactions among soil quality, available moisture, and N supply could be responsible for the significance ($P < 0.05$ or $P < 0.01$) of the interaction of year, site, and N rate in aboveground parameters (Table 5). Adequate, but not excessive, N supply can promote maize growth in rainfed agroecosystems to optimize maize yield when available moisture is limited (Paolo and Rinaldi, 2008).

Therefore, optimum N rate recommendation should take into account yearly climate and the interactions of climate, site, and N rate. A recommended range of optimum N rate is more feasible than a static N rate because the use of a single recommendation to meet a high target yield would result in overfertilization if yield declined due to adverse conditions. It is important to recognize that the surplus N remaining in the soil because of overfertilization will not leach out of the rooting zone under drought conditions and will remain in the soil to be utilized by the following crop (Qiu et al., 2012), especially in the rainfed agroecosystems of Northeast China. Thus, the recommended N range in the next year can be adjusted by the local extension services using the response curves (Fig. 2) and considering residual soil N, to meet crop N demand, avoid excess N application and improve NUEs (Fig. 2).

CONCLUSION

In the rain-fed maize agroecosystem in Northeast China, the interactions of N rate, soil fertility (site) and available water supply (year) significantly affected maize growth and grain yield ($P < 0.05$), N uptake, and NUEs (Table 5). The maximum maize grain yield of 11.0 Mg ha^{-1} was achieved at the Liufangzi site under normal precipitation in 2008 (Table 2) and the corresponding RE_N, AE_N, IE_N, and PFP_N values were 25.2%, 7.4, 58.7, and 52.4 kg kg^{-1}, respectively (Table 4). Based on regression analysis, the range of optimum N rate for maize production fell into 140 to 210 kg N ha^{-1} at the three sites from 2008 to 2010 in the "golden maize belt" in Northeast China. In our studies, crop yield and NUEs decreased substantially when grown under drought stress. The NUEs in our study was lower than that reported by Ciampitti and Vyn (2012), indicating that the RE_N and AE_N in Northeast China can be further improved by more accurate N management practices and by reducing the gap between yield potential and farmers' actual yield (Chen et al., 2011; Lobell et al., 2009).

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