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Research Article

Evaluation of In-Season Nitrogen Management for Summer Maize in North Central China

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We conducted field experiments in which nitrogen (N) was applied to summer maize at different rates and different basal/topdressing ratios. The experiments were carried out in 2009 in Hengshui and Xinji, Hebei province, China. The results showed that basal application of N was necessary for maize growth in early summer and for high grain yields. For the Hengshui and Xinji sites, 30 and 57 kg N ha^{-1}, respectively, would meet the N demands of maize before 7-leaf stage. The total rates of 120 and 180 kg N ha^{-1}, respectively, would maximize grain yields, and in-season N management based on crop N demands and soil N supply could reduce N inputs by more than 50% in Hengshui and 25% in Xinji, respectively, in one maize growth season, compared with farmers' practice, but the sustainability of the optimum N rates for maximum grain yield of next seasons crop needs to be further studied. Optimum N management should take into account the existing nutrient conditions at each site, soil fertility and texture, and crop demands.

1. Introduction

The North China Plain (NCP) is one of the most important areas for cereal production in China. To meet the high demands for food, excessive amounts of nitrogen (N) fertilizer have been applied in this intensive agricultural region during the last two decades [1–3]. Summer maize (*Zea mays.* L.) is one of the staple grain crops in the NCP, and its planting area and total grain production accounted for 32 and 31% of the China maize crop in 2002 [4].

In the Shandong province, one of the provinces in the NCP, the amount of mineral N fertilizer applied to summer maize ranges from 50 to 600 kg N ha^{-1}, and the average application rate is 240 kg N ha^{-1} [5]. These rates of application exceed the requirements of the crop to achieve maximum grain yield [6]. Overapplication of N fertilizer results in accumulation of N as nitrate-N in the soil, leading to groundwater pollution. Residual soil nitrate-N after winter wheat and summer maize harvest was reported to be 316 and 271 kg N ha^{-1} in the top 100-cm soil profile when N was applied at rates of 300 and 240 kg N ha^{-1}, which are the rates used in normal farmers' practice in this region [7, 8]. In 2001, the groundwater nitrate-N concentration exceeded 45 mg NO_3^- L^{-1} in 49% of samples from this area [9]. High accumulation of soil nitrate-N and excessive rates of N application result in low nitrogen use efficiency (NUE), and the NUE of summer maize crops in this area has decreased from 30–35% in the 1980s to less than 20% in the 2000's [10, 11]. At present, normal farmers' N practice is to apply all N fertilizer only once during the maize growth season, either as basal fertilizer before planting or by topdressing at 7-leaf stage. However, these patterns of N application do not synchronize with crop N demand and the N supply from soil during the maize growing season. Moreover, N losses via volatilization and leaching occur readily because of the high temperatures and high precipitation during the summer maize growth season.

It is essential to develop appropriate N management methods to overcome the environmental problems and low NUE that result from excess N application and to allow sustainable development of agriculture in this region. Such methods should optimize N inputs so that crops can achieve maximum yields and high NUE, while minimizing impacts of N loss on the environment. Previous N management practices based on target yield specified only the total N rate and one ratio of basal to topdressed N at the 6 to 7-leaf stages during the summer maize growing season [12]. However, this strategy was not ideal, because the N fertilizer was applied indiscriminately across all fields and regions and did not take into account the timing and rates of N demands of crops or the soil N supply. In fact, there were wide variations in soil fertility among the different fields and regions [13, 14]. The most logical approach for increasing NUE is to apply basal N and topdressing N at critical growth stages to coincide with crop N demand and soil N supply. The high-yielding maize variety that is currently grown on the NCP shows increased N uptake after anthesis, and the 8- to 10-leaf stages are critical stages for N topdressing [15–17]. However, the current N management practices for summer maize in this region are not tailored to these growth requirements. In this study, we evaluated the effects of different rates of N fertilizer application on growth of summer maize. We applied N at different rates and at different ratios of basal to topdressing at the 10-leaf stage. The aims of this study were (1) to evaluate N in-season management based on grain yield and crop N uptake; (2) to determine the optimum N application rates at different maize growth stages based on plant biomass and grain yield; (3) to provide a theoretical base for reducing N application and enhancing NUE in this highly intensified cropping region.

2. Materials and Methods

2.1. Experimental Sites and Growth Conditions. The field experiments were conducted simultaneously on farms in the region between Hengshui (37.19°N, 115.32°E) and Xinji (37.44°N, 115.22°E), Hebei province, from June to October 2009. The two sites were approximately 25 km apart and had similar climatic conditions. This region has a warm temperate, subhumid continental monsoon climate. The annual mean temperature is 12.6°C and the annual precipitation is 500–600 mm, with approximately 70–80% of the annual precipitation occurring in the summer maize growth season. The temperature and precipitation in the 2009 summer maize growth season are shown in Table 1.

In Hengshui, the soil texture was clay loam, and the chemical properties of tested soil in the 0–20 cm soil profile were as follows: pH 8.4; organic matter 13.4 g kg^{-1}; Olsen-P 8.9 mg kg^{-1}; NH_4OAc-K 103 mg kg^{-1}. Before planting, the NH_4^+-N content in the 0–20, 20–40, 40–60, 60–80, and 80–100 cm soil layers was 3.1, 0.9, 2.5, 13.2, and 10.0 mg kg^{-1}, respectively, and NO_3^--N content was 12.2, 11.6, 12.7, 7.2, and 6.3 mg kg^{-1}, respectively. In Xinji, the soil texture was sandy loam, and the chemical properties in the 0–20 cm soil profile were as follows: pH 8.6; organic matter 8.2 g kg^{-1}; Olsen-P 6.2 mg kg^{-1}; NH_4OAc-K 97 mg kg^{-1}. Before planting, the NH_4^+-N content in the 0–20, 20–40, 40–60, 60–80, and 80–100 cm soil layers was 1.2, 1.2, 1.1, 1.0, and 0.8 mg kg^{-1}, respectively, and NO_3^--N content was 14.8, 11.9, 10.4, 7.8, and 6.1 mg kg^{-1}, respectively. The previous crop was winter wheat.

2.2. Experimental Design. The experiment consisted of seven N treatments that varied in the amount and/or ratio of basal to topdressed N (Table 2) and a no-N control. The N240 (0/240) treatment was designed to simulate the N application pattern commonly used by farmers. The treatments were arranged in a randomized complete block design with three replications. The plot size was 5 m × 8 m, and with a row spacing of 55 cm. Urea was used as the N source, and basal N was applied by broadcasting before planting with 600 m^3 ha^{-1} irrigation water, and topdressing N was applied using the same approach at the V10 (10-leaf) stage. Before planting, all plots received 90 kg P_2O_5 ha^{-1} in the form of superphosphate and 90 kg K_2O ha^{-1} in the form of potassium chloride. No organic manure was applied at the two experimental sites, but all winter wheat residue were left on the fields. The maize variety was Zhengdan 958, which is one of the most popular hybrid variety grown in North Central China at present. Maize was sown on 13 June and harvested on 3 October. These fields were managed by farmers, who used normal farm practices except for N fertilizer treatments.

2.3. Sampling and Soil Analyses. Eight soil samples were taken from each field before planting, and five to eight soil samples were taken from each plot after maize harvest from a depth of 0–100 cm in 20-cm increments. Soil samples of the same soil layer from each plot were mixed before analyses. Soil samples were then transported in an icebox from the field to the laboratory and then immediately extracted in 0.01 mol L^{-1} $CaCl_2$ (1 : 10 soil: liquid w/v) and analyzed for NO_3^--N and NH_4^+-N using Continuous Flow Analysis (FIAstar 5000, Foss, Sweden). Soil water concentration was measured by oven drying at 105°C. Soil NO_3^--N and NH_4^+-N concentration (kg N ha^{-1}) was calculated for 0–20, 20–40, 40–60, 60–80, and 80–100 cm soil layers using average bulk density values of 1.35, 1.40, 1.35, 1.36, and 1.35 g cm^{-3}, respectively, for Hengshui, and 1.40, 1.42, 1.38, 1.35, and 1.35 g cm^{-3}, respectively, for Xinji.

Five plants per plot were sampled at the V4 (4-leaf stage), V7 (7-leaf stage), R1.5 (silking), and R3 (milking) stages [18]. The plants were oven-dried at 60°C until constant weight to calculate biomass. At harvest, maize plants were harvested from an area of 7.5 m^2 (3 or 4 rows, each 5 m in length) in the middle of each plot to determine grain and stover yield. Five subsamples were randomly selected from the harvested plants, and stover, cob, and grain were separated, oven-dried at 60°C, and weighed. Subsamples of grain and stover were analyzed for N content by the Kjeldahl method.

2.4. Calculations and Data Analyses. Harvest index (HI), and N harvest index (HI_N) were calculated using (1), (2) using values for grain yield, total plant aboveground biomass, total

Table 1: Weather conditions during summer maize growth season at field sites in 2009.

Sites	Index	June	July	August	September	October	Annual
Hengshui	Tmax (°C)[†]	37.3	37.5	36.8	29.9	26.7	37.5
	Tmin (°C)[‡]	17.5	19.4	20.3	9.6	5.1	−13.6
	Precipitation (mm)	93.0	123.7	237.0	136.8	21.0	786.4
Xinji	Tmax (°C)	38.4	36.8	33.9	27.4	24.7	38.4
	Tmin (°C)	15.9	15.8	13.2	7.5	4.6	−14.3
	Precipitation (mm)	70.5	155.5	304.0	152.0	34.0	821.7

[†] Tmax: maximum temperature. [‡] Tmin: minimum temperature.

Table 2: Experimental design for N treatments at field sites for summer maize in 2009.

Treatments	Total N rate ($kg\,ha^{-1}$)	Basal N rate before planting (June 12) ($kg\,ha^{-1}$)	Topdressing N rate ($kg\,ha^{-1}$)	Date of N topdressing
N0	0	0	0	June 25
N120 (0/120)	120	0	120	June 25
N120 (30/90)	120	30	90	June 25
N120 (60/60)	120	60	60	June 25
N180 (0/180)	180	0	180	June 25
N180 (45/135)	180	45	135	June 25
N180 (90/90)	180	90	90	June 25
N240 (0/240)	240	0	240	July 17

N in grain, and total N in aboveground plant biomass at maturity [19].

$$\text{Harvest index} = \frac{\text{Grain yield}}{\text{aboveground biomass}} \times 100, \quad (1)$$

$$\text{N harvest index} = \frac{\text{Total N in grain}}{\text{total N in aboveground plant biomass}} \times 100. \quad (2)$$

Apparent N mineralization rate during the maize growth season was calculated as the difference between N output (plant N uptake plus residual soil Nmin (soil mineral N, $NO_3{}^{-}$-N + $NH_4{}^{+}$-N) after harvest in the 0–100 cm soil layer) and the soil Nmin at planting in the 0–100 cm soil layer in the no-N control plot [20]:

$$\text{N mineralization} = (\text{soil Nmin at harvest} + \text{crop N uptake}) - \text{soil Nmin at planting}. \quad (3)$$

Recovery N efficiency (RE_N) and agronomic N efficiency (AE_N) were calculated using (4), (5). The RE_N is the efficiency of N recovery from applied N, and AE_N is the yield increase per unit of N applied:

$$\text{Recovery N efficiency } (RE_N) = \frac{(U_N - U_0)}{N} \times 100, \quad (4)$$

$$\text{Agronomic N efficiency } (AE_N) = \frac{(Y_N - Y_0)}{N}, \quad (5)$$

where U_N and U_0 are crop N uptake ($kg\,N\,ha^{-1}$) in applied N plots and no-N plots, respectively, Y_N and Y_0 are grain yield ($kg\,ha^{-1}$) in applied N plots and no-N plots, respectively, and N is application rate of N fertilizer ($kg\,N\,ha^{-1}$) [2]. For maize biomass at the 7-leaf stage, the "linear plus plateau" model described by Cerrato and Blackmer [21] was the best fit for data from both sites.

Data were analyzed by ANOVA using SPSS 13.0 for Windows (SPSS, Inc., Chicago, ILL, USA). Mean values of treatments were compared using least significant difference (LSD) at the 0.05 level of probability.

3. Results

3.1. Effects of Different N Treatments on Maize Growth. At the V4 and V7 stages, application of N as basal fertilizer significantly affected maize growth (Table 3). In Hengshui, maize biomass was significantly higher in treatments that received basal N than in those that did not. Maize biomass increased with increasing basal N rate, but there were no significant differences among different N treatments when the basal rate exceeded 30 $kg\,N\,ha^{-1}$. In Xinji, maize biomass also showed an increasing trend with increasing basal N rate, but it did not increase significantly compared with treatments without basal N until N rates exceeded 45 kg $N\,ha^{-1}$.

From R1.5 to maturity, maize biomass increased with maize growth. In Hengshui, the differences in plant biomass between treatments with and without basal N decreased gradually after N topdressing at V10 stage, and there were no significant differences among all N treatments at maturity. The same trend for maize biomass was observed in Xinji. The

Table 3: Effects of different N treatments on maize biomass in summer growth season ($kg\,ha^{-1}$).

Sites	Treatments	V4†	V7†	R1.5†	R3†	Maturity
Hengshui	N0	48.4b‡	2646.2b	7675.5b	10034.4b	14465.1b
	N120 (0/120)	50.5b	2652.2b	7984.5b	11985.3b	16296.5ab
	N120 (30/90)	65.7a	3186.4a	8925.0a	12580.0ab	17187.7a
	N120 (60/60)	67.6a	3196.1a	8976.4a	13940.3a	18864.5a
	N180 (0/180)	52.3b	2822.0ab	7854.6b	12444.5ab	17052.2ab
	N180 (45/135)	68.3a	3240.6a	9367.0a	13940.0a	16681.6ab
	N180 (90/90)	71.5a	3264.0a	9673.2a	12971.4ab	17603.7a
	N240 (0/240)	48.9b	2652.3b	7995.0b	14042.0a	18514.3a
Xinji	N0	58.7c	1086.5c	3645.6d	6856.7d	10680.0c
	N120 (0/120)	58.2c	1141.7c	5338.0bc	8440.2c	12592.5b
	N120 (30/90)	72.3b	1396.9b	5551.8b	8772.3bc	13779.9ab
	N120 (60/60)	79.8ab	1707.6a	6227.8a	9648.1ab	13161.8b
	N180 (0/180)	59.5c	1179.2c	4645.7c	8942.3bc	12825.4b
	N180 (45/135)	80.3ab	1616.9a	4882.2c	8956.4bc	13791.8ab
	N180 (90/90)	88.6a	1664.9a	5953.2ab	9909.5a	13825.9ab
	N240 (0/240)	65.4c	1291.4b	4677.9c	9163.3ab	14490.0a

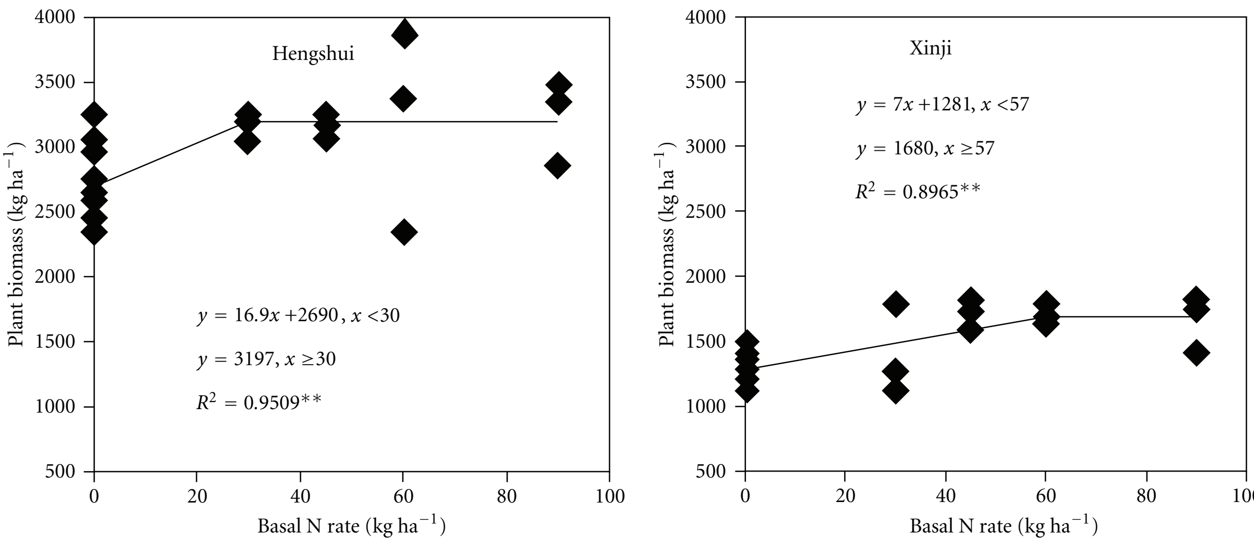
† V4: 4-leaf stage; V7: 7-leaf stage; V10: 10-leaf stage; R1.5: Silking; R3: Milking. ‡Within each column, means followed by different letters are significantly different ($P < 0.05$).

differences in plant biomass between N treatments with and without basal N also decreased gradually after N topdressing at V10 stage, and there were almost no significant differences in biomass at maturity except that the biomass of N240 (0/240) treatment was significantly higher than treatments without basal N fertilizer. Thus, although basal N influenced maize biomass at the vegetative stage, it did not affect significantly final biomass. In addition, after V7 stage, the biomass of maize grown in Hengshui was higher than that of maize grown in Xinji when comparing plants receiving the same rates of N application.

At the V7 stage, maize biomass responses to basal N rates fitted the "linear plus plateau" model. The model predicted that the optimal basal N rates were 30 and 57 $kg\ N\,ha^{-1}$ in Hengshui and Xinji, respectively, when maize biomass reached the plateau phase (Figure 1).

3.2. Grain Yield, Crop N Uptake, NUE, HI, and HI_N. Treatments that received basal N showed increased grain yield and NUE (Table 4) compared with the no-N control and N-topdressing only treatments. In Hengshui, there were no significant differences in grain yield among all N treatments and the application of N at rate of 120 $kg\,ha^{-1}$ achieved the maximum grain yield, but basal application of N promoted crop N uptake and then enhanced N use efficiency parameters of RE_N and AE_N. However, there were no significant differences in HI and HI_N except that the HI of the N240 (0/240) treatment was significantly lower than those of treatments that received N as basal fertilizer. In Xinji, all treatments that received basal N showed significantly higher grain yields than that of the no-N treatment, and the application of N at rate of 180 $kg\,ha^{-1}$ achieved the maximum grain yield. When N was applied as topdressing only; however, there were no significant differences in grain yield among N0, N120 (0/120), and N180 (0/180) treatments. Crop N uptake, RE_N, and AE_N showed similar trends to those observed in Hengshui. Treatments that received basal N showed higher HI values than that of the no-N control, but there were no significant differences in HI_N except for the low HI_N value of the N240 (0/240) treatment. At both sites, RE_N and AE_N decreased with increasing total N application, and for the treatments that received the same amount of total N, these values showed an increase with increasing basal N rates. Maize grown in Hengshui showed higher grain yield, crop N uptake, and NUE than those of maize grown in Xinji. However, the HI and HI_N values were lower for maize grown in Hengshui.

3.3. N Balance of Different N Treatments during Maize Growing Season. The initial Nmin, apparent N mineralization, and crop N uptake in Hengshui were higher than those in Xinji, which indicated that indigenous N supply in Hengshui was higher than that in Xinji (Table 5). Compared with treatments that only receiving topdressing N applications at V10 stage, those that received N as basal and topdressing fertilizer showed reduced residual Nmin after maturity. This pattern was observed at both sites and resulted from increased N uptake by the maize plants in these treatments. In Hengshui, the soil residual Nmin was higher in the N240 (0/240) treatment than in the N120 (0/120) treatments. In Xinji, however, there were no significant differences among the three N treatments that did not receive N as basal fertilizer. At both sites, the apparent N losses during the maize growing season increased with increasing total N applications. For treatments receiving the same amount of total N, the apparent N loss increased with increasing topdressing N rates, and these values were significantly higher in Xinji than in Hengshui.



(a) (b)

Figure 1: Maize biomass at V7 stage as a function of increasing basal N rate ($P < 0.01$).

Table 4: Maize grain yield, crop N uptake, nitrogen use efficiency (RE_N and AE_N), HI, and HI_N of different N treatments.

Sites	Treatments	Grain yield (kg ha^{-1})	Crop N uptake (kg N ha^{-1})	RE_N (kg kg^{-1})	AE_N (kg kg^{-1})	HI (%)	HI_N (%)
Hengshui	N0	7384.0b[†]	178.8c	—	—	54.5a	60.2a
	N120 (0/120)	7877.3ab	207.1b	23.6d	4.1b	54.2a	59.9a
	N120 (30/90)	8181.3a	230.6ab	43.2b	6.6a	54.8a	60.7a
	N120 (60/60)	8231.1a	246.7a	56.6a	7.1a	54.5a	60.6a
	N180 (0/180)	8037.3ab	212.3b	18.6d	3.6bc	53.3ab	60.5a
	N180 (45/135)	8088.0ab	217.4b	21.5d	3.9b	54.7a	62.9a
	N180 (90/90)	8181.3a	239.1a	33.5c	4.4b	52.3ab	60.6a
	N240 (0/240)	8073.8ab	239.5a	25.3d	2.9c	50.1b	57.1a
Xinji	N0	6157.8c	103.2d	—	—	57.6a	70.1a
	N120 (0/120)	6298.6c	124.1c	17.5e	1.2d	51.7b	63.9ab
	N120 (30/90)	6907.5b	153.4a	41.9a	6.2ab	55.8a	67.3ab
	N120 (60/60)	6769.2b	146.8ab	36.3b	5.1b	55.8a	65.2ab
	N180 (0/180)	6677.2bc	137.3b	19.0e	2.9c	51.3b	64.0b
	N180 (45/135)	7228.3ab	150.7ab	26.2c	5.9b	56.2a	68.8ab
	N180 (90/90)	7434.5a	154.1a	28.3c	7.2a	56.6a	67.4ab
	N240 (0/240)	6911.9b	155.4a	21.8d	3.1c	50.2b	62.4b

[†] Within each column, mean values followed by different letters are significantly different ($P < 0.05$).

4. Discussion

Intensive fertilizer management and continuous cultivation of winter wheat and summer maize lead to imbalances and overfertilization in this rotation system. These imbalances mean that nutrient supply is not synchronized with the nutrient needs of the crops, resulting in lower nutrient-use efficiencies and increased risks to the environment in the North Central China. In this study, we compared growth of maize among treatments receiving various amounts and ratios of basal/topdressed N fertilizer. Compared with the no-N control and topdressing-only treatments, treatments that received basal N showed increased maize biomass at the V4 and V7 stages, but the final biomass at maturity almost did not differ significantly among different N treatments (Table 3). These results indicate that N applied as basal was required for maize normal growth at early growth stages in two sites, and the adequate rates of N applied as topdressing at the V10 stage can eliminate the effects of N deficiency on maize growth at early growth stages [15]. In Xinji, the grain yields showed significant differences across all N treatments (Table 4). Treatments that received basal N showed significantly higher harvest index (HI) values than those of other treatments and the no-N control.

Table 5: N balance sheet of different N treatments during maize growth season (all data are kg N ha^{-1}).

Site	Treatment	N input			N output		Apparent N loss
		N rate (1)	Initial Nmin† (2)	Apparent N mineralization‡ (3)	Crop N uptake (4)	Residual Nmin§ (5)	(1) + (2) + (3) − (4) − (5)
Hengshui	N0	0	217.4	107.8	178.8c¶	146.4d	0
	N120 (0/120)	120	217.4	107.8	207.1b	242.0b	−3.9d
	N120 (30/90)	120	217.4	107.8	230.6ab	237.0b	−22.4e
	N120 (60/60)	120	217.4	107.8	246.7a	218.5c	−20e
	N180(0/180)	180	217.4	107.8	212.3b	257.3ab	35.6b
	N180 (45/135)	180	217.4	107.8	217.4b	255.6ab	32.4b
	N180(90/90)	180	217.4	107.8	239.1ab	246.8b	19.3c
	N240 (0/240)	240	217.4	107.8	239.5ab	271.9a	53.8a
Xinji	N0	0	156.6	60.6	103.2c	114.0d	0
	N120 (0/120)	120	156.6	60.6	124.1b	154.9ab	51.2c
	N120 (30/90)	120	156.6	60.6	153.4a	131.1c	45.7c
	N120 (60/60)	120	156.6	60.6	146.8ab	138.5c	44.9c
	N180 (0/180)	180	156.6	60.6	137.3b	156.1ab	96.8b
	N180 (45/135)	180	156.6	60.6	150.7ab	149.0bc	95.5b
	N180 (90/90)	180	156.6	60.6	154.1a	142.7bc	93.4b
	N240 (0/240)	240	156.6	60.6	155.4a	164.9a	129.9a

† Initial Nmin: soil mineral N in 0–100 cm soil layer before planting. ‡ Apparent N mineralization during growing season was calculated by (3). § Residual Nmin: soil mineral N in 0–100 cm soil layer after harvest. ¶ Within each column, means followed by different letters are significantly different ($P < 0.05$).

However, there were no significant differences in N harvest index (HI_N) among the different N treatments. Binder et al. [15] showed that N deficiency at an early growth stage decreased maize grain yield, even when N was applied as topdressing at mid- or later growth stages. This was because the carbohydrate synthesized at an early growth stage was insufficient for crop growth, and most of the carbohydrate synthesized after application of topdressed N was diverted to regeneration of source tissues (stalk, leaf, and root) rather than being translocated to the sink tissues (grain). That is, the competition between source and sink tissues affected the translocation of photosynthates from vegetative parts to grain at the grain-filling stage [22]. These patterns of resource allocation explain why the HI of treatments that did not receive basal N was lower than those of treatments that received both basal and topdressed N. Because of the higher indigenous N supply in Hengshui, the N deficiency was not severe enough to limit photosynthate translocation from source to sink, and therefore, the different N treatments had little effect on HI and HI_N. In Hengshui, the maximum yield response to N was less than 1 t ha^{-1} while that in Xinji was more than 1 t ha^{-1}. These results demonstrated that the lower yield response of maize grown in Hengshui resulted from the higher indigenous N supply in that area, whereas maize grown in the lower indigenous N supply soils in Xinji showed lower yields.

In Hengshui, the basal N of 30 kg ha^{-1} meets the N demands of maize growth before 7-leaf stage (Figure 1, Table 3), and 120 kg ha^{-1} total N was sufficient to meet the demands for the entire growing season to achieve high grain yield (Tables 3 and 4). But on the other hand, the differences were not significant among three different treatments with the same total N rate of 120 kg ha^{-1} and between N0 and N120 (0/120) treatments, that is, the further lower N rates than 120 kg ha^{-1} may be be sufficient to meet the demands for the entire growing season to achieve high grain yield, and the optimum N rates could not be achieved solidly due to less N levels that were designed in this experiment. In Xinji, the maize biomass and grain yield were not affected by the rate of N application until the basal N application exceeded 45 kg ha^{-1} the topdressing N at 10-leaf stage exceeded 90–135 kg ha^{-1}, and the application of N at rate of 180 kg ha^{-1} achieved the maximum grain yield (Tables 3 and 4). The values of 45 kg N ha^{-1} were similar to the predicted for basal N (57 kg ha^{-1}) from the "linear plus plateau" model (Figure 1). That is, basal N of 57 kg ha^{-1} and topdressing N of 123 kg ha^{-1} at 10-leaf stage would meet the N demands of maize growth for the entire season and would achieve high grain yield. These results were consistent with different indigenous N supply at the two sites (Table 5) and are consistent with values reported elsewhere [1, 23]. Cui et al. [23] reported that the grain yield was unlikely to respond to added N if soil nitrate-N exceeded 180 kg ha^{-1} in the top 90 cm soil layer before planting on the NCP. Similarly, Binford et al. [24] and Sims et al. [25] showed that grain yield was unlikely to respond to added N if soil nitrate-N exceeded 20–30 mg kg^{-1} in the top 30 cm soil layer when plants were 10 to 30 cm tall. The levels of nitrate-N in the top 20 and 40 cm soil layers at the two sites were lower than these values (see Section 2). This explains why the additional N supply increased plant biomass and grain yield in this study.

Compared with treatments receiving topdressing N only, those receiving split-applied N showed increased grain yield (especially in Xinji), crop N uptake, and RE_N and decreased residual Nmin after harvest and apparent N loss (Tables 4 and 5). This result indicated that split N application synchronized fertilizer application with crop N demand and N supply from the soil during the crop growing season [26, 27]. Normal farmers' practice is to apply 240 kg N ha^{-1} to summer maize in this area. According to these results above, these N rates could be reduced by more than 50% in Hengshui and 25% in Xinji in one summer maize growth season. Decreasing the rates of N fertilizer and increasing NUE by synchronizing N supply from soil and fertilizer with N demand of crop is an important objective at current agricultural production; however, the sustainable development of agricultural production also should be considered for higher grain yield to meet the demand of increasing population, whether these N rates (120 kg N ha^{-1} in Hengshui and 180 kg N ha^{-1} in Xinji) will limit high grain yield of wheat or maize next season? and how many N fertilizers should be added to sustain higher grain yield as occurred in this experiment next year? these all need be further studied.

Previous studies have shown that little N is absorbed before 6-leaf stage [28]. In maize, N uptake increases rapidly during the middle vegetative growth period, and the maximum rate of N uptake occurs around the silking stage. Application of N as sidedressing at the peak stage of N uptake could increase maize yield and NUE more than when it was applied only as basal fertilizer before planting. This is because application of N as sidedressing results in lower gaseous N losses and lower nitrate-N leaching than when it is applied as basal fertilizer, and it was a more effective practice on coarse-textured soils [4, 15, 28, 29]. At both the sites in this study, the grain yield, crop N uptake, RE_N, and AE_N were increased, and apparent N loss decreased with increasing rates of basal N (Tables 4 and 5). This appears to contradict results of previous studies. However, for maize grown on fine-textured soils, application of all the N fertilizer at the preplanting stage can result in similar yields as split applications of N [30–32]. There are two possible explanations for our result; basal N may be necessary for early maize growth because of low soil indigenous N supply (Nmin), or heavy precipitation after the R1.5 stage may have resulted in increased N loss (Table 1). In general, higher nutrient use efficiency is achieved more easily in low fertility soils [33]. However, when we compare treatments with the same rates of N application between the two sites, maize in Xinji showed lower crop N uptake, RE_N, AE_N, and soil residual Nmin after harvest, but greater apparent N loss than that grown at the Hengshui site. The main reason for these differences was the different soils at the two sites. The sandy loam in Xinji had a lower capacity to immobilize and conserve mineral nutrients. This results in nutrient loss by leaching into deeper soil layers under heavy precipitation or irrigation conditions [34–36].

The "linear-plus-plateau" model predicted the optimum rate of basal N required to achieve the maximum plant biomass at critical growth stages. For the Hengshui site, the amounts of total N applied in this study might be significantly higher than the optimum N rate. The basal N rates and topdressing N rates were also not consist with the N rates from "linear plus plateau" model in Xinji site. This suggests that the constant amount and pattern of N application is difficult to synchronize with crop N demand and N supply from soil during the maize growing season. For optimum N management, the rates of basal and topdressing N should be determined based on soil N supply and crop N demand at different growing stages [7, 17, 37]. The effects of N fertilizer differ among different fields or regions because of the spatial variability of soils fertility and soil textures, and these different effects were evident as the different rates of crop N uptake, RE_N, residual Nmin after harvest, and apparent N losses in this study. These results indicated that the soil indigenous N supply and soil texture are important factors in determining optimum rates of N application. Thus, variations in soil nutrient status among fields and regions should be taken into account to optimize N management. Although the study was conducted only in two different sites for one year, these results were reliable; they demonstrated that the synchronizing soil N supply and N fertilizer with crop N demand could decrease the rates of N fertilizer and increase NUE, and optimizing N management should consider greater spatial variability of soil indigenous N supply and soil textures among different fields and regions; furthermore, more precise and more comprehensive conclusions will be gained if these studies are conducted in more regions and for more years.

5. Conclusions

Because of the limited understanding of the relationship between crop N demand and soil N supply, most farmers on the NCP apply a large amount of N (average, 240 kg N ha^{-1}) only once before planting or at V7 stage for summer maize production. This results in low NUE and has significant environmental impacts in this area. In this study, basal application of N did not affect final biomass or grain yield in Hengshui, because soil at this site had high initial Nmin and indigenous N supply. In Xinji, the highest grain yield was achieved via application of N as basal and topdressed fertilizer. Basal applications of N were necessary for early summer maize growth and high grain yield. In Hengshui and Xinji, 30 and 57 kg N ha^{-1}, respectively, could meet the N demands of maize growth before V7 stage, and 120 and 180 kg N ha^{-1}, respectively, could meet the N demands of maize growth during the entire growth season for maximum grain yield. Common farmers' N practice in this area is to apply fertilizer N at a rate of 240 kg N ha^{-1} as topdressing fertilizer at V7 stage. The optimal N application rates for maximum grain yield indicated that N fertilizer could be reduced by more than 50% and 25% in one summer maize growth season in Hengshui and Xinji, respectively, and whether this N rates of 120 and 180 kg ha^{-1} are sustainable for higher grain yield of next season crop need be further studied. For optimum N management, therefore, N applications should be tailored to each specific field or region because N availability and N use vary according to crop growth, soil fertility, and soil texture.

Abbreviations

NCP: North China Plain
NUE: Nitrogen use efficiency
RE_N: Recovery nitrogen efficiency
AE_N: Agronomic nitrogen efficiency
HI: Harvest index
HI_N: Nitrogen harvest index
Nmin: Soil mineral N, NO_3^--N + NH_4^+-N
V4: 4-leaf stage
V7: 7-leaf stage
V10: 10-leaf stage
R1.5: Silking stage
R3: Milking stage.

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