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Fertilizer nitrogen use efficiency and fates in maize cropping systems across China: Field ^{15}N tracer studies

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ABSTRACT

Maize (*Zea mays* L.) is a staple crop that is grown worldwide. The heavy use of nitrogen (N) fertilizers in maize cropping systems has resulted in low N use efficiency (NUE) and even caused N pollution in some regions of China. To evaluate the environmental impacts of over-fertilization, it is essential to reveal NUE and the fates of the applied N fertilizers, which can be accurately quantified only by the field ^{15}N tracer technique. In this study, we conducted six on-farm ^{15}N tracer experiments with four in Northeast (NE) China where maize is extensively cropped. We combined the results from these field experiments with previous ^{15}N tracer results (most in the North-Central (NC) region) to estimate the fates of N fertilizer in maize cropping systems throughout China. In total, there were 23 site-year field experiments. We found that, on average, 34%, 35% and 31% of the applied N fertilizers (222 kg N ha^{-1} on average) was taken up by aboveground biomass, retained in the soil and lost to the environment, respectively. The NUE, as the percentage of ^{15}N removal by aboveground biomass, was much higher in NE China than in NC China (47% vs. 28%, n = 6 and 16, respectively). The regional NUE differences suggested that the overall NUE in the Chinese maize cropping system would be underestimated if only data from NC China were considered. Additionally, NE China had a higher crop N uptake (260 vs. 192 kg N ha^{-1}) and a lower N loss proportion (21% vs. 34%) than NC China. These regional differences were controlled more by soil properties than by climatic factors. In addition to fertilizer N, our ^{15}N results indicated that, on average, 64% of the maize N was derived from soil, implying that native soil N is also an important N source for crop N uptake. Based on the mass balance of N input and N output, exogenous N replenishment to soil N pool consumption is a vital mechanism for maintaining the long-term fertility of the soil. To evaluate the long-term fates and use efficiency of N fertilizer, future research needs to quantify the contribution of N fertilizer to soil N consumption - replenishment.

1. Introduction

Nitrogen (N) is an essential nutrient for crop growth, and its limitation usually negatively impacts crop productivity. Nitrogen fertilization is an effective way to improve and sustain crop yields. As the world's population continues to grow, cropland is becoming limited, and N fertilization plays an increasingly critical role in ensuring food security (Tilman et al., 2011). Generally, > 50% of N fertilizer is unutilized by crops (Ladha et al., 2005). Nitrogen losses through leaching, runoff and gaseous emissions (NH_3, N_2O, and NO_x) cause water and air pollution risks and contribute to global warming (Galloway et al., 2003; Battye et al., 2017). Quantifying the fates of fertilizer N, especially the crop N uptake, is pivotal for local agricultural management (Burzaco et al., 2014; Chen et al., 2014). However, influenced by soil type, climatic conditions, and crop management, the fate of N fertilizer might vary considerably across regions and in

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different crops. Recognizing the variations as well as their underlying causes can help us design appropriate measures to improve N behaviors in soil-crop systems (Zhang et al., 2015b).

Nitrogen use efficiency (NUE) refers to the kg of crop N uptake per kg of N that is applied and is often estimated indirectly by measuring the difference in crop N uptake between treated and check plots and then divided by the amount of N fertilizer applied. This method is supposed to indicate the net effect of N fertilizer and has been widely applied to study the nutrient responses of crops (Zhang et al., 2008; Cui et al., 2010). There is an assumption associated with the calculation that soil N plays the same role in crop N uptake in treated and check plots. However, the indigenous soil N supply is usually altered by N fertilization, which has been described as "added-N interaction" or "substitution and replenishment effects" in the literature (Jenkinson et al., 1985; Kuzyakov et al., 2000; Cassman et al., 2002). In addition, calculations based on the difference method cannot provide extra information on the soil retention and N losses of applied N fertilizer. To eliminate the possible errors inherent in the difference method and to explore the realistic fates of N fertilizer, many researchers have used the ^{15}N-enriched tracer technique to quantify the use efficiency of N fertilizer (NUE). The ^{15}N tracer technique allows for the quantification of the direct fate of N fertilizer (including plant uptake, soil retention, and loss) and allows the sources of N utilized by crops to be differentiated (Stevens et al., 2005; Rimski-Korsakov et al., 2012; Quan et al., 2018).

Maize (*Zea mays* L.) is one of the major cereal crops in China. Its cultivation area and grain production have increased rapidly since the 1950s (Fig. 1). Northeast (NE) China and North-Central (NC) China are the two central regions for intensive maize cultivation (accounting for ~75% of China). The corresponding corn productions increased by 237% and 69% from 2000 to 2015, respectively. The fates and use efficiency of N fertilizer in the two regions are expected to be largely different due to their significant differences in soil properties and climatic conditions. However, until now, previous ^{15}N tracer studies in Chinese maize systems have mainly focused on NC China, and other regions, including NE China, have been studied less often (Fig. 2).

In this study, we performed six new field ^{15}N tracer experiments with four in NE China to increase the representativeness and combined our data with previous studies (17 site-years) across China to provide a more comprehensive understanding of the fate of N fertilizer in maize cropping systems at a national scale. Only data obtained under field conditions (plot experiment) were considered in this study because greenhouse or laboratory studies cannot accurately represent field conditions (Schindler and Knighton, 1999; Smith and Chalk, 2018). The objectives of this study were twofold: 1) to investigate the fates and NUE of N fertilizer in main maize production areas in China and 2) to explore the regional differences and controlling factors of NUE.

2. Materials and methods

2.1. New ^{15}N tracer field experiments

Six new ^{15}N tracer experiments were conducted in local farmers' fields in 2015 and 2016 in three typical maize cropping regions in China, including Gongzhuling, Harbin, Shenyang in NE China, Xuchang in NC China and Taoyuan in southern China. These sites have had a history of more than ten years of cultivating maize, except Taoyuan (rice cultivation had occurred previously). The initial soil characteristics, as well as the climatic conditions for the study locations, are given in Table 1.

Two or three treatments with four replicates for each treatment were initially set up in each experiment by using a randomized block design. In this study, we only reported the results of conventional fertilization (the farmers' practice in the local region, Table 1) to facilitate the comparison of the different sites and regions. The plot size of each experiment was 25 m^2 (3.125 m × 8 m). Nitrogen, phosphorus, and potassium fertilizers were all in solid form (urea, calcium triple superphosphate, potassium chloride, respectively). The rates were 200 kg N ha^{-1}, 90 kg P_2O_5 ha^{-1} and 90 kg K_2O ha^{-1} at all six sites. The ^{15}N abundance of the urea applied was 1.2 atom% (δ^{15}N: 2276‰).

All fertilizers were applied once as basal dressing before planting. The depth of fertilizer placement was 4–6 cm. Local agronomic management, such as stripe fertilization and ridge-furrow cultivation, were practiced to simulate the real situation. Maize hybrids that are widely used by local farmers were chosen. The planting density of maize was 70,000 plants per hectare. Other practices, such as pesticide and herbicide applications, were performed according to local practices. No other fertilizer or irrigation was applied during the growth period.

The yields of grain and straw biomass were measured at harvest. Then, five maize organs and four layers of soil were collected and mixed thoroughly; then, subsamples were analyzed for the total N concentration and ^{15}N isotopic ratio. The sampling methods were the same in all sites, as described by Quan et al. (2018). Briefly, considering the

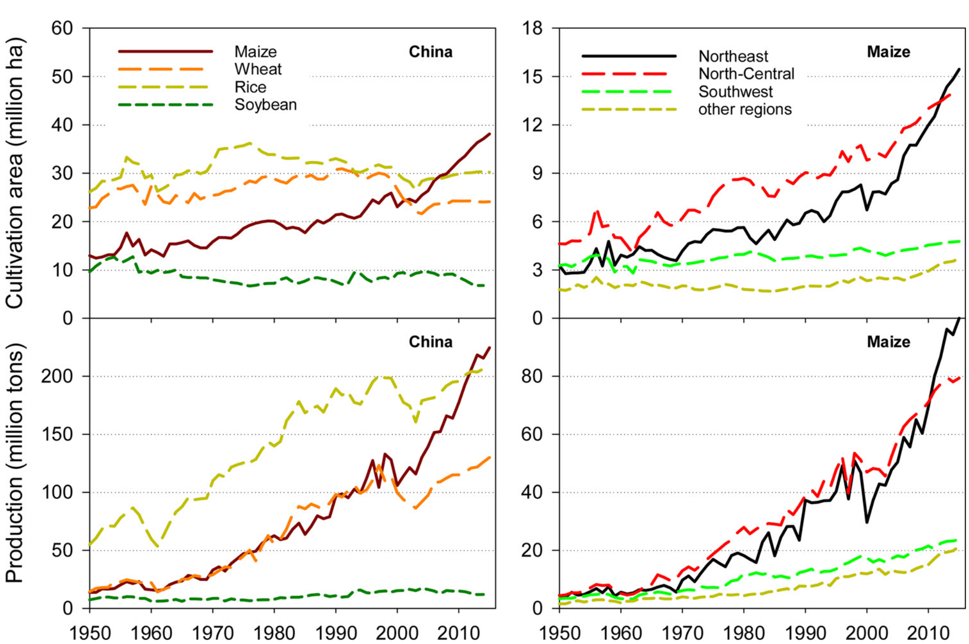

Fig. 1. Cultivation area and production of maize in four major regions of China. The four regions are: Northeast China (including Liaoning, Jilin, Heilongjiang, and Inner Mongolia); North-Central (including Beijing, Tianjin, Hebei, Henan, Shandong, Shanxi, Shannxi, Ningxia, and Gansu,); Southwest China (Sichuan, Chongqing, Guizhou, Yunnan, and Guangxi); and other regions (11 other provinces and autonomous regions in China). Data were obtained from the website of the National Bureau of Statistics (http://data.stats.gov.cn).

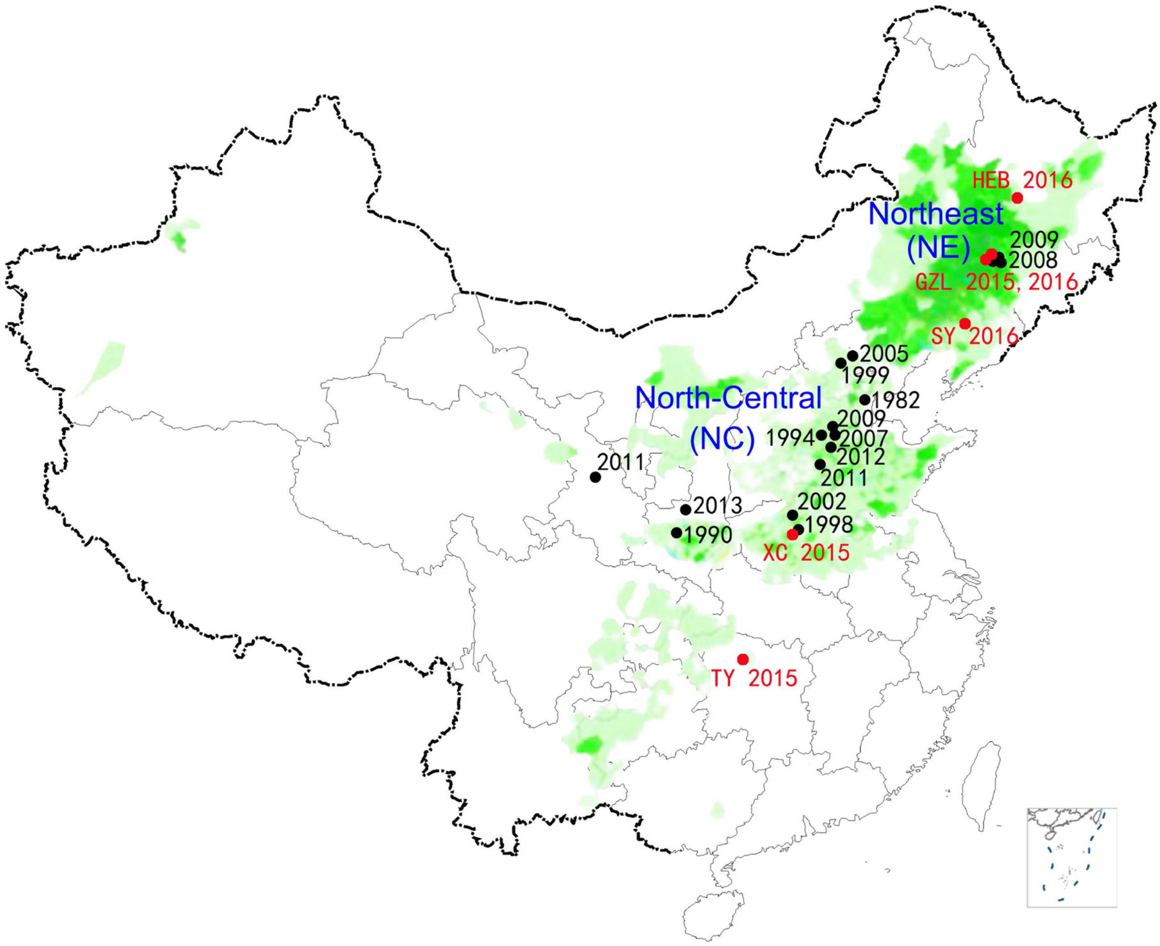

Fig. 2. The locations of the field ^{15}N tracer studies in soil-maize systems in China. Black dots are sites that were assessed in previous studies. Red dots indicate our six new study sites. The year besides the dot is the experimental year. The background map was cited from Chen et al. (2014), with greenness indicating the maize density.

Table 1
The experimental location, soil properties, crop rotations, and management in the six new study sites.

	Gongzhuling1 (GZL1)	Gongzhuling2 (GZL2)	Harbin (HEB)	Shenyang (SY)	Xuchang (XC)	Taoyuan (TY)
Year	2015	2016	2016	2016	2015	2015
Period of maize cultivation	26 April–28 Sept	06 May–07 Oct	02 May–06 Oct	26 April–23 Sept	02 June–02 Oct	07 June–13 Sept
Latitude	43°31'N	43°31'N	46°14'N	41°31'N	34°09'N	28°55'N
Longitude	124°49'E	124°49'E	126°52'E	123°21'E	113°48'E	111°26'E
Altitude (m)	204	203	173	34	82	76
Soil classification	Mollisols	Mollisols	Mollisols	Alfisols	Inceptisols	Ultisols
Soil texture	16% sand	15% sand	9% sand	25% sand	24% sand	14% sand
	45% silt	52% silt	68% silt	54% silt	61% silt	55% silt
	39% clay	33% clay	23% clay	21% clay	15% clay	32% clay
pH (1:5, w/v in water)	6.2	6.4	6.1	6.7	8.0	5.6
Organic C (g kg^{-1})	16.7	17.2	19.8	14.6	15.2	19.1
Total N (g kg^{-1})	1.56	1.61	1.86	1.17	1.38	2.35
NH_4^+-N (mg kg^{-1})	6.0	18.5	25.0	12.8	5.9	5.8
NO_3^--N (mg kg^{1})	47.7	43.9	43.1	32.8	44.2	22.3
Olsen-P (mg kg^{-1})	21.6	19.8	25.3	9.5	17.3	23.6
Rotation	Maize	Maize	Maize	Maize	Maize-wheat	Maize
Cultivar	ZD958	XY335	XY335	ZD958	ZD958	JY3

spatial heterogeneity of fertilizer N, soils from the 0–10 and 10–20 cm layers were excavated from a steel frame (62.5 × 23.5 × 20 cm, maize plant was at the middlemost location) that had been inserted into the soil beforehand and mixed thoroughly; subsamples were taken, and five soil cores that were 2.5 cm in diameter were randomly taken from the 20–30 cm and 30–40 cm depths using a soil auger. In each plot, one row from the central area was selected at harvest to determine the fresh weight of fruit (grain and cob), root and straw (stem and leaf). Then, five plants were randomly collected as samples to determine the water content, N concentration, and ^{15}N abundance. Maize roots were only collected in the steel frame (0–20 cm layer).

The nitrogen concentrations and ^{15}N abundances of the soil and plant samples were measured by an elemental analyzer (Elementar Vario MICRO cube, Hanau, Germany) coupled with a stable isotope ratio mass spectrometer (Isoprime 100, Stockport, UK). We ran a standard every ten samples to check the stability and drift. The standard deviations (n = 15) of standards were less than 0.23% for the N concentration and 0.15‰ for the $\delta^{15}N$ abundance.

The proportion of maize N derived from fertilizer ($N_{fertilizer}$) and the fates and use efficiency of applied N fertilizer in the soil-maize systems were calculated based on the principle of ^{15}N mass balance (Stevens et al., 2005; Quan et al., 2018).

$N_{fertilizer}$ (%) = ^{15}N uptake/(^{14}N uptake + ^{15}N uptake) × 100

NUE (%) = aboveground ^{15}N uptake/^{15}N application × 100

Retention (%) = ^{15}N retention (0–40 cm soil and roots)/^{15}N application × 100

Loss (%) = 100 - NUE (%) - retention (%)

where ^{15}N and ^{14}N indicate the N of fertilizer and nonfertilizer sources, respectively.

2.2. Data collection from previous ^{15}N tracer studies

To provide insights into a general spatial pattern of NUE, soil N retention and losses across China, we collected results from previous research articles and dissertations on-field ^{15}N tracer studies in Chinese maize systems (Fig. 2). The Web of Science and China National Knowledge Infrastructure databases were used to search for studies published before March 2017. The criteria for inclusion were limited to field studies using a ^{15}N tracer that explored the fates of N fertilizer in the soil-maize system at harvest. Labeled N must have been applied evenly during one-season maize cultivation, and studies where labeled N and unlabeled N were applied separately were excluded in this study. In total, 17 sites that met the screening criteria were included in our analysis.

The mean precipitation and mean temperature during the maize growth period in the last 22 years were obtained from the Atmospheric Science Data Center after inputting the longitude and latitude for each site (https://eosweb.larc.nasa.gov/). The maize growth periods were distinguished by location: May to September in NE China, June to September in NC China and June to August in South China.

Statistical analyses, including Pearson correlation, stepwise regression, and ANOVA, were performed using the software package SPSS 13.0 for Windows (SPSS Inc., Chicago, IL, USA). Comparisons among different regions were based on the Duncan test at the 0.05 probability level ($P < 0.05$). Graphics were prepared using SigmaPlot 12.5 software (Systat Software Inc., San Jose, CA, USA).

3. Results

3.1. The six new experiments

In all six site-year combinations, the mean biomasses of grain, stem, leaf, cob, and root at harvest were 10.4, 5.7, 3.8, 1.4 and 1.1 tons of dry weight per hectare (Table 2). Grain was the most critical organ and accounted for approximately half (47% on average) of the total biomass. The N concentrations ranged from 1.1 to 1.7% in the grains and leaves to 0.3–1.0% in the roots, stems, and cobs (Table 2). The aboveground N uptake ranged from 192 to 332 kg N ha^{-1}. Among them, the highest was in Harbin, and the lowest was in Shenyang. Of the aboveground N, 53% to 70% was equivalent to 120 to 212 kg N ha^{-1} and was distributed to the grain. The proportion of uptake N derived from fertilizer ($N_{fertilizer}$) varied little among the organs within the same experiment. However, the $N_{fertilizer}$ for the whole crop varied widely, from 26% in Xuchang to 46% in Shenyang, averaging 42% across all six new experiments (Table 2).

Of the applied ^{15}N tracer, an average of 44% (range from 28% to 51%) was recovered in the aboveground biomass at harvest, with the highest in Harbin and the lowest in Xuchang (Table 3). Soil ^{15}N retention, including both organic and inorganic forms, ranged from 14% in Taoyuan to 35% in Xuchang, with an average of 24%, and was mainly distributed in the topsoil (0–20 cm). Unrecovered ^{15}N (defined as losses) was ranged from 22% to 44% (Table 3).

3.2. Comparisons between regions

In total, there were 23 site-year combinations in which the ^{15}N tracer was used to explore the fates of N fertilizer under field conditions (Table 4); six of the site-year combinations were in NE China, 16 were in NC China, and only one was in another region (South China). In these site-years, the mean precipitation during maize growth and soil total N (TN) were significantly higher in NE China than that in NC China, while the mean temperature during maize growth and soil pH were significantly lower in NE China than in NC China (Fig. 3).

The grain yield, fertilizer N rate, and aboveground N uptake varied from 5.1 to 14.8 t ha^{-1}, 150 to 360 kg N ha^{-1} and 123 to 332 kg N ha^{-1}, respectively, and were significantly higher in NE China than in NC China; however, for $N_{fertilizer}$ (% of N uptake derived from fertilizer), there was no significant regional difference (36 ± 7%). For ^{15}N uptake, the NUE was significant higher in NE China (47 ± 7%, n = 6) than in NC China (28 ± 8%, n = 16). For both ^{15}N retention and ^{15}N loss, the values were lower in NE China than in NC China, but the differences were not significant at the 95% level (P = 0.401 and 0.099, respectively) (Fig. 3).

3.3. Correlation analysis

According to the calculation formula, NUE was correlated with crop N uptake, $N_{fertilizer}$, and the fertilizer N rate, but in this study, no significant relationship was found between NUE and $N_{fertilizer}$ (Fig. 4). Correlation analysis further showed that NUE was positively correlated with the mean precipitation and soil total N but negatively correlated with the soil pH (Table 5). For soil ^{15}N retention, soil total N was the only significant influencing factor. Stepwise regression analysis revealed that soil pH and the N rate were negatively correlated with NUE, but no significant stepwise regression models were found for soil N retention and loss (Table 5).

4. Discussion

4.1. Overall NUE comparison with other continents

Despite many years of research efforts, no overall evaluation of the fate of N fertilizer in Chinese maize production systems has been conducted (Ju et al., 2009; Ju and Christie, 2011). The results of our new experiments combined with the results of previous studies showed that 34 ± 11%, 35 ± 15% and 31 ± 16% of applied N fertilizer was taken up by aboveground biomass (NUE), retained in the soil and lost to the environment, respectively, in current season of the cultivation. The average NUE in Chinese maize systems was 38% if the NUEs in NE China and CN China were weighted by planting area. This proportion was higher than those in similar studies in Southeast Asia (33 ± 12%, n = 4, Dourado-Neto et al., 2010) but lower than those in North America (42 ± 13%, n = 82) and the European Union (54 ± 17%, n = 10) (Quan et al., unpublished synthesized data).

4.2. Regional difference in China and controlling factors

Our study showed that the fate of N fertilizer in Chinese maize systems was region-specific. Northeast China had a higher NUE than NC China (47% vs. 28%). Significant regional variations were also observed for Chinese rice and wheat systems (Cassman et al., 2002; Wang et al., 2011). The regional NUE difference observed in this study suggests that previous studies might have underestimated the overall NUE for Chinese maize production due to lack of information from northeastern China (Ju et al., 2011; Ju and Zhang, 2017). Even considering the NUEs in both regions, changes in the planting area of each year can

Table 2
Biomass (dry weight, 10^3 kg ha^{-1}), N concentration (%), N uptake (kg N ha^{-1}) and the proportion of uptake N derived from fertilizer ($N_{fertilizer}$) in different maize organs at harvest in the six new study sites.

	GZL1	GZL2	HEB	SY	XC	TY	Mean
Yield or biomass (10^3 kg ha^{-1})							
Grain	8.5 ± 1.8	12.2 ± 0.5	14.8 ± 0.6	8.4 ± 0.4	9.2 ± 0.6	9.3 ± 1.7	10.4 ± 2.6
Cob	1.0 ± 0.3	1.4 ± 0.1	1.8 ± 0.1	1.2 ± 0.1	1.3 ± 0.2	1.6 ± 0.2	1.4 ± 0.3
Leaf	4.8 ± 0.2	3.4 ± 0.2	5.5 ± 0.1	3.3 ± 0.8	3.1 ± 0.1	2.8 ± 0.4	3.8 ± 1.1
Stem	6.9 ± 0.4	6.1 ± 0.3	7.7 ± 0.2	5.1 ± 0.5	4.0 ± 0.5	4.5 ± 1.3	5.7 ± 1.4
Root	0.9 ± 0.1	0.9 ± 0.1	1.2 ± 0.1	0.7 ± 0.3	1.4 ± 0.1	1.3 ± 0.1	1.1 ± 0.3
N concentration (%)							
Grain	1.7 ± 0.1	1.5 ± 0.1	1.4 ± 0.1	1.4 ± 0.1	1.6 ± 0.2	1.5 ± 0.1	1.5 ± 0.1
Cob	0.7 ± 0.1	0.4 ± 0.1	0.4 ± 0.1	0.3 ± 0.1	0.3 ± 0.1	0.6 ± 0.1	0.4 ± 0.1
Leaf	1.4 ± 0.1	1.1 ± 0.1	1.4 ± 0.1	1.2 ± 0.1	1.4 ± 0.1	1.5 ± 0.1	1.3 ± 0.2
Stem	0.7 ± 0.1	0.5 ± 0.1	0.4 ± 0.1	0.5 ± 0.1	0.6 ± 0.1	0.5 ± 0.1	0.5 ± 0.1
Root	0.9 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	0.6 ± 0.1	0.6 ± 0.1	0.7 ± 0.1
Maize N uptake (kg N ha^{-1})							
Grain	147 ± 30	184 ± 12	212 ± 7	120 ± 4	143 ± 28	143 ± 24	158 ± 33
Cob	5 ± 1	6 ± 0	6 ± 0	3 ± 0	4 ± 1	10 ± 1	6 ± 2
Leaf	69 ± 8	36 ± 3	75 ± 3	39 ± 9	42 ± 4	42 ± 4	51 ± 17
Stem	50 ± 3	29 ± 4	31 ± 2	25 ± 2	23 ± 5	23 ± 12	30 ± 10
Root	9 ± 1	7 ± 1	9 ± 0	5 ± 1	8 ± 2	8 ± 2	8 ± 2
Sum	**279 ± 32**	**262 ± 27**	**332 ± 22**	**192 ± 9**	**221 ± 36**	**226 ± 32**	**252 ± 50**
$N_{fertilizer}$ (%)							
Grain	37 ± 5	38 ± 1	29 ± 2	45 ± 3	25 ± 4	38 ± 9	35 ± 7
Cob	34 ± 3	38 ± 1	31 ± 2	43 ± 5	28 ± 3	41 ± 9	36 ± 6
Leaf	38 ± 4	41 ± 1	37 ± 3	49 ± 2	27 ± 4	40 ± 8	39 ± 7
Stem	35 ± 5	38 ± 1	34 ± 4	49 ± 2	29 ± 6	41 ± 9	37 ± 5
Root	41 ± 5	41 ± 5	37 ±	45 ± 2	25 ± 3	38 ± 9	38 ± 7
Weighted average	**36.8 ± 4.8**	**38 ± 1**	**32 ± 5**	**46 ± 3**	**26 ± 2**	**39 ± 9**	**36 ± 7**

Data are the means of triplicate samples ± one standard deviation.

also affect the overall NUE evaluation. The cropping area of maize is increasing in NE China than in NC China, and as a result, the planting area-weighted NUE had gradually increased from 36% to 38% from 2000 to 2015 if their NUEs were unchanged during that period.

Under normal conditions, a high N application rate indicates low NUE according to the "law of the diminishing returns". In addition to the fertilizer N rate, the other direct factors that cause NUE differences are crop N uptake and $N_{fertilizer}$ (NUE = aboveground N uptake × $N_{fertilizer}$ / fertilizer N rate). In this study, the influence of N uptake was greater than $N_{fertilizer}$ on NUE, meaning that increasing N uptake instead of $N_{fertilizer}$ is an effective strategy to increase NUE in addition to decreasing the fertilizer N rate (Fig. 4). Differences in climatic and soil properties might make indirect contributions to regional NUE differences by affecting N use and loss potentials. The regression analysis in our study showed that the fate of N fertilizer was mainly influenced by soil properties (soil organic carbon and soil pH) but not by climatic factors (mean precipitation and mean temperature during maize growth). A similar relationship between NUE and soil organic matter (SOM) was also found in tropical cropping systems (Dourado-Neto et al., 2010). Soil with a low SOM content tends to have a low buffering capacity for the conservation and supply of nutrients and water, which influences crop yields under field conditions (Oldfield et al., 2019). Due to long-term cultivation and frequent agricultural use (> 1000 yrs), the soil in NC China had a lower SOM content than that in NE China, which might result in low crop N uptake and a low NUE. To avoid possible yield losses, farmers in regions with low SOM contents usually try to apply excess fertilizer to ensure a sufficient N supply throughout the growing period. In a global meta-analysis of the relationship between SOM and crop yields, Oldfield et al. (2019) found that crop yield increased significantly with the increase of SOM contents when the SOM content was below 2%. In addition to SOM, soil pH might be another important factor affecting N fates. The soil pH is relatively higher in NC China than NE China; this situation usually leads to a higher ammonia volatilization potential and a higher nitrification potential (denitrification and leaching), which favors N losses, such as NH_3 and NO_3^-. In our experiments, the Xuchang site in NC China, with a higher soil pH, had higher ^{15}N-TN abundances in the 20–30 cm and 30–40 cm soil layers than the other sites, indicating that more N leaching losses might have occurred in NC China than in NE China (Tables 1 and 4).

Table 3
Fates of the N fertilizer (%) in soil-maize systems in the six new study sites.

	GZL1	GZL2	HEB	SY	XC	TY	Mean
Grain	27.5 ± 8.8	34.5 ± 1.0	31.1 ± 2.4	27.1 ± 2.4	18.2 ± 5.2	27.0 ± 2.8	27.6 ± 5.5
Cob	0.8 ± 0.2	1.1 ± 0.1	0.9 ± 0.2	0.6 ± 0.1	0.6 ± 0.1	2.1 ± 0.7	1.0 ± 0.6
Leaf	13.1 ± 1.6	7.4 ± 0.6	14.0 ± 1.2	9.5 ± 1.0	5.7 ± 1.0	8.4 ± 2.0	9.7 ± 3.3
Stem	8.8 ± 1.2	5.6 ± 0.6	5.2 ± 0.4	5.5 ± 0.8	3.3 ± 1.6	4.7 ± 3.2	5.5 ± 1.8
Aboveground (NUE)	**50.2 ± 11.2**	**48.6 ± 1.4**	**51.2 ± 2.9**	**42.7 ± 2.7**	**27.7 ± 9.7**	**42.2 ± 6.9**	**43.8 ± 8.7**
Root	1.8 ± 0.4	1.4 ± 0.4	1.7 ± 0.2	1.1 ± 0.2	1.0 ± 0.4	1.5 ± 0.4	1.4 ± 0.3
Soil 0-10 cm	12.8 ± 8.5	18.9 ± 9.6	8.6 ± 2.4	17.5 ± 6.4	12.2 ± 7.9	6.6 ± 0.7	12.8 ± 4.8
Soil 10-20 cm	9.4 ± 5.7	6.4 ± 3.8	4.4 ± 2.0	3.4 ± 0.8	7.1 ± 4.2	3.4 ± 0.7	5.7 ± 2.4
Soil 20-30 cm	1.4 ± 0.8	1.5 ± 0.4	2.1 ± 0.6	0.9 ± 0.1	6.9 ± 3.7	1.5 ± 0.4	2.4 ± 2.2
Soil 30-40 cm	1.0 ± 0.6	1.2 ± 0.4	1.0 ± 0.4	1.0 ± 0.2	6.8 ± 4.9	1.1 ± 0.3	2.0 ± 2.3
Belowground (0-40 cm)	**26.3 ± 14.8**	**29.4 ± 11.5**	**17.8 ± 4.1**	**24.0 ± 7.0**	**34.6 ± 14.1**	**14.1 ± 1.8**	**24.4 ± 7.5**
Loss	**23.5**	**22.0**	**31.0**	**33.4**	**38.3**	**43.7**	**32.0 ± 8.4**

Data are the means of triplicate samples ± one standard deviation.

Table 4
Fates of N fertilizer in ^{15}N tracer studies in maize cropping system across China (under local farmers' management).

Site	Mean precipitation	Mean temperature	Soil pH	SOC	TN	N rate	Grain yield	Total N uptake#	Soil depth	$N_{fertilizer}$	Aboveground (NUE)	Retention	Loss	Reference
	mm	°C		g kg^{-1}	g kg^{-1}	kg N ha^{-1}	10^3 kg ha^{-1}	kg N ha^{-1}	cm	%	%	%	%	
Northeast, China														
Gongzhuling, Jilin	488	19.8	6.2	14.9	1.35	180	11.0	–	60	–	36.6	35.1	28.3	Zhang et al., 2010
Gongzhuling, Jilin	488	19.8	5.4	12.7	1.30	150	12.2	234	40	34.4	54.7	57.9	−12.6	Li, 2011
Gongzhuling, Jilin	488	19.8	6.2	16.7	1.56	200	8.5	279	40	36.8	50.2	26.3	23.5	This study
Gongzhuling, Jilin	488	19.8	6.4	17.2	1.61	200	12.2	262	40	38.1	48.6	29.4	22.0	This study
Harbin, Heilongjiang	475	18.3	6.1	19.8	1.86	200	14.8	332	40	31.8	51.2	17.8	31.0	This study
Shenyang, Liaoning	604	19.9	6.7	14.6	1.17	200	8.4	192	40	45.8	42.7	24.0	33.4	This study
North-Central, China														
Tianjin	394	23.9	–	15.0	–	–	–	–	30	–	44.2	14.9	40.9	Zhao et al., 1985
Shijiazhuang, Hebei	386	23.9	7.9	18.8	–	225	5.1	200	50	25.4	22.4	46.3	31.3	Chen et al., 1996
Yangling, Shannxi	392	19.9	7.7	7.0	0.85	210	5.2	123	60	46.0	27.0	21.3	51.7	Rees et al., 1997
Fengqiu, Henan	433	24.7	8.6	9.8	1.00	200	–	–	80	–	24.0	9.0	67.0	Cai et al., 2002
Beijing	374	20.7	8.3	26.7	1.43	360	9.6	177	50	45.8	22.5	23.1	54.4	Chen, 2006
Beijing	374	20.7	8.0	21.4	–	360	5.5	191	100	52.4	24.5	48.4	27.1	Ju et al., 2007
Beijing	374	20.7	7.7	4.7	0.70	263	8.5	–	–	–	25.5	33.9	40.1	Ju et al., 2009
Zhengzhou, Henan	450	25.0	8.6	11.4	0.69	225	5.9	143	–	28.4	18.0	–	–	Ren et al., 2011
Xinji, Hebei	400	25.4	8.2	12.5	0.78	180	10.5	224	150	34.6	41.4	49.7	9.0	Yang et al., 2011
Quzhou, Hebei	424	25.1	7.7	16.3	0.70	250	8.6	185	100	27.1	20.8	56.2	23.0	Xu et al., 2015
Yuzhong, Gansu	286	15.7	8.4	9.8	0.59	276	5.3	127	170	50.0	23.3	57.7	19.0	Liu et al., 2015
Xinji, Hebei	400	25.4	8.1	18.4	1.04	180	9.6	171	100	39.2	37.2	29.6	33.1	Yang et al., 2016
Shenzhou, Hebei	376	24.6	8.6	11.7	0.81	168	8.4	253	200	28.0	42.1	32.8	25.1	Wang et al., 2016b
Changwu, Shannxi[a]	323	19.4	8.3	8.1	1.00	225	12.8	232	200	26.3	27.2	52.8	20.0	Wang et al., 2016a
Changwu, Shannxi[a]	323	19.4	8.3	8.1	1.00	225	13.5	236	200	27.2	28.6	47.1	24.3	Wang et al., 2016a
Xuchang, Henan	450	25.0	8.0	16.2	1.42	200	9.2	221	40	26.1	27.6	34.6	38.3	This study
Other regions in China														
Taoyuan, Hunan	408	24.2	5.6	19.1	2.35	200	9.3	226	40	38.8	42.2	14.1	43.7	This study

[a] Two years of experiments (2013 and 2014) under the practice of soil mulching. #The total N uptake in most studies included only aboveground biomass N. For the few studies that include root N uptake but did not mention its specific value, we used crop N uptake instead (root N uptake is relatively low compared with total N uptake).

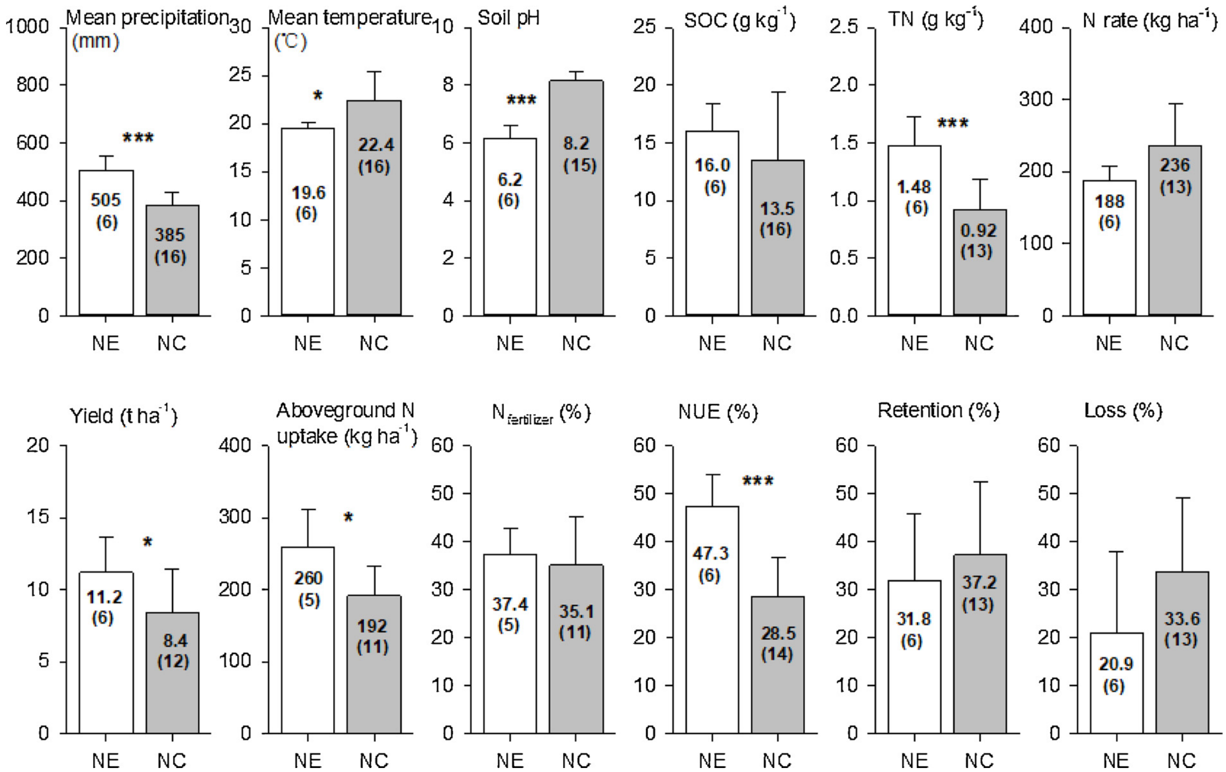

Fig. 3. Comparison of the 12 variables (mean precipitation, mean temperature, soil pH, TOC, TN, yield, aboveground N uptake, N rate, $N_{fertilizer}$ (%), and the three N fertilizer fates) between Northeast (NE) China and North-Central (NC) China. The number on the column is the mean value of each variable, and the number in parentheses is the number of samples. The error bars are standard deviations. Duncan's test was used to test the differences. *P < 0.05; **P < 0.001.

4.3. Fertilizer N replenishment to soil N consumption

Although high levels of N fertilizer are applied to maize systems, soil N remains the primary source of N uptake for crops (Dourado-Neto et al., 2010). Some soil N is converted from fertilizer N and other N sources (e.g., N deposition, biotic fixation) from previous years. The results of our six new studies combined with the results of previous studies in China showed that an average of 64% of aboveground N came from the soil N pool over-cultivation without regional differences. This percentage was close to that of previous reports (56–63%) despite wide variations in yields, soil types, and N management regimes (Gardner and Drinkwater, 2009; Blesh and Drinkwater, 2014). Large soil-derived N proportions have also been reported in rice and wheat cropping systems (Bacon et al., 1989; Garabet et al., 1998). Total crop N uptake from unlabeled sources is mainly related to the mineralization of native soil organic N, including immobilized N from fertilizer in previous years. The high reliance of crop N uptake on the soil indigenous N supply indirectly indicates that exogenous N replenishment to soil N consumption is an important mechanism to maintain long-term soil fertility and productivity. Because N fertilizer application accounts for > 75% of the total N input in Chinese maize systems (Zhang et al., 2015b), the N fertilizer remaining in the soil was expected to be the largest contributor to replenishment for soil N consumption. After complex N stabilization processes, residual N fertilizer in the soil would be continuously utilized by crops during cultivation in subsequent seasons (Ladha et al., 2005; Xu et al., 2014; Zhao et al., 2018). An

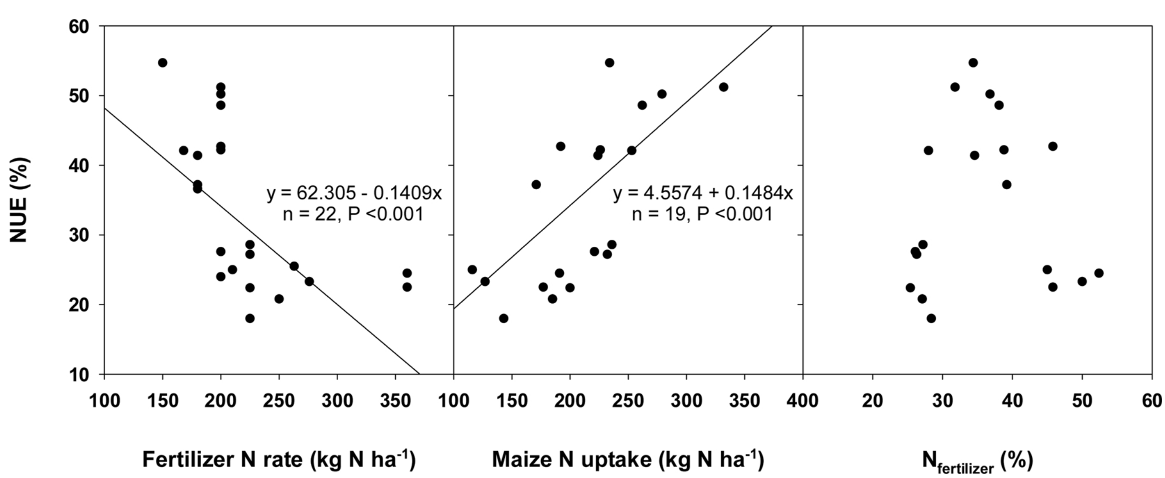

Fig. 4. The correlations of fertilizer N rate, maize N uptake, $N_{fertilizer}$ (%), and NUE (n = 23, only the treatment with the local farmers' N practice was included). NUE = N uptake × $N_{fertilizer}$ / N rate.

Table 5
Pearson correlation analysis of the indices of climatic, soil and management factors for the yield, N uptake, $N_{fertilizer}$ and ^{15}N fates (NUE, soil retention, and loss, respectively).

	Climate		Soil properties			Management
	Mean precipitation	Mean temperature	Soil pH	Soil organic C	Soil total N	Fertilizer N rate
Yield	0.18	−0.18	−0.40	−0.06	0.36	−0.34
N uptake	0.31	−0.10	−0.50*	0.33	0.61**	−0.37
$N_{fertilizer}$ (%)	0.02	−0.45	−0.12	0.09	0.02	0. 50*
NUE (%)	0.52*	−0.15	−0.75**	0.23	0.60**	−0.60**
Retention (%)	−0.37	−0.21	0.26	−0.07	−0.47*	0.14
Loss (%)	−0.10	0.24	0.30	−0.12	0.03	0.31

Stepwise regression model. NUE = 100.7 – 6.481 × pH − 0.082 × N rate (kg N ha^{-1}). Adjusted R = 0.659, $P < 0.001$.
* $P < 0.05$.
** $P < 0.001$.

appraisal of 60 years of ^{15}N tracer studies showed that the recovery of remainder fertilizer was 5.4 ± 4.5% in the first residual season and < 3%, with diminishing recoveries, in ≥ 2 residual seasons (Smith and Chalk, 2018).

The majority of crop N came from the soil, indicating that maintaining the soil N supply at a reasonable level is crucial for sustainable agricultural production. In this research, the average N retention amounts from fertilizer were 60 and 88 kg N ha^{-1} in NE and NC China, respectively, under conventional nutrient management practices, while the total N supplies from the soil were much higher (153 and 118 kg N ha^{-1} $season^{-1}$, respectively). If soil N were balanced in terms of inputs and outputs, the gaps between soil N consumption and fertilizer N replenishment would imply that other forms of exogenous N compensated for the soil N deficits, such as N deposition and biotic N fixation. However, if exogenous N replenishment were lower than soil N consumption, the soil N supply capacity would hardly be sustained after long-term soil N mining, which will eventually lead to soil fertility degradation and crop yield reductions (Mulvaney et al., 2009; Ju and Christie, 2011). In this study, soil N was most likely deficient because the environmental N input (N deposition and biotic N fixation) in maize planting system in NE China was excepted to be only 45 kg N ha^{-1} yr^{-1} between 2005 and 2010, much lower than the gap mentioned above (Zhang et al., 2019). The soil N deficit might be apparent due to the relatively higher yields in the experimental plots than in the nearby farms, which might be realistic because evidence indicated soil fertility degradation in large-scale soil survey and long-term monitoring experiments. Huang and Sun (2006) found that 74% of the investigated soils in NE China had lower SOM contents in 2002 than during the last investigation in 1982. The mean decrease rate was 0.1–0.3 g SOM-C kg^{-1} yr^{-1} during maize cultivation in NE China from 1985 to 2015 (Zhang et al., 2015a; Tong et al., 2017). Building up soil fertility is much more difficult than losing soil fertility (Kopittke et al., 2017). In a long-term field experiment in Yangling, NC China, the soil organic carbon and total N concentrations in the unfertilized control were 20% and 16% lower, respectively, than those in the fertilized treatment after 19 years of winter wheat and summer maize cultivation (Liang et al., 2013). The soil fertility depletion due to long-term N deficit in the control could not be recovered quickly after returning to regular fertilization, and a much lower yield (1.1 vs. 7.6 t ha^{-1}) and NUE (13% vs. 50%) were observed in the control than in the fertilized treatment in the first recovery year (Liang et al., 2013). Therefore, to maintain a sustainable N supply for long-term grain production, more nutrient management measures should be encouraged to improve exogenous N conservation and the soil N supply capacity (Sebilo et al., 2013).

5. Conclusion

Our new ^{15}N experiments enhanced the assessment of N use in Northeast China, where the NUE is higher than that in the heavily studied North-Central region. Regression analysis showed that the fate of N fertilizer was mainly influenced by soil properties rather than by climatic factors. The higher NUE in Northeast China was mainly caused by the near-neutral soil pH and high soil total N concentration. The regional difference implied that the NUE estimation for maize at a national scale should consider major regions and would be underestimated if only the results from North-Central China were considered. Native soil N is the primary source of N for crops. To maintain the soil N supply and crop productivity in the long term, we suggest that improved N management aimed at increasing the conservation of N fertilizer should be widely applied to alleviate the soil degradation associated with high N fertilization and high N loss in China.

Declaration of Competing Interest

The authors declared that they have no conflicts of interest to this work.

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