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Special Section:

Quantifying Nutrient Budgets for sustainable nutrient management

Key Points:

- Globally, $41 \pm 14\%$, $31 \pm 14\%$, and $28 \pm 19\%$ of N fertilizer was taken up by maize, retained in the soil and lost one season after its application
- The nitrogen use efficiency measured with ^{15}N approach is low in Chinese maize cropping system mainly due to low soil organic carbon
- Deep placement of N fertilizer and split fertilization can improve yield and reduce N loss

Supporting Information:

Supporting Information may be found in the online version of this article.

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Fates and Use Efficiency of Nitrogen Fertilizer in Maize Cropping Systems and Their Responses to Technologies and Management Practices: A Global Analysis on Field ^{15}N Tracer Studies

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Abstract Nitrogen (N) fertilization has boosted grain production during the past century, while excess N fertilization with declining N use efficiency (NUE) has led to severe pollution in many regions. To achieve the goal of sustainable food production, Technologies and Management Practices (TMPs, e.g., optimum N application rate and methods, N-transformation inhibitors) have been developed to improve crop yield and NUE and to reduce N losses. However, it remains unclear how N fate has been changed by environmental factors and TMPs. Here, we compiled a dataset of 366 field ^{15}N tracer observations from 74 publications worldwide and conducted a meta-analysis to examine how environmental conditions and management practices influence the fertilizer-N fate one growing season after the fertilization of maize. We show that the proportion of ^{15}N taken up by aboveground biomass ($\text{NUE}_{15\text{N}}$), was significantly lower in China (33%) than that in North America (42%) and the European Union (54%). Soil organic carbon was the most critical environmental factor positively correlated with $\text{NUE}_{15\text{N}}$. Among the nine selected categories of TMPs, deep placement of fertilizer and split application increased the grain yield and decreased the fertilizer-N loss consistently among studies. Reducing the fertilizer-N rate could increase the $\text{NUE}_{15\text{N}}$ but presents risks of yield reduction in some regions. This study demonstrates the importance of SOC and varying impacts of TMPs on the efficiency of fertilizer use in cropping systems globally and provides critical information for farmers and policymakers to improve N management for higher productivity and less pollution.

Plain Language Summary The efficient use of Nitrogen (N) fertilizer benefits both food security and environmental quality. To characterize the fate and the efficiency of fertilizer-N in maize production, we conducted a comprehensive meta-analysis with existing field ^{15}N -tracer trials. Our results show that higher organic carbon content in the soil is associated with higher ^{15}N recovery under conventional management practices. Among nine N management practices developed for more efficient use of N, deep placement in the soil (rather than surface application) and split application of N fertilizer (dividing annual fertilization into two or more smaller applications) improved yield, ^{15}N recovery, and environmental impacts. This study improves our understanding of management practices on the fate of fertilizer-N and provides guidance for farmers and policymakers to improve N fertilizer management.

1. Introduction

Maize (*Zea mays* L.) is one of the major cereal crops, and its planting area has reached 194 million ha worldwide, accounting for 27% of the total cereal planting area in 2017 (FAO, 2018). Given the growing demands for food, fuel, animal feed and forage, the average grain yield of maize per unit area was enhanced from 3,150 kg ha⁻¹ in 1980 to 5,640 kg ha⁻¹ in 2015 (FAO, 2018). In 2010, over 17 Mt Haber-Bosch nitrogen (N)

was applied to maize cropping systems to increase maize yield (Heffer, 2013). Using N fertilizer, however, has also led to a cascade of severe N pollution to the environment, and threatened the function of ecosystems and also the health of human beings (Chen et al., 2014; Galloway et al., 2003; Guo et al., 2010). For example, in the winter wheat and summer maize rotation systems in North China, up to 43% of applied N fertilizer was lost into the environment through the processes of ammonia volatilization, nitrate leaching, and nitrification/denitrification (Ju & Zhang, 2017; F. Zhang et al., 2012). Therefore, more efficient uses of N fertilizer are needed to benefit both maize production and the environment (Huang et al., 2018; Qiu et al., 2015). Among the indices accepted for evaluating the environmental effects of N fertilization, N use efficiency has been frequently used, because it is closely linked to both economic return and N loss (Brentrup & Pallière, 2010; EU Nitrogen Expert Panel, 2015; Fixen et al., 2014; Norton et al., 2015).

The ^{15}N tracer approach has been regularly used to track N fate since the mid-twentieth century, which has greatly improved our understanding of N cycling (Low & Piper, 1957; Sharp et al., 1956). When applied in soil-crop systems, ^{15}N tracers can identify contributions of indigenous soil-N and exogenous fertilizer-N to crop N uptake, allowing calculation of the direct proportion of N fertilizer absorbed by maize. Generally, the N use efficiency in ^{15}N tracer studies ($\text{NUE}_{15\text{N}}$) refers to the proportion of aboveground ^{15}N recovery (including grain and straw). Therefore, $\text{NUE}_{15\text{N}}$ can be calculated by:

$$\text{NUE}_{15\text{N}} = \text{aboveground N uptake} \times \text{Ndff\%} / \text{fertilizer} - \text{N rate}$$

where Ndff% is the proportion (%) of crop N derived from the fertilizer, which can be directly determined by measuring the enrichment of ^{15}N in plant samples. Given that most ^{15}N tracer studies only lasted for one crop season, the $\text{NUE}_{15\text{N}}$ in the literature usually refers to aboveground ^{15}N recovery one growing season after ^{15}N fertilization. According to the equation, a higher fertilizer-derived N uptake due to better climate, soil and management conditions, or a lower fertilizer-N input will improve $\text{NUE}_{15\text{N}}$. Besides $\text{NUE}_{15\text{N}}$, NUE can also be defined and calculated by other approaches, such as N recovery efficiency, and partial factor productivity (Cassman et al., 2002; Ladha et al., 2005).

Many technologies and management practices (TMPs) have been developed to better synchronize N supply with N demand, increase fertilizer-N retention, and improve NUE in maize cropping systems (Xia et al., 2017). Examples of these practices include application of “enhanced efficiency fertilizers” (EEFs, a marketing term representing a series of products), optimum N application rate and method, applying no-tillage, and co-application with organic materials. To explore how these practices affect the fate of N, many ^{15}N tracer trials have been conducted to trace the fate of N in maize cropping systems at the field scale (Chabrol et al., 1988; Clay et al., 1990; Gabriel et al., 2016; Kitur et al., 1984; Legg et al., 1979; Quan et al., 2018; Rees et al., 1997; Russelle et al., 1981; Ssali, 1990; Stevens et al., 2005; X. Wang et al., 2016). However, no study has synthesized this existing body of literature worldwide to characterize the impact of different TMPs on the fate of N fertilizer. Gardner and Drinkwater (2009) conducted a meta-analysis of ^{15}N field experiments in temperate grain agroecosystems and concluded that management practices have a wide range of abilities to improve total ^{15}N recovery in plant and soil; among these practices, diversified crop rotations (e.g., with cover crops) and organic N sources (green manure or animal manure) performed the best. However, this study focused on all temperate grain crops under various experimental conditions and did not distinguish the specific influence of environmental factors (e.g., climate and soil) on the fate of N fertilizer for a specific crop (e.g., maize).

To address this knowledge gap and to characterize the factors controlling the fate of fertilizer-N in maize cropping systems, we conducted a comprehensive meta-analysis of published field ^{15}N -tracer trials under maize cultivation. We separated the treatments depicted in the literature into conventional management practice and various TMPs from 366 observations in 74 field ^{15}N tracer studies globally. We focused our analysis on two key questions: (1) Which environmental factors most strongly influence the fate of N fertilizer in maize cropping systems? (2) How are the fate and use efficiency of N fertilizer changed by different TMPs and what are the related mechanism?

2. Materials and Methods

2.1. Data Collection and Compilation

To compare the fate of fertilizer-N under conventional practice and TMPs, we collected peer-reviewed journal articles on field studies using ^{15}N tracers in maize cropping systems published before December 2017. The articles were acquired from the Web of Science, Google Scholar and China Knowledge Resource Integrated Database and different combinations of search keywords (“maize,” “corn,” “nitrogen,” “ ^{15}N ,” “label,” “fate,” “recovery,” and “trace”) were used to search for relevant papers. The articles were selected using the following criteria: (1) only field ^{15}N tracer studies with plot experiments were selected; pot, lysimeter, column and tube experiments were not included; (2) Labeled N fertilizer and nonlabeled N fertilizer was mixed homogeneously before application; studies with multiple N applications but applying labeled and nonlabeled N separately at different stages were excluded; (3) The calculation of fertilizer-N fate was for the whole growing period, from planting to physiological maturity; (4) Fertilizer-N rates, proportions of fertilizer- ^{15}N taken up by maize at harvest, and the replication of treatments in the field trial were clearly stated; (5) Treatments included a control of conventional management, where fertilizer-N rate was in the range of 100–300 kg N ha⁻¹. This range represents the typical N application rates for a single annual maize crop (i.e., without multi-cropping within a year) reported in the literature and is used to avoid the impact of extremely high and low N rates on the results; and (6) For the same experiment published at different times, only the latest article was included.

We adopt the following principles to extract data from the literature. (1) Record the data by site and year; if there were several site-years in one article, all “site-years” were extracted; if there were multiple observations in one site-year, for example, plots under different crop rotation systems or different planting history, the averaged values were recorded. (2) For ^{15}N tracer studies that lasted for multiple seasons, only the first season was included; (3) In each study, the treatment closest to the local agronomic management practice was selected as the control, while other treatments were categorized as one of the nine TMPs (see the next paragraph). (4) For multifactorial studies, partial effects of treatments compared to the control were used while interacting effects were excluded. (5) Besides fertilizer-N fate, background information of climate and soil properties, soil sampling depth, and information on agronomic management practices were also collected. If there were no data on mean annual temperature (MAT) and mean annual precipitation (MAP) during the maize growth period were provided, we estimated them using the monthly data obtained from Atmospheric Science Data Center (<https://eosweb.larc.nasa.gov/>). When data were graphically presented in the articles, data were extracted by Engauge Digitizer (Free Software Foundation, Inc., Boston, MA, USA).

The final database consists of 366 field measurements (124 for the control and 242 for various treatments) derived from 74 publications, of which 39 were conducted in North American, 18 in China, 7 in European Union, and 11 in other countries (Figure 1). The database covers field studies from 1970 to 2017. The average fertilizer-N rate for the control was 181 ± 38 kg N ha⁻¹ (Figure S1). The form and application method of N fertilizer in ^{15}N tracer trials sometimes differed from usual practices in order to mix the ^{15}N label properly.

Among the selected studies, we identified nine TMPs from all treatments and analyzed their effects on maize grain yield, N uptake, Ndff% (% of aboveground N derived from fertilizer), and fertilizer-N fate (uptake %, soil retention %, and unrecovered %). These TMPs are (1) the use of “Enhanced efficiency N fertilizers” products, including slow-release fertilizers and co-application with urease and nitrification inhibitors; since the observations were limited, we did not further subdivide them into different categories according to type. (2) Forms of N fertilizer other than urea, mainly as ammonium-based fertilizer (ammonium sulphate, ammonium chloride, ammonium bicarbonate, calcium ammonium nitrate). (3) No-tillage or reduced tillage. (4) Deep placement of N fertilizer rather than surface broadcasting or shallow application. (5) Increasing splitting frequency of fertilizer-N application; for example, use two split applications instead of a single application. (6) Reducing the proportion of basal N fertilizer application; under the same N application rate and splitting frequency, the proportion of base fertilizer was reduced and the proportion of topdressing was increased. (7) Co-application with organic materials; organic materials (e.g., animal manure, cover crop) were co-applied with synthetic N fertilizer; the application rate of fertilizer- ^{15}N was the same between the “control” and the “treatment,” while total N input might be different due to the input of organic materials. (8) Increasing fertilizer-N rate. Many ^{15}N field studies in maize cropping systems focused on exploring the

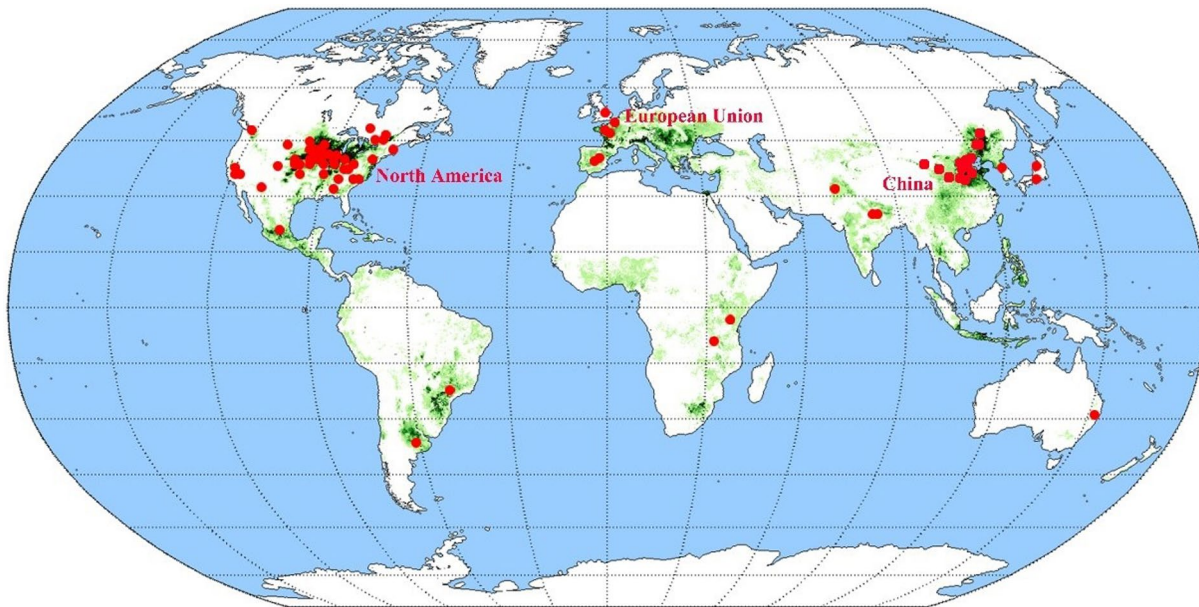


Figure 1. Global distribution of sites for field ^{15}N tracer study in maize systems ($n = 114$ site-years). The background figure was compiled by the Institute on the Environment, the University of Minnesota with data obtained by Monfreda et al. (2008). URL: <https://commons.wikimedia.org/wiki/File:MaizeYield.png#filelinks>. The green color denotes the average intensity of regional maize output, with darker green indicating higher intensity.

influence of fertilizer-N rate on fertilizer-N fate, and some of them did not identify the “control” application rate. In those cases, we selected the treatment with fertilizer application rate around 200 kg N ha^{-1} and in the range of $100\text{--}300 \text{ kg N ha}^{-1}$ as the control. Experiments with fertilizer-N rates higher than the control were considered as the treatment of “increasing fertilizer-N rate.” According to the magnitude of the increase in fertilizer-N rates, all data were subdivided into two categories, namely low increase (i.e., the increase is smaller than 100%) and high increase (i.e., the increase is 100% or larger than 100%). (9) Reducing fertilizer-N rate. Similar to increasing fertilizer-N rate, experiments with fertilizer-N rates lower than the control were subdivided into three categories, corresponding to low, medium, and high reductions in fertilizer-N rates that were $<50\%$, 50% , and $>50\%$, respectively, comparing to the “control” application rate. The medium reduction is categorized separately here because it has a large number of observations ($n = 61$). Site-years and observations of each TMPs are listed in Table S1.

2.2. Evaluated Variables

The impacts of TMPs on fertilizer-N fate were evaluated by six variables: (1) maize grain yield (measured as kg ha^{-1}), (2) aboveground N uptake (including grain and straw; measured as kg N ha^{-1}); (3) $\text{Ndff}\%$ (% of aboveground N derived from fertilizer); (4) ^{15}N uptake % (the proportion of ^{15}N recoveries in aboveground biomass; i.e., $\text{NUE}_{^{15}\text{N}}$ defined in this study); (5) ^{15}N soil retention % (the proportion of ^{15}N recovered in soils); (6) ^{15}N unrecovered (the proportion of unrecovered ^{15}N calculated by ^{15}N mass balance). The last three variables constitute the fertilizer-N fate during one growing season after its application. Soil retention of N fertilizer refers to ^{15}N residue in the soil profile. Although the depth of soil sampling varied from 15 to 300 cm in the studies included here (Figure S1), the observed ^{15}N retained in soil was still representative because residual N fertilizer was mainly distributed in the surface soil. In addition, the soil sampling depth was usually the same for control and TMPs within each study, alleviating the concern about the potential impacts of different soil sampling depth on the assessment results. The above six variables all showed normal distributions for the control and all TMPs (Figure S2).

To compare the regional differences of ^{15}N fate in maize cropping systems under conventional management, we developed and examined the dataset (including climatic, soil and other background information) by four regional groups, namely North America, China, European Union, and other countries. In addition to

NUE_{15N} , we calculated two other commonly used indicators for assessing the efficiencies of N fertilization: N recovery efficiency (RE_N) and partial factor productivity (PF_{PN}), where:

$$RE_N = \text{aboveground N uptake} / \text{fertilizer - N rate}$$

$$PF_{PN} = \text{maize grain yield} / \text{fertilizer - N rate}$$

The differences of these indicators between North America, China, European Union, other countries were examined by one-way ANOVA. Multiple comparisons were performed based on the Duncan test at a confidence level of 95%. In addition, Pearson correlation analysis was performed to investigate the influences of climatic, soil and other factors on fraction of aboveground N derived from fertilizer and ^{15}N recoveries under conventional N management conditions.

2.3. Meta-analysis

For a given variable (X), the effect of individual TMP on maize yield, N uptake, fraction of aboveground N derived from fertilizer, and ^{15}N fates were calculated as the effect size ($\ln RR$), the natural log of the response ratio (RR) of the control and the treatment groups (Hedges et al., 1999; Xia et al., 2017):

$$\ln RR = \ln \left(X_t / X_c \right)$$

where X_t and X_c represent the mean of the treatment and the control groups for variable X , respectively. To facilitate interpretation, a converted presentation, $((RR - 1) \times 100)$, was used to present the percentage changes under certain practices comparing to the control. Positive values denote an increase due to TMPs, whereas negative values indicate a decrease.

In meta-analyses, the effect sizes are often weighted with a nonparametric weighting function, in which the independent variables include the standard deviation and the replication of each observation (Bai et al., 2013; W. Li et al., 2016). However, in our collection, most studies did not report the standard deviation. Variance-based weighting function may generate extreme weights if the standard deviation is missing for part of the database. Consequently, only replication-based weighting was adopted in the analysis using the following equation (Lam et al., 2012; Xia et al., 2017):

$$\text{weight} = (n_t \times n_c) / (n_t + n_c)$$

where n_t and n_c are the sample sizes (the number of repetitions in field trials, for example, the number of plots in a randomized complete block design) for the treatment and the control groups, respectively.

Mean effect sizes and the 95% confidence intervals (CIs) were generated by a bootstrapping procedure with 4999 iterations, using MetaWin 2.1 (Rosenberg et al., 2000). The effects were considered significant if the 95% CIs did not overlap with zero. Means of categorical variables were considered significantly different from each other if their 95% CIs did not overlap (Hedges et al., 1999).

3. Results

3.1. Conventional Nutrient Management

Even though all studies were conducted for maize production, experimental sites had a wide range of climate and soil conditions have been reported. Compared with the sites in China, those in North America had higher precipitation and soil N content but lower soil pH, while those in European countries had higher temperature and soil organic C. In addition, the average experimental plot size was higher in North America (6.9 m^2) and European Union (6.1 m^2) than in China (1.2 m^2), although these differences were not significant due to high variations of plot size among individual experiments.

Under conventional nutrient management, many indicators of the fertilizer-N fates (e.g., NUE_{15N}) in maize cropping systems showed significant regional patterns (Table 1). The grain yield and maize N uptake,

Table 1
Site Conditions and the Fate of N Under Conventional Nutrient Management in Soil-Maize Systems of China, North American, European Union, and Other Countries

¹⁵ N plot size	Mean temperature	Mean annual precipitation	Soil properties				Grain yield	Maize N uptake	Grain yield/N uptake/N rate (PPN)	Maize N uptake/N rate (REN)	¹⁵ N recoveries at harvest				
			Soil pH	Soil organic C	Soil N	Fertilizer-N rate					Maize uptake	Ndiff%	Maize uptake ^c (NUE _{15N})	Soil retention	Unrecovered
North America															
Mean ^a	8.9 ^c	820 ^b	6.42 ^b	22.9 ^b	2.04 ^a	183 ^{ab}	8,290 ^a	175 ^a	46.1 ^b	94.7 ^a	45.8 ^a	42.3 ^b	27.8 ^a	30.5 ^b	
SD ^a	3.3	250	0.61	13.7	0.70		32	40	18.3	23.7	14.0	13.2	11.8	17.2	
n ^a	83	83	31	23	19	82	51	47	51	47	37	82	44	44	
China															
Mean	10.8 ^c	565 ^c	7.70 ^a	14.4 ^b	1.05 ^b	198 ^a	8,770 ^a	191 ^a	46.3 ^b	101.2 ^a	33.6 ^b	33.0 ^c	34.3 ^a	31.5 ^a	
SD	3.9	128	0.97	9.2	0.42	45	2,810	54	17.1	37.4	7.5	11.7	15.9	19.9	
n	20	20	17	19	18	20	16	15	16	15	14	20	18	18	
European Union															
Mean	14.3 ^b	539 ^c	7.17 ^a	31.9 ^a	1.19 ^b	160 ^b	10,400 ^a	191 ^a	68.2 ^a	123.0 ^a	44.4 ^{ab}	54.0 ^a	36.2 ^a	9.5 ^b	
SD	2.5	141	1.14	12.0	0.42	38	3,200	44	26.5	34.1	12.5	16.8	15.3	9.0	
n	9	9	10	9	3	10	9	10	9	10	9	10	9	9	
Other countries															
Mean	18.0 ^a	1,016 ^a	6.01 ^b	17.2 ^b	1.12 ^b	164 ^b	8,870 ^a	192 ^a	54.7 ^{ab}	88.4 ^a	37.8 ^{ab}	39.5 ^{bc}	30.9 ^a	28.8 ^a	
SD	3.3	379	1.26	9.9	0.56	57	2,970	102	23.6	37.0	8.1	10.3	17.3	22.9	
n	10	11	11	11	8	11	8	5	8	5	5	11	10	10	
All															
Mean	10.3	775	6.78	20.6	1.46	181	8,660	181	49.3	99.3	42.4	41.5	30.6	28.2	
SD	4.3	275	1.09	12.8	0.73	38	2,990	48	20.4	30.0	13.1	13.9	14.0	18.8	
n	122	123	69	62	48	124	84	77	84	77	65	123	81	81	

^a "Mean," "SD," and "n" represent the average value, standard deviation and site-year of all observations under conventional nutrient management.

^b The same lowercase letters after the "Mean" value in the same column indicate no significant difference between the regions (North America, China, European Union, or Other countries).

^c NUE_{15N} = N uptake * Ndiff%/N rate. NUE_{15N} (% of ¹⁵N absorbed by maize) is controlled by three major factors: maize N uptake, Ndiff% (% of maize N derived from fertilizer) and fertilizer-N rate.

Table 2

The Correlation Coefficients (Pearson R) of Climatic, Soil, and N Inputs and Outputs with the N Uptake, Fraction of above ground N Derived From Fertilizer (Ndff%), and ¹⁵N Fate

	Climate		Soil properties			N inputs and outputs		
	Mean temperature	Mean precipitation	Soil pH	Soil organic C	Soil total N	Fertilizer N rate	Grain yield	Maize N uptake
Ndff%	-0.163	-0.164	0.054	0.538**	0.121	0.233	-0.180	-0.088
¹⁵ N uptake % (NUE _{15N})	<0.001	-0.085	-0.090	0.307*	0.219	-0.174	0.221*	0.460***
¹⁵ N soil retention %	-0.099	-0.183	0.158	0.097	-0.117	-0.039	0.206	0.040
¹⁵ N unrecovered %	0.020	0.135	-0.078	-0.268*	-0.021	0.293**	-0.355*	-0.367*

Only data from the control with conventional nutrient management were included in this analysis.

* $P < 0.05$; ** $P < 0.001$; *** $P < 0.001$.

indicators for crop productivity, were in the range of $8.29\text{--}10.4 \times 10^3 \text{ kg ha}^{-1}$ and $175\text{--}192 \text{ kg N ha}^{-1}$ under conventional management conditions without significant differences among the four regions. In contrast, the three indicators for measuring the efficiency of N fertilization show different regional patterns: the N recovery efficiency was in the range of 88%–123% without significant regional differences; the partial factor productivity was significantly higher in the European Union (68.2 kg kg^{-1}) than that in China and North American ($46.1\text{--}46.3 \text{ kg kg}^{-1}$); the $\text{NUE}_{15\text{N}}$ was significantly lower in China (33%) than that in North American (42%) and European Union (54%).

The fertilizer-N fates under conventional management are significantly related to indicators for soil properties, fertilizer-N input levels, and crop uptake rates but not climate conditions (Table 2). For example, both fraction of aboveground N derived from fertilizer and $\text{NUE}_{15\text{N}}$ had a significant positive relationship with soil C concentration. $\text{NUE}_{15\text{N}}$ was also positively correlated with grain yield and maize N uptake. In contrast, unrecovered ¹⁵N was positively correlated with the fertilizer-N rate and negatively correlated with soil C concentration, grain yield, and maize N uptake. No significant correlation was found between soil ¹⁵N retention and any variables in the dataset.

3.2. The Impacts of Different Technologies and Management Practices

Besides climate and soil properties, TMPs also contributed to differences in maize yield, aboveground N uptake, and ¹⁵N fates. Compared with the conventional practice, both increasing splitting frequency of fertilizer-N application and co-application with organic materials significantly increased the grain yield by 7%, while other forms of N fertilizer, no-tillage or reduced tillage, and all levels of reducing fertilizer-N rate (low, medium, and high) significantly decreased the grain yield by 8%, 11%, 5%, 12%, and 12% (Figure 2a). No significant changes were observed for enhanced efficiency N fertilizers, deep placement of N fertilizer, and increasing fertilizer-N rate. Similarly, the increasing splitting frequency of fertilizer-N application and low level of increasing fertilizer-N rate significantly increased the maize N uptake by 10% and 8%, while medium and high levels of reducing fertilizer-N rate significantly decreased the maize N uptake by 19% and 33%. For the fraction of aboveground N derived from fertilizer, it was promoted by 16% and 7%–39% by increasing splitting frequency of fertilizer-N application and increasing fertilizer-N rate, while it was suppressed by 20% and 18%–53% by co-application with organic materials and reducing fertilizer-N rate.

For $\text{NUE}_{15\text{N}}$, deep placement of N fertilizer and increasing splitting frequency of fertilizer-N application introduced the highest increases (by 29% and 31%, relative change for treatment vs. control instead of the difference between two $\text{NUE}_{15\text{N}}$ values), but it was only significant for the latter (Figure 2d). Reducing the proportion of basal N fertilizer application, low and medium levels of reducing fertilizer-N rate obtained lower but significant increases of $\text{NUE}_{15\text{N}}$ (7%, 13%, and 17%) compared to that in the control. With regards to other forms of N fertilizer, no-tillage or reduced tillage, co-application with organic materials, low and high levels of increasing fertilizer-N rate, significant reductions of $\text{NUE}_{15\text{N}}$ were observed, ranging from 14% to 42%. Almost all practices listed in this study had insignificant influences on the soil retention of N fertilizer except for other forms of N fertilizer (reduction by 26%). The unrecovered ¹⁵N was calculated by ¹⁵N mass balance, and its proportion was altered significantly by other forms of N fertilizer (+60%), deep placement

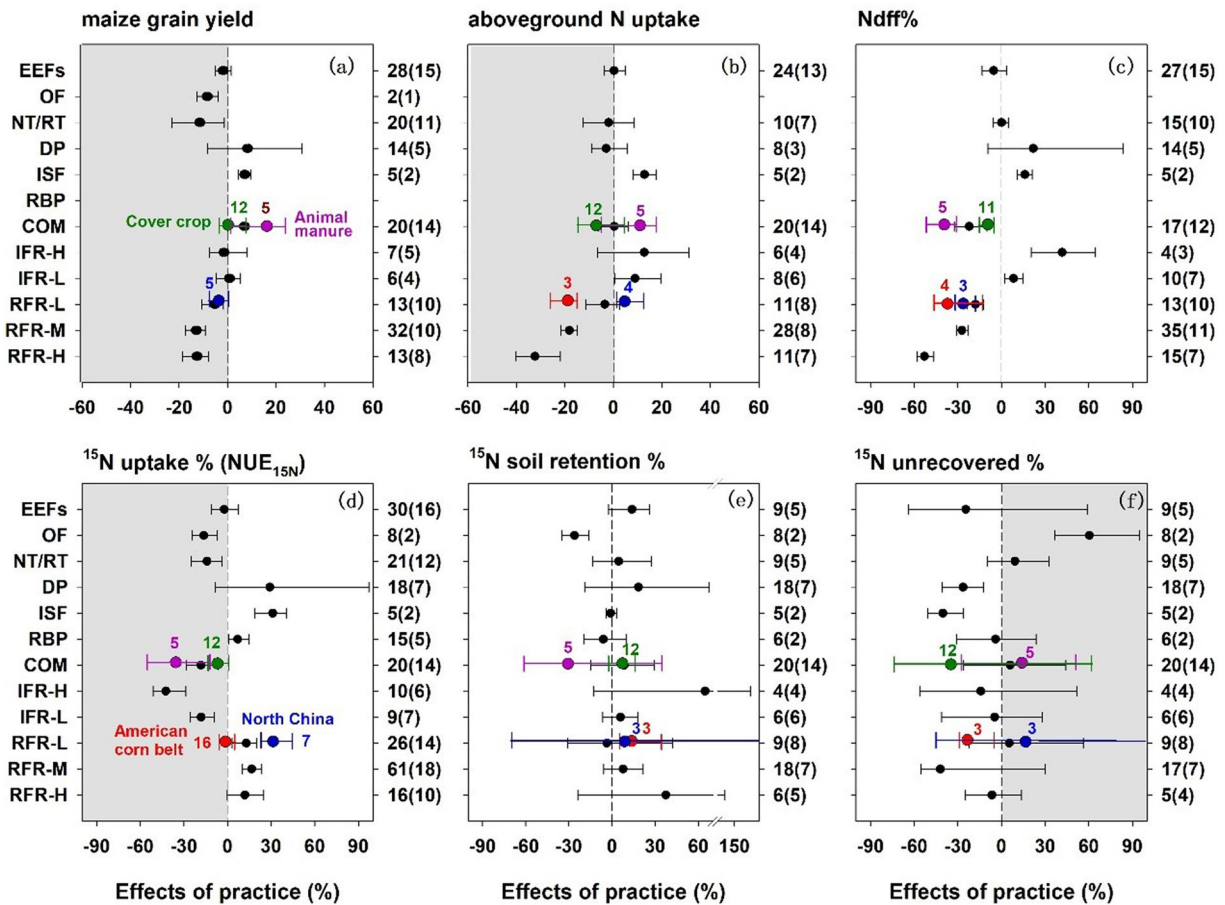


Figure 2. The impact of technologies and management practices (TMPs) on maize grain yield (a), N uptake(b), fraction of aboveground N derived from fertilizer (Ndff%, (c), and N fertilizer fates (uptake, soil retention and unrecovered, (d–f). Numbers of experimental observation and site-year (within brackets) were listed by the vertical axis. Different TMPs: Enhanced efficiency N fertilizers (EEFs); Using other forms of chemical N fertilizer (OF); No-tillage or reduced tillage (NT/RT); Deep placement of N fertilizer (DP); Increasing splitting frequency of fertilizer-N application (ISF); Reducing the proportion of basal N fertilizer application (RBP); Increasing fertilizer-N rate (IFR); Reducing fertilizer-N rate (RFR); Co-application with organic materials (COM). According to the magnitudes of the increase and decrease, IFR and RFR were subdivided into five categories: IFR-L (<100%), IFR-H (≥100%), RFR-L (<50%), RFR-M (=50%), and RFR-H (>50%). Missing data points for some indices in the figure indicated that the number of observations was less than two. Different changes induced by COM as cover crops and animal manures are shown by green and purple symbols. Different changes induced by RFR-L in regions of North China and American corn belt are shown by blue and red symbols in the figure. The missing red dot in Figure 2a means there is no data referring to the change of yield caused by RFR-L in American corn belt. The gray shading for the part of the figure indicates the direction of a potential undesirable change. The original data for making this figure, as well as the absolute number of unrecovered N fertilizer for each TMPs, can be found in Table S2.

of N fertilizer (−26%), and increasing splitting frequency of fertilizer-N application (−40%), corresponding to +30, −13, and −20 kg N ha^{−1} (Table S2).

In particular, co-application with organic materials was subdivided into two categories, namely cover crop and animal manure (Figure 2). Compared with the cover crop, co-application of animal manure caused more increase in maize grain yield and aboveground N uptake but also more suppression on fraction of aboveground N derived from fertilizer, NUE_{15N}, and ¹⁵N soil retention.

We compared the performance of different TMPs in the two regions with the most abundant observations, Northern China and the American corn belt (Figure S3). Most of the TMPs with more than two observations had similar effects in these two regions, except for low levels of reducing fertilizer-N rate. Even though the level of fertilizer-N reduction is very similar in North China (i.e., from 199 to 139 kg N ha^{−1}) and in the American corn belt (i.e., from 196 to 140 kg N ha^{−1}), the resulting impacts on aboveground N uptake and NUE_{15N} are different. In the American corn belt, the low level of reducing fertilizer-N rate significantly reduced aboveground N uptake with negligible impacts on NUE_{15N}; while in North China, it significantly

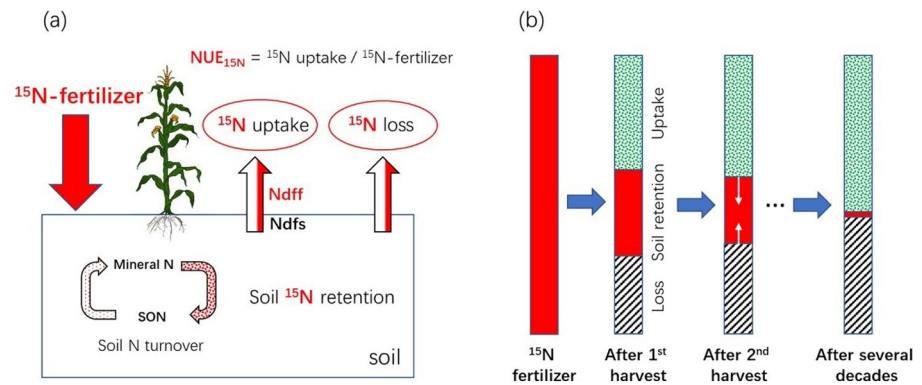


Figure 3. Schematic representation of fertilizer-N-fate and N use efficiency ($\text{NUE}_{15\text{N}}$) in maize cropping systems (a), and the impact of time scale (b). SON: soil organic nitrogen. Ndff: crop N derived from fertilizer. Ndffs: crop N derived from soil.

increased both aboveground N uptake and $\text{NUE}_{15\text{N}}$, although a lower fraction of aboveground N derived from fertilizer was observed in both regions (Figure 2).

4. Discussion

4.1. Conventional Nutrient Management

Under conventional nutrient management, a significantly higher $\text{NUE}_{15\text{N}}$ was observed in North America than in China (Table 1). The higher $\text{NUE}_{15\text{N}}$ in North America is likely attributed to a higher fraction of aboveground N derived from fertilizer (46%, in contrast to 34% in China) according to the definition of $\text{NUE}_{15\text{N}}$, because there were very small differences in N uptake and fertilizer-N rate between North America and China. Both $\text{NUE}_{15\text{N}}$ and fraction of aboveground N derived from fertilizer demonstrated a significantly positive relationship with SOC, suggesting the important role of SOC in determining fertilizer-N fate (Quan et al., 2020). This finding aligns with the existing literature which shows that soils with high SOC usually have a strong buffering capacity to conserve and supply N for crop growth through soil N turnover (Oldfield et al., 2019), either in the current season or in subsequent seasons (Smith & Chalk, 2018).

Even though $\text{NUE}_{15\text{N}}$ is lower in China, the other fertilizer efficiency parameters (i.e., N recovery efficiency and partial factor productivity) and the unrecovered ^{15}N (Table 1) are the same as North America, suggesting that Chinese maize production depends more on soil N supply (or legacy effects of previous N inputs) than that of North American to obtain the similar maize yield and N uptake (Figure 3). This is verified by the higher soil ^{15}N retention in maize cropping system in China than in North America (Table 1). However, the background content of soil N in China was only about half of the level in North America (Table 1). There are two possible explanations for this apparent paradox: (1) In Chinese cropland with low SOC, the capacities of microbial N immobilization and mineralization have been weakened by intensive agricultural use (e.g., with more than two growing seasons a year), long-term tillage, and low residue return rates. Consequently, a large amount of inorganic N was left in soil profiles after long-term excessive N input (Cui et al., 2010), which caused the dilution effect of fertilizer-N in the current season before being absorbed by roots, and led to more N subject to being lost to the environment in the following seasons (McLellan et al., 2018; X. Zhang, Mauzerall et al., 2015). While for North America, high soil TN does not necessarily mean high soil N availability or high N supply capacity. On one hand, North American crops may depend more on soil mineralization-immobilization-turnover processes than Chinese crops due to lower land-use intensity and higher crop residue return rates; on another hand, much of the soil organic N is derived from relatively recalcitrant components, although some crop residue inputs can decompose and release N during one growing season. (2) The size of the experiment plot (usually confined micro-plot) in China is usually small (Table 1). This might lead to overestimation of the contribution of original soil N prior to fertilization because part of the maize roots could move out of the plot border. Although many tracer studies were conducted in pots or micro-size field plots, it is recommended that field ^{15}N experiments with maize cultivation require larger plots than those used in regular experiments (Hauck et al., 1994; Smith & Chalk, 2018).

Besides SOC, we also found significant impacts of maize yield and N uptake on ^{15}N fate. Factors or practices that contribute to the increase of maize yield and N uptake may indirectly increase ^{15}N recovery in uptake, such as hybrid improvements, advanced cultivation, optimized nutrient management (Figure 3). With the development of breeding technology and mechanization, the increase of maize yield and N uptake in the future will likely lead to increases in $\text{NUE}_{15\text{N}}$ (Chen et al., 2013). While earlier literature showed that the partitioning of fertilizer-N fate in agricultural cropping systems could be significantly affected by climatic factors, such as precipitation and temperature (Dourado-Neto et al., 2010; Jensen et al., 2011), our meta-analysis did not find significant impacts of mean precipitation and temperature on fertilizer-N fate indicators. The annual means of precipitation and temperature may not be effective to reflect the pivotal influence of weather conditions on maize growth and fertilizer-N fate at critical growth stages. For example, the drought events caused by high temperature and low rain during the seedling stage or the flood events caused by too much rainfall during the silking stage may severely reduce the maize grain yield, though the mean temperature and precipitation are still in a reasonable range (Cociu, 2012; Ge et al., 2016; Hawkins et al., 2013).

Compared to crop ^{15}N uptake, the uncertainty of soil ^{15}N retention is much greater because of the spatial heterogeneity of soil ^{15}N distribution, as well as the inconsistent depth of soil sampling at harvest (Figure S1). This was indicated by the wider confidence interval of ^{15}N soil retention % (Figure 2e) than that of ^{15}N uptake % (Figure 2d) under different TMPs. The average proportion of ^{15}N unrecovered under the control condition was 28% with a standard deviation up to 19% due to error propagation (^{15}N unrecovered % = $1 - ^{15}\text{N}$ uptake % - ^{15}N soil retention %). In comparison, the unrecovered ^{15}N reported by another meta-analysis (Gardner & Drinkwater, 2009) was 37%, higher than the mean value reported in this study but still within the uncertainty range. In addition to the high uncertainties, other possible reasons for the difference include the following: (1) New varieties developed in recent years increased the absorption capacity of crops, especially for maize; (2) One-season-fate of N fertilizer in the maize cropping system might underestimate the total ^{15}N uptake and loss; (3) This study only included experiments with fertilizer-N rates within the range of 100–300 kg N ha⁻¹ season⁻¹ as conventional nutrient management cases while Gardner and Drinkwater (2009) included all available fertilizer-N rates. For example, the average fertilizer-N rate in Gardner and Drinkwater (2009) was 114 kg N ha⁻¹, while it was 181 kg N ha⁻¹ in this study (Table 1).

Based on the average fertilizer-N rate listed in Table 1, the unrecovered ^{15}N in the current season was calculated as 51 kg N ha⁻¹ season⁻¹ ($181 \times 28\%$). This rate is much lower than the threshold of desired N surplus initiated by the European Union (<80 kg N ha⁻¹ yr⁻¹, EU Nitrogen Expert Panel, 2015). However, the total N loss for the observation season is likely to be greater than 51 kg N ha⁻¹ yr⁻¹, when including N loss from nonfertilizer-derived N and fertilizer N input from previous years. In addition, if the measurement of ^{15}N in harvested crops and soil continues after one growing season, ^{15}N in soil retention is likely to decrease over time, because it may be lost to the environment after the growing season or in the following seasons, or it may be taken up by crops in following seasons. Consequently, the cumulative proportion of ^{15}N loss and ^{15}N uptake will increase over time (Figure 3b). Because very few experiments have tracked the fate of ^{15}N over a long term, and some of the long-term experiments showed relatively small and slow release of ^{15}N from soil retention (Sebilo et al., 2013), we chose to use the measurements of ^{15}N after one growing season in this study. However, we acknowledge that this approach does not account for the potential N loss during the fallow period after the growing season and has its limitation in reflecting the long-term effect of fertilizer-N and TMPs, mainly due to the uncertainty related to the long-term fate of ^{15}N in soil retention.

4.2. Different Technologies and Management Practices

TMPs, even though designed for improving N management (e.g., following the “4R” fertilizer management principles with right rate, right source, right timing and right place), have variable impacts on fertilizer-N fate and multiple goals of sustainable crop production (e.g., yield or N uptake promotion, $\text{NUE}_{15\text{N}}$ improvement and loss reduction) (T. Li et al., 2019).

Based on experimental data synthesized by this study, enhanced efficiency N fertilizers did not significantly increase $\text{NUE}_{15\text{N}}$ or yield. Enhanced efficiency N fertilizers were designed to delay ammonification and nitrification and eventually improve the synchronization between crop N demand and soil N supply throughout the crop growing season (Ladha et al., 2005; Qiao et al., 2015; M. Yang et al., 2016). However, in

the practice, enhanced efficiency N fertilizers may not improve NUE and crop yield because their impacts may be constrained to particular environmental conditions (T. Li et al., 2018, 2019). For example, in this study, the use of enhanced efficiency N fertilizers had no significant enhancement on grain yield, N uptake, fraction of aboveground N derived from fertilizer, and NUE_{15N} (Figure 2). Similar results were found in another synthesis, where N conversion inhibitors had no significant effect on the crop ^{15}N uptake in temperate agroecosystems (Gardner & Drinkwater, 2009). The lack of detectable effects of the enhanced efficiency N fertilizers might be caused by various soil and climatic conditions, cropping systems, and management practices (Abalos et al., 2014; Sha et al., 2020). For example, the urease and nitrification inhibitors tended to have a stronger impact on crop yield, plant N uptake and fertilizer-N fates in high-pH soils than in low-pH soils (Linguist et al., 2013; M. Yang et al., 2016).

Using other forms of N fertilizer (mainly ammonium-based fertilizer) rather than urea, significantly reduced NUE_{15N} and increased unrecovered $^{15}N\%$ based on the current eight observations (Figure 2). This result is different from a meta-analysis using data from nonlabeling trials, where it shows that the volatilization potential of urea is higher than many ammonium-based fertilizers, including calcium ammonium nitrate, ammonium sulfate, ammonium nitrate, but is lower than ammonium carbonate (Pan et al., 2016). Admittedly, this result based on ^{15}N trails has its limitations due to the small numbers of existing observations. More observations from ^{15}N -labeled trials are needed to reconcile the different results from labeled and nonlabeled studies.

No-tillage or reduced tillage reduced grain yield and NUE_{15N} by 11% and 14% after switching from the conventional tillage (Figure 2). The effects of no-tillage or reduced tillage may need a long time to show its advantages in achieving sustainable N management, through preventing soil erosion (wind erosion and water erosion) and increase carbon stock (Y. Li et al., 2018), however, as noted above, the ^{15}N data collected by this study has limitations in reflecting long-term effects of a TMP. As mentioned by Pittelkow et al. (2015), the practice of no-tillage or reduced tillage should be continued for several years and combined with the implementation of supporting measures (e.g., straw incorporation and crop rotation) to assure the maintenance of soil fertility and crop yield, especially for resource-poor regions and smallholder-dominated farming systems.

Deep placement of N fertilizer showed a tendency to improve yield (9%), fraction of aboveground N derived from fertilizer (22%), NUE_{15N} (29%) and retention (18%), and to reduce unrecovered ^{15}N by 26% (from 51 to 38 kg N ha⁻¹), but the confidence intervals overlapped with zero for all of these indices except for the unrecovered proportion (Figure 2, Table S2). Although the advantages of deep placement of N fertilizer are well established, farmers' adoption is still limited in developing countries because of the low degree of mechanization. Additional labor cost is required for placing the fertilizer at the right location. Besides, the depth of fertilizer placement is critical when considering the balance of N uptake and N loss. In addition, deep placement of fertilizer is not favorable for N uptake by crops with shallow roots. For example, decreasing NUE_{15N} (37%, 31%, and 19%) was found in another field study, where ^{15}N -labeled urea was placed at 8, 16, 24 cm below soil surface, respectively, in a summer maize system in China (Y. Yang et al., 2016).

Optimizing the timing and amount of fertilizer application, such as reducing the basal fertilizer-N proportion and increasing the splitting frequency of fertilizer-N application, can avoid excess fertilization as base fertilizer and increase N uptake along with crop growth (F. Zhang et al., 2012). As a result, NUE_{15N} was increased and N loss was reduced (Xia et al., 2017). Our dataset supports that conclusion and shows a higher enhancement of NUE_{15N} by increasing the splitting frequency of fertilizer-N application (31%) than by reducing the basal fertilizer-N proportion (7%) (Figure 2). The effects of these two TMPs are affected by other environmental factors, such as weather conditions. For example, a continuous drought event can hinder the movement and absorption of N fertilizer in the soil. Therefore, topdressing before a rainfall or irrigation event can help the release and use of N fertilizer while reducing its volatilization loss, while caution must be exercised because excessive precipitation may increase N loss through leaching and runoff.

Combined application of N fertilizer and organic materials can accelerate the microbial N turnover and then preserve N as organic forms in the soil for future use, but it can also fuel denitrifying microorganism and consequently increase N gaseous losses (Ladha et al., 2005; Quan et al., 2018; M. Wang et al., 2018). In general, the co-application extended agroecosystem-scale N retention and reduced N loss across a range of

environments, particularly in the presence of surplus N (Gardner & Drinkwater, 2009). This was verified by other meta-analyses based on nonlabeling trials, where they have found substantial reductions in N loss (e.g., nitrate leaching and nitrogenous gas emission) with cover crops (Eagle et al., 2011; Thapa et al., 2018; Tonitto et al., 2006). However, in this study, organic additions did not change soil ^{15}N retention and ^{15}N unrecovered significantly, though the contribution of fertilizer-N to crop N and $\text{NUE}_{15\text{N}}$ were significantly reduced. This inconsistency may be related to the different inclusion and attribute of research object (chemical fertilizer N input vs. total N input). The enhanced grain yield under co-application of N fertilizer and organic materials might be due to the improvement of soil physical, chemical and biological environment, as well as the increased nutrient supply from the mineralization of the organic material itself rather than the direct contribution by N fertilizer (X. Zhang et al., 2020). Consequently, co-application of N fertilizer and organic materials can potentially improve their performances in $\text{NUE}_{15\text{N}}$ and N loss by allowing for reductions in N fertilizer over time. For example, the use of cover crops increases soil resilience to adverse growing conditions which may benefit fertilizer N storage and subsequent use (Bowles et al., 2020). In contrast, animal manure had a greater impact on maize grain yield, aboveground N uptake, and fertilizer-N-fate in current season than cover crops because animal manure could provide more active nonfertilizer-derived nutrients than cover crops at short term (Figure 2).

Reducing fertilizer-N rate improved $\text{NUE}_{15\text{N}}$, while increasing fertilizer-N rate reduced $\text{NUE}_{15\text{N}}$ due to the “law of diminishing return” regarding the yield response to fertilizer-N input (X. Zhang, Mauzerall et al., 2015). The aboveground N uptake and the fraction of aboveground N derived from fertilizer in this study suggested increasing trends with the increase of N rate. However, the increase of N uptake was not significant under the practices of low and high levels of increasing fertilizer-N rate, suggesting that the yield response is close to the threshold N rate and more N supply does not benefit N uptake. The different responses to low reduction of fertilizer-N rate in the regions of North China and the American corn belt implied that maize N uptake derived more from the nonfertilizer-N supply in North China than that in the American corn belt. Those results also demonstrated that farmers in the American corn belt may face a risk of yield or N-uptake reduction when reducing fertilizer-N rate in the range of 0%–50%. However, in North China, the low reduction in fertilizer-N rate increased both N-uptake and $\text{NUE}_{15\text{N}}$ significantly under the condition of decreased fraction of aboveground N derived from fertilizer, which implied that the conventional N fertilization rate might exceed the threshold N rate for maximum yield (Ju et al., 2009). Excessive N application over many years and high N deposition in intensive agricultural areas in China, leads to available N accumulation in the soil. Consequently, even if the fertilizer-N rate is reduced during the short term (e.g., one or several seasons), its potential negative effect on crop growth may not be reflected immediately due to the indigenous N supply (David et al., 2010).

How to feed the growing population while reducing impacts on the environment is a challenging task. Therefore, it is critical to improve the efficiency of N fertilizer and reduce N losses (X. Zhang, 2017; X. Zhang, Davidson et al., 2015). Based on a meta-analysis, Xia et al. (2017) found N management practices in 376 nonlabeling studies were all effective in decreasing reactive N losses and increasing grain yield in China. In contrast, our data collected from ^{15}N tracer studies worldwide indicated that TMPs aiming to improve nutrient management may have variable effects. For example, deep placement of N fertilizer and increasing the splitting frequency of fertilizer-N application have relatively consistent positive performance and may become the recommended options to increase grain yield and $\text{NUE}_{15\text{N}}$ and decrease potential N loss in intensively managed maize systems. As for enhanced efficiency N fertilizers, other forms of N fertilizer, no-tillage or reduced tillage, co-application of N fertilizer and organic materials, increasing fertilizer-N rate, and reducing fertilizer-N rate, the sustainable N management goals of yield increase, $\text{NUE}_{15\text{N}}$ increase, and N loss reduction were not achieved simultaneously in this data set. However, the performance of these TMPs varies largely among regions with diverse climate and soil conditions. The different results from non-labeling trails and labeling trials could be partly attributed to the limitations of the two methods: (1) The ^{15}N -tracer method usually tracks fertilizer-N-fate only in one or a few growing seasons. While it can precisely track the fate of the applied fertilizer in a season and distinguish the influence of soil legacy effect, it has limitations in reflecting the fate of fertilizer inputs and the effect of TMPs over the long term. (2) In contrast, the nonlabeling trial method is limited in identifying the contributions of soil N and management practices from previous seasons and the current season. Synthesizing observations from the two methods may generate more insights on the effectiveness of different TMPs and should be considered for future research.

In addition to improving the assessment of TMPs on their influences on fertilizer-N-fate, increasing N fertilizer use efficiency and reducing N loss will also rely on an improved understanding of TMPs' performance under region-specific environmental and socioeconomic conditions. Limited by the number of observations, we did not compare the performance for all TMPs in each region, so whether these TMPs are more efficient than others under specific conditions still requires further verification. The economic feasibility for implementing a TMP is also critical for the wide adoption of TMP, but it varies due to region-specific market conditions and policies (T. Li et al., 2019). Therefore, future investigations on strategies for improving crop N management should sufficiently consider these region-specific characteristics.

5. Conclusions

Both food security and environmental quality require the efficient use of N fertilizer in practice. Meanwhile, the low use efficiency for grain production implies that there is still much room for improvement. Our results show that under conventional management practices, the fate of fertilizer-N was mainly impacted by soil organic matter, which was the major reason why the NUE_{15N} in China was significantly lower than that in the North America and Europe countries. While high soil organic matter does not necessarily represent high soil N supply capacity, a higher proportion of crop N derived from fertilizer (Ndff%) demonstrated that maize growth depends more on the new applied fertilizer-N in North America than in China. Among the nine TMPs considered, deep placement and split application were shown to improve yield performance and NUE_{15N} and to reduce N losses. In addition, our results also showed that in regions where the agronomically recommended rate has not been exceeded, such as in American corn belt, reducing fertilizer-N rate might face the risk of reducing current-season productivity. To sum up, our study provides a new perspective for the understanding of the environmental and anthropogenic controls on farmland N cycles and provides guidance for improving N management with higher yield and lower unintended N pollution.

Data Availability Statement

Data sets used in this meta-analysis are available in the supporting information.

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