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Estimation of Nitrogen Supply for Summer Maize Production through a Long-Term Field Trial in China

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Abstract: Supplying adequate nitrogen (N) to meet crop demand is critical for enhancing agricultural sustainability. Not only fertilizer N, but also N from other available sources should be considered in N supply capacity. We conducted a 10-year farming experiment using a split-plot design with two different main fertilizer management approaches and three N application strategies as add-on sub-treatments. Based on the experiment, we estimated the total N supply (TN_{supply}) for the summer maize cropping system, through considering environmental, soil, crop residue, and fertilizer N sources. An appropriate TN_{supply} was established by correlating TN_{supply} with the relative yield (RY), N input and output, and N use efficiency (NUE). The results revealed a wide variation in TN_{supply} (from 88 to 755 kg ha^{-1}). The RY, N input, and N output fitted well to TN_{supply} using linear-plateau, linear, and linear-plateau models, respectively. The lower limits of TN_{supply} for achieving the maximum RY and N output were 361 and 358 kg ha^{-1}, respectively. The relationship between N input and N output was described as linear-plateau. We determined the slope of the linear curve (55.4%) as the lower limit of NUE, beyond which the upper limit of TN_{supply} was determined to be less than 497 kg ha^{-1}. Thus, appropriate TN_{supply} values ranged from 325 to 497 kg ha^{-1} for summer maize production, which could ensure enough N supply for higher yields and avoid excessive N input for higher NUE and lower environmental N loss. Our findings highlight that TN_{supply} can be an alternative indicator for evaluating N management.

Keywords: total nitrogen supply; relative yield; nitrogen use efficiency; summer maize

Citation: Huang, S.; Yang, W.; Ding, W.; Jia, L.; Jiang, L.; Liu, Y.; Xu, X.; Yang, Y.; He, P.; Yang, J. Estimation of Nitrogen Supply for Summer Maize Production through a Long-Term Field Trial in China. *Agronomy* **2021**, *11*, 1358. https://doi.org/10.3390/agronomy11071358

Received: 16 May 2021
Accepted: 30 June 2021
Published: 2 July 2021

1. Introduction

Approximately 30% of synthetic nitrogen (N) fertilizers produced globally are used in China, with an N use efficiency (NUE) of 25%, compared to 52% in European countries and 68% in the United States of America [1,2]. Excessive application rate and low use efficiency of synthetic N fertilizers have caused serious environmental problems, such as nitrous gases emissions, soil nitrate accumulation, and groundwater pollution [3–5]. It is not realistic and is problematic to expect higher crop yields by increasing N fertilizer application rates.

Maize (*Zea mays* L.) is one of the leading grain crops for global food security [6,7]. In China, a summer maize–winter wheat rotation is a highly intensified cropping system [8], and the total sown area of summer maize (23.7 million hectares) accounts for 57.5% and 24.2% of the whole maize and cereal crops, respectively [9]. Maize production in China is dominated by small-scale farms with high N fertilizer inputs (200–300 kg N ha^{-1}), low NUE (lower than 30%), and heavy environmental pollution (40.1% of N fertilizer lost via NH_3 volatilization, leaching, and denitrification) [5,8,10]. Moreover, mineral N accumulating in the 0–1 m soil profile has exceeded 400 kg ha^{-1} [11,12]. The nitrate levels in the groundwater near these farms are dangerously high and cause a serious public health crisis for people acquiring their drinking water from these watersheds [12].

Residual mineral N in the soil profile can be used as an important N source for crops, and should be fully considered in N management practices [13,14]. Moreover, other sources of N, such as deposition N, irrigation N, and returned-straw (crop residue) N, should be also included [15–17]. Previous studies have focused on the response of grain yield or N uptake to N application [18,19]. However, the grain yields did not keep rising as the N fertilizer rates increased, especially when mineral N content in the top 20 cm of soil went above 20–30 mg kg^{-1} [20]. The nonfertilizer N sources, such as soil N, environmental N, and crop residue N, were utilized by crops. In 2015, China introduced a "Zero Growth of Chemical Fertilizer Use by 2020" plan to reduce N input from synthetic N fertilizers, improve crop N management, and maintain crop yields [21]. To achieve this goal, all N sources need to be taken into account in the N supply. In north-central China, it was reported that the deposition of N surpassed 50 kg N ha^{-1} year^{-1}, which significantly affected the cropping systems [22]. Returning crop residue to the field has been widely adopted in China and could provide extra N for meeting subsequent crop demand via microbial decomposition [23]. Returned N from crop residues has been demonstrated, accounting for 14.1%, 27.5%, and 37.4% of the total N requirements for wheat, rice, and maize, respectively [24]. Therefore, balancing environmental, residual soil, organic inputs (crop residue), and fertilizer N is essential for improving N management and protecting the environment. However, to date, an exact quantification of total N supply (TN_{supply}) for maize production is still lacking, and an optimum N supply level for sustainable summer maize cropping is urgently needed.

For this purpose, we conducted a field experiment in a summer maize–winter wheat rotation system from 2009 to 2019. The experiment included two fertilizer management approaches and three N application strategies. Relationships among TN_{supply} level (involving environmental, soil, crop residue, and fertilizer Ns) and the crop yields, N input, and N output of maize crops were systematically examined. Our goals were (i) to assess the responses of the TN_{supply} to crop yield, N input, and N output, and (ii) to determine appropriate TN_{supply} levels that are needed for maintaining yields and achieving increased NUE for summer maize production.

2. Materials and Methods

2.1. Experimental Design

The long-term experiment started in 2009 at the Dahe Experimental Station (38°07′44″ N, 114°29′21″ E, under the WG-S84 geographic system) in Shijiazhuang city, Hebei Province, north-central China. The location is characterized by a semi-humid continental monsoon climate with 300–600 mm of annual precipitation and 14.3 °C average annual air temperature. The monthly precipitation and maximum and minimum temperatures in each season at the experimental station are shown in Figure 1. Maize was planted and harvested in mid-June and early October, respectively. Wheat was sowed and harvested in mid-October and in early June of the following year, respectively. Such maize–wheat rotations are typical for this and similar agricultural regions, which are characterized by fluvo-aquic soil type with sandy loam. The 20 cm topsoil layer in 2009 possessed pH_{H2O} (soil:water 1:2.5) equal to 7.1, and organic matter and N contents equal to 16.4 and 1.14 g kg^{-1} respectively, while NO_3^--N, Olsen-phosphorus (P), and available potassium (K) contents were equal to 27.9, 13.6, and 96.6 mg kg^{-1}, respectively.

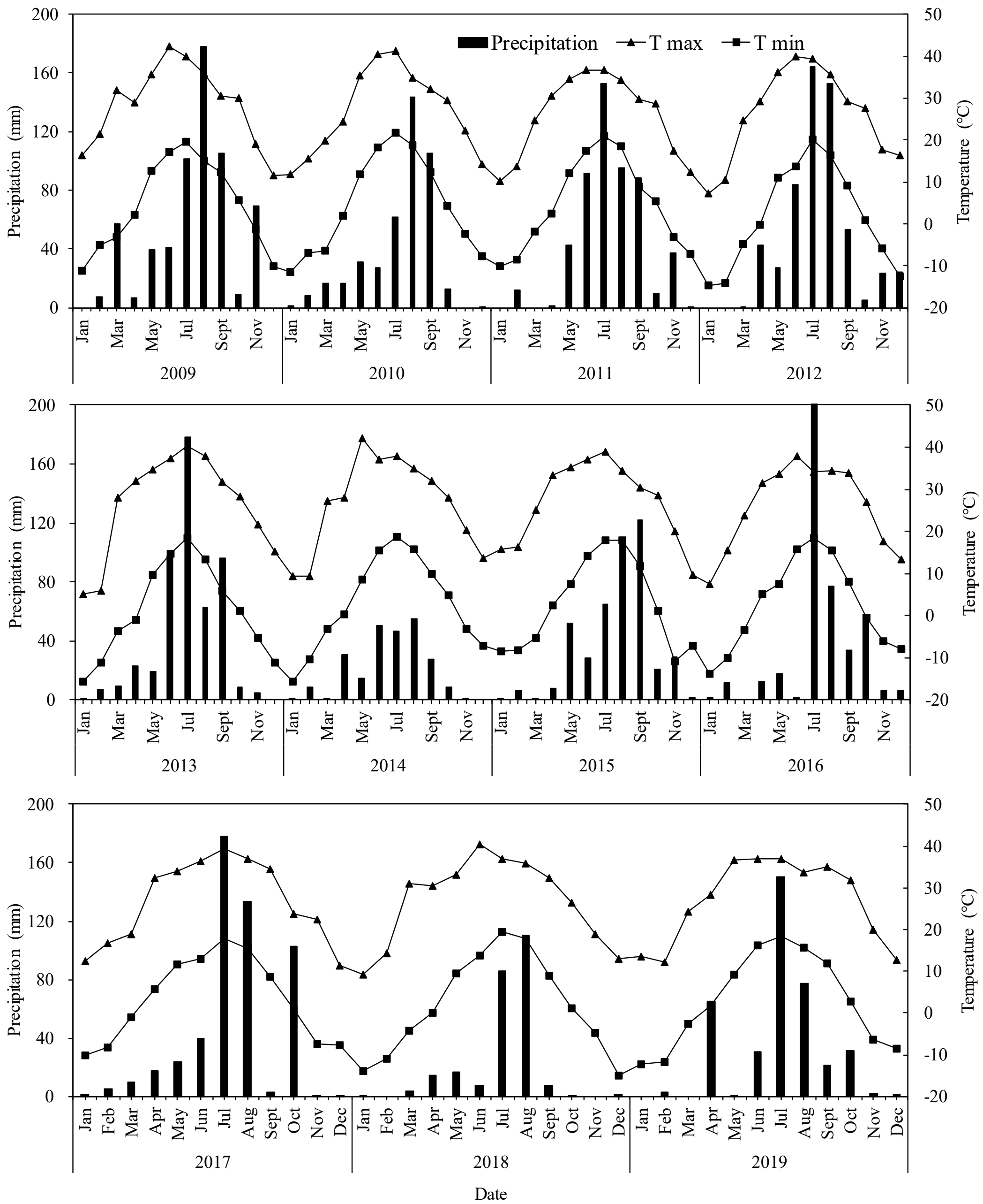

Figure 1. Monthly precipitation and maximum and minimum temperatures from 2009 to 2019 at Dahe station in north-central China.

The long-term experiment used a split-plot design, as reported by Huang et al. [16]. The main treatments contained Nutrient Expert (NE), a Nutrient Decision Support System (NDSS) [19] that combines 4R (right source, right place, right time, and right rate) nutrient management together with improved varieties and optimized plant density, and Farmers' Practice (FP), which relies on the field managing practices of local farmers. Three different N addition strategies were used in subplots of each of the main plots, characterized by their treatments with different TN_{supply} levels, as follows:

(1) 0N (zero additional N was introduced).

(2) 2N (N fertilizers were introduced every two out of three years, with no fertilizer application during the first year).

(3) 3N (fertilizer was applied every year; in this case, one cycle lasted three years).

P and K applications were consistent in all three subplots. Thus, six treatments were marked as NE_{0N}, NE_{2N}, NE_{3N}, FP_{0N}, FP_{2N}, and FP_{3N}.

The FP fertilizer application rates were calculated using the data obtained for over 100 farmers collected in 2009–2012. A fixed rate was applied from 2013 to 2019 due to the widespread use of compound fertilizers (shown in Supplementary Table S1). We relied on the NDSS to determine the fertilizer rates for the NE treatments (Supplementary Table S1). The system was used to recommend location-specific fertilizer applications with the 4R strategy to help to meet the nutrient demand at different stages of crops and in combination with other optimal agronomic practices [19,25]. For maize, similar fertilizer application methods were applied in both NE and FP: 1/2 of the N, total P, and total K were applied as basal fertilizers and the remaining 1/2 of the N was top-dressed at the V12 stage [26] (lasting from approximately 25 July to 5 August each year). All fertilizers were applied and banded for both basal and top-dressing. We used ZhengDan958 maize variety for FP and NE planted at 60,000 ha^{-1} density in 2009–2019 and in 2009–2013. In 2014–2019, XianYu335 with higher yield potential was planted for NE treatments at a density of 75,000 ha^{-1} (Supplementary Table S1).

2.2. Sampling and Measurements

At wheat harvest, the N concentration of crop residue was determined by harvesting three 2 m^2 areas in the middle of each plot. Three rows in the middle of each plot were manually harvested. The grains were dried to determine the yield (moisture content of 14%). Five succussive plants located in one spot were sampled to determine the nutrient concentrations. Before sowing and after harvesting, the soil was sampled at 0–5, 5–10, 10–20, 20–30, 30–60, and 60–100 cm layers, after which mineral N content was analyzed. The stock, foliage, and grains were separated and dried at 70 °C until no weight change was observed. The total N contents were obtained by the Kjeldahl automated method after the samples were subjected to wet digestion by the H_2SO_4 and H_2O_2 mixture [27]. For the residual mineral N content analysis, the fresh soil was extracted using 1 M KCl [28], and then analyzed by a high-resolution AA3 instrument (manufactured by Bran + Luebbe, Norderstedt, Germany).

2.3. Data Analysis

2.3.1. Agronomic Indices of Nitrogen Use Efficiency

Four indicators of NUE were calculated as follows [29]:

$$\text{Recovery efficiency of N } (\mathrm{RE_N}, \%) = (\mathrm{N_{up}} - 0\mathrm{N_{up}})/\mathrm{N_{rate}} \times 100\%, \quad (1)$$

$$\text{Agronomic efficiency of N } (\mathrm{AE_N}, \mathrm{kg\ kg^{-1}}) = (\mathrm{N_{yield}} - 0\mathrm{N_{yield}})/\mathrm{N_{rate}}, \quad (2)$$

$$\text{Physiological efficiency of N } (\mathrm{PE_N}, \mathrm{kg\ kg^{-1}}) = (\mathrm{N_{yield}} - 0\mathrm{N_{yield}})/(\mathrm{N_{up}} - 0\mathrm{N_{up}}), \quad (3)$$

$$\text{Partial factor productivity of N } (\mathrm{PFP_N}, \mathrm{kg\ kg^{-1}}) = \mathrm{N_{yield}}/\mathrm{N_{rate}}, \quad (4)$$

where N_{up} and $0N_{up}$ indicate N uptake from 3N and 0N treatments in NE or FP plots (kg ha^{-1}), N_{yield} and $0N_{yield}$ indicate grain yields from 3N and 0N treatments in NE or FP plots (kg ha^{-1}) respectively, and N_{rate} were the corresponding N application rates in NE or FP plots (kg ha^{-1}).

2.3.2. Total Nitrogen Supply and Nitrogen Budgets

To narrow the variations of the maize yield caused by climate differences during the 2000–2019 period, the relative grain yields (RY) were obtained using the formula below [16,30]:

$$\mathrm{RY} = \mathrm{Y_{treatment}}/\mathrm{Y_{max}} \times 100\%, \quad (5)$$

where $Y_{treatment}$ and Y_{max} are normal and maximum grain yields of the treatments in the same year (in kg ha^{-1}).

The TN_{supply} (kg ha^{-1}) was calculated as follows:

$$TN_{supply} = N_{soil} + N_{env} + N_{straw} + N_{fert}, \quad (6)$$

where N_{soil} is the mineral N content in the 0–1 m soil layer before planting, N_{env} is the environmental N from irrigation and precipitation during the maize growing season, N_{straw} is the returned-straw N from the preceding wheat crop (also equal to the N in the aboveground wheat straw), and N_{fert} is the N fertilizer applied during the maize growing. N_{soil} is the theoretical end-product of mineralization and immobilization of soil organic matter, environmental N, crop residue, or previously applied fertilizer [14,31], and TN_{supply} and N_{soil} comprise the residual N from the previous seasons.

NUE (in %), a popular indicator, was used to assess the crop system N efficiency, which was established by the EU Nitrogen Expert Panel [32]. In this case, crop uptake was the only N output, while inorganic, organic, and soil mineral N were the only inputs [15,16,33].

$$NUE = N\ output/N\ input \times 100\%, \quad (7)$$

$$N\ output = N_{uptake}, \quad (8)$$

$$N\ input = N_{env} + N_{straw} + N_{fert} + \Delta N_{soil}, \quad (9)$$

where N_{uptake} is the N content in the maize grain and straw (in kg ha^{-1}) and ΔN_{soil} is the change in soil mineral nitrogen content, which is the difference between residual soil N content in the samples collected before maize sowing and after maize harvesting (in kg ha^{-1}).

RY, N output, and N input were plotted vs. TN_{supply} using SAS software (1993). Linear and linear-plateau models were used to fit the corresponding data [34]. The variance analyzed differences among the obtained data and the least significant difference ($LSD_{0.05}$) tests via SPSS version 19.0 software (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Grain Yield and Agronomic Indices of NUE

There were no significant differences in grain yield between the NE_{3N} and FP_{3N} treatments (Table 1). NE management could maintain a high crop yield with reduced fertilizer N application. Compared with FP, NE increased the recovery efficiencies of the N applied by 10.3 percentage points, and improved agronomic efficiency, physiological efficiency, and partial productivity of the N applied by 54.8%, 10.3%, and 28.8%, respectively (Table 2).

Table 1. Grain yields of summer maize in NE and FP treatments from 2009 to 2019.

Year	NE (Mg ha^{-1})			FP (Mg ha^{-1})		
	0N	2N	3N	0N	2N	3N
2009	6.1b [1]	6.0b	6.9a	5.9b	5.9b	6.5ab
2010	5.6cd	6.2bc	6.9ab	5.4d	6.6ab	7.0a
2011	5.9b	7.0a	7.5a	5.9b	7.0a	7.3a
2012	7.4c	8.1abc	8.6a	6.5d	7.8bc	8.5ab
2013	6.5b	7.8a	7.8a	5.3c	7.1ab	7.6a
2014	6.1c	7.8a	8.1a	6.3bc	7.5ab	7.5ab
2015	3.9c	5.7a	6.0a	4.8b	5.8a	6.3a
2016	3.9c	6.5ab	7.1a	4.0c	6.3b	6.0b
2017	6.7b	7.8a	7.9a	6.5b	7.6a	7.5a
2018	6.1c	7.0b	8.0a	5.8c	6.7b	7.5ab
2019	5.2b	7.4a	7.7a	6.4b	7.2ab	6.9ab
Average	5.8c	7.0b	7.5a	5.7c	6.9b	7.1ab

[1] Values followed by different letters in the same column for different treatments are significantly different at the 0.05 probability level.

Table 2. Recovery efficiency, agronomic efficiency, physiological efficiency, and partial factor productivity of nitrogen in NE and FP treatments from 2009 to 2019.

Year	RE_N (%)		AE_N (kg kg^{-1})		PE_N (kg kg^{-1})		PFP_N (kg kg^{-1})	
	NE	FP	NE	FP	NE	FP	NE	FP
2009	19.5a [1]	15.6b	3.2b	4.0a	16.4b	25.4a	28.7b	46.2a
2010	28.3a	23.1b	7.2a	5.4b	25.3a	23.5a	38.3a	23.4b
2011	30.3a	14.8b	10.7a	4.7b	35.2a	31.7b	49.8a	24.2b
2012	25.5a	27.6a	6.8b	8.7a	26.6b	31.4a	47.4a	37.6b
2013	26.6b	44.9a	6.9b	10.2a	25.8a	22.8b	42.8a	33.7b
2014	43.2a	33.9b	10.5a	5.3b	24.3a	15.6b	44.2a	33.4b
2015	58.6a	35.9b	11.7a	6.7b	19.9a	18.7a	33.0a	28.2b
2016	53.8a	29.5b	17.3a	9.1b	32.1a	30.9a	38.9a	26.7b
2017	47.1a	25.8b	6.3a	4.3b	13.5b	16.5a	43.3a	33.1b
2018	42.5a	37.2b	10.6a	7.5b	24.9a	20.0b	43.9a	33.4b
2019	51.8a	24.7b	14.0a	2.1b	27.0a	8.5b	42.4a	30.7b
Average	38.8a	28.5b	9.6a	6.2b	24.6a	22.3b	41.1a	31.9b

[1] Values followed by different letters in the same column for different treatments are significantly different at the 0.05 probability level.

3.2. Estimation of Total N Supply

A wide range of TN_{supply} (88–755 kg ha^{-1}) was observed under different long-term management and N application strategies in 2010–2019 (Table 3). The soil residual mineral N content ranged from 21 to 448 kg ha^{-1}, which was 12.1–82.6% (51.8% on average) of the TN_{supply}. The environmental N accounted for 3.7–41.3% of the TN_{supply}, with an average of 11.8%. The average crop residue N was 32.5 kg ha^{-1}, which accounted for 10.2% of the TN_{supply}. Fertilizer N accounted for 0% to 65.0% of the TN_{supply}, with an average of 26.3%.

Table 3. Different sources of nitrogen and total nitrogen supply during the whole maize growing season.

Year	Treatment	NE (kg ha^{-1})					FP (kg ha^{-1})				
		N_{soil}	N_{env}	N_{straw}	N_{fert}	TN_{supply}	N_{soil}	N_{env}	N_{straw}	N_{fert}	TN_{supply}
2010	0N	209	28	19	0	256	188	28	18	0	233
	2N	194	28	18	180	420	213	28	22	300	563
	3N	211	28	28	180	447	204	28	34	300	566
2011	0N	163	28	20	0	211	145	28	18	0	191
	2N	209	28	38	150	424	216	28	44	300	588
	3N	212	28	45	150	435	221	28	49	300	598
2012	0N	63	28	25	0	115	58	28	29	0	114
	2N	283	28	43	0	354	347	28	45	0	420
	3N	191	28	42	182	443	323	28	55	225	631
2013	0N	48	28	13	0	88	64	28	12	0	104
	2N	77	28	17	182	304	77	28	21	225	351
	3N	110	28	45	182	365	182	28	60	225	494
2014	0N	56	28	20	0	104	67	28	19	0	114
	2N	65	28	31	182	306	70	28	39	225	362
	3N	218	28	48	182	475	420	28	50	225	723
2015	0N	97	27	14	0	138	87	27	13	0	127
	2N	139	27	51	0	217	245	27	54	0	326
	3N	229	27	58	182	496	412	27	68	225	732
2016	0N	134	28	8	0	170	137	28	11	0	175
	2N	133	28	13	182	356	141	28	23	225	417
	3N	242	28	37	182	488	448	28	55	225	755
2017	0N	106	34	10	0	150	99	34	12	0	145
	2N	113	34	27	182	356	144	34	40	225	444
	3N	143	34	37	182	396	180	34	41	225	479

Table 3. *Cont.*

Year	Treatment	NE (kg ha^{-1})					FP (kg ha^{-1})				
		N_{soil}	N_{env}	N_{straw}	N_{fert}	TN_{supply}	N_{soil}	N_{env}	N_{straw}	N_{fert}	TN_{supply}
2018	0N	89	32	8	0	129	86	32	10	0	129
	2N	222	32	32	0	286	285	32	45	0	363
	3N	308	32	42	182	564	357	32	49	225	664
2019	0N	57	19	5	0	82	21	19	6	0	46
	2N	52	19	54	182	306	42	19	60	225	346
	3N	90	19	44	182	335	168	19	55	225	467

3.3. Relationships between Total N Supply and Relative Yields, N Output, and Input

The best fit of the relationship between TN_{supply} and RY was obtained using a linear-plateau model (shown in Figure 2a). The minimum TN_{supply} capable of providing the maximum RY (equal to 95.0%) was 361 kg ha^{-1}. After that, the RY increased linearly (with a slope equal to 0.084). The relationship between TN_{supply} and N input was also linear (Figure 2b). Moreover, 63.4% (the slope) of the TN_{supply} was added to the system, while 36.6% was predicted to remain. The best fit of the N output plotted vs. TN_{supply} was obtained by the linear-plateau model (see Figure 2c). The minimum TN_{supply} level needed for maximum N output was 358 kg ha^{-1}, and the maximum N output (maize N uptake) was 164 kg ha^{-1}.

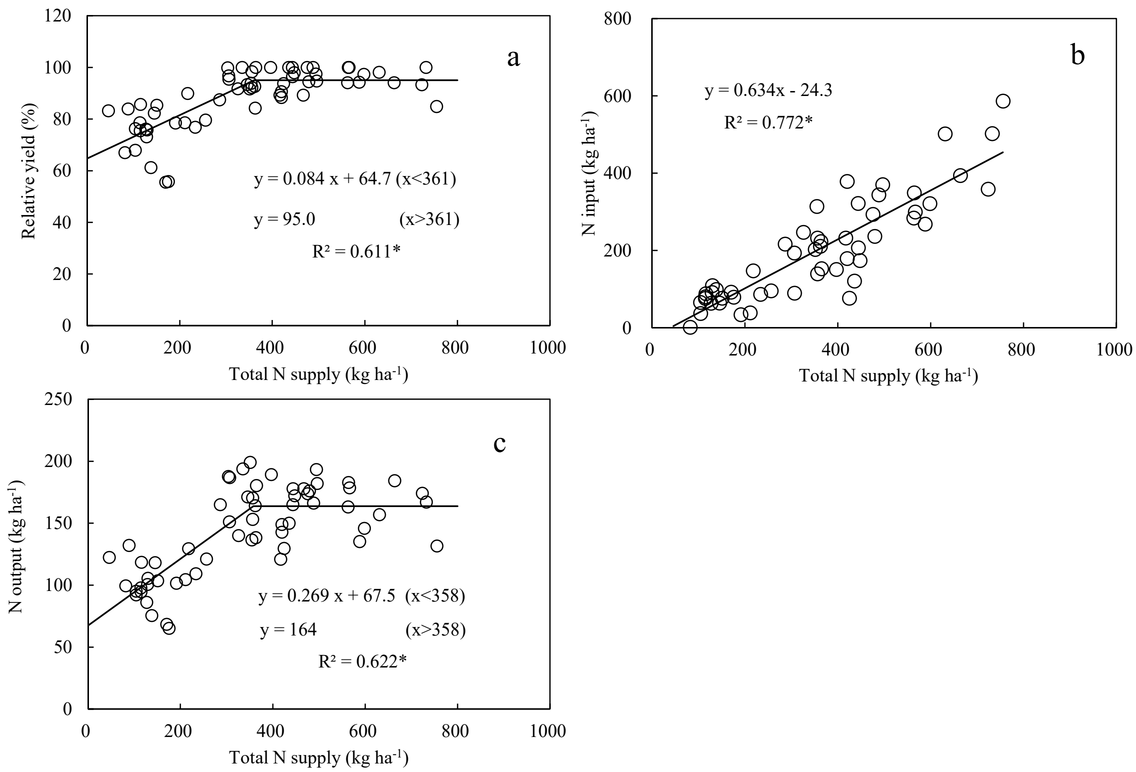

Figure 2. Response of relative yield, N input, and N output as a function of $TN_{supply.}$ (**a**). Relationship between $TN_{supplyy}$ and relative yield. (**b**). Relationship between $TN_{supplyy}$ and N input. (**c**). Relationship between $TN_{supplyy}$ and N output. "*" means $p < 0.05$.

3.4. N Input vs. N Output and NUE

The N input and output demonstrated a linear-plateau relationship (Figure 3). The minimum input that could achieve the maximum N output (161 kg ha^{-1}, similar to the values observed in Figure 2c) was 160 kg ha^{-1}. Using the NUE conceptual framework developed by the EU Nitrogen Expert Panel, we added the upper and lower limits of NUE in Figure 3. The slope of the linear curve was determined to be the lower limit of NUE (55.4%), and the upper limit was 90.0%. We added two auxiliary lines that represented those NUE values in Figure 3. The points where the NUE lines intersected the plateau line were the thresholds of N input within the NUE targets (55.4–90.0%), which were 179–291 kg ha^{-1}. Considering that N input tendency on TN_{supply} could be expressed as y = 0.634x − 24.3 (see Figure 2b), the TN_{supply} ranged from 321 to 497 kg ha^{-1}, within which the system would achieve a sustainable NUE value.

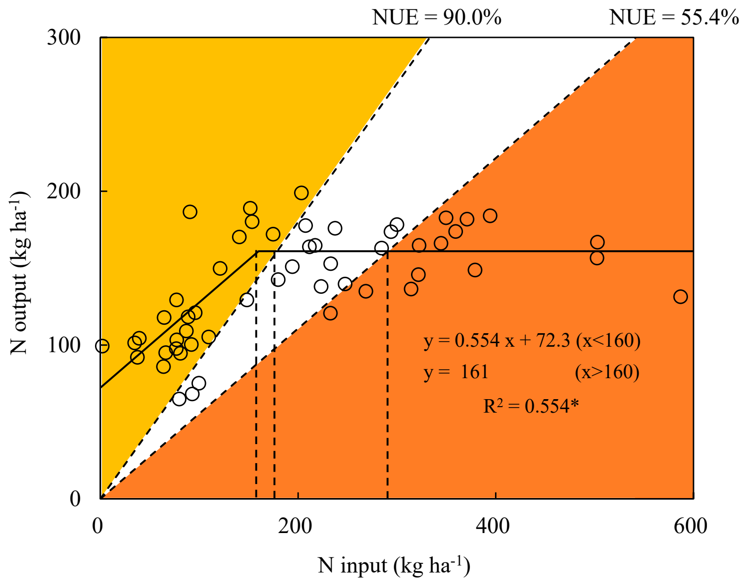

Figure 3. Relationship between N input and N output. The slope of the diagonal wedge represents a range of desired NUE between 55.4% and 90.0%: the orange part means lower values of NUE, which could exacerbate N pollution, while the yellow part means higher values of NUE, which risk mining of soil N stocks. "*" means $p < 0.05$.

3.5. Suitable Total N Supply

Based on the correlation between the TN_{supply} and the RY, N input, and N output, the suitable TN_{supply} level that could maintain grain yields and achieve increased NUE with reduced environmental N loss was 361–497 kg ha^{-1} (Figure 4).

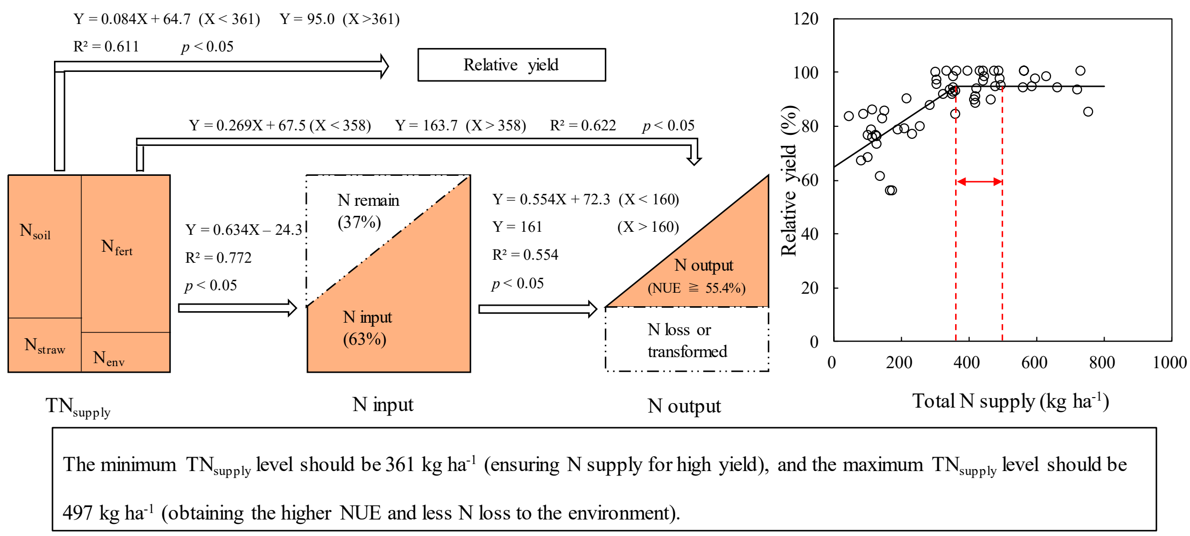

Figure 4. Correlation between TN_{supply} and relative yield, N input, and N output, respectively. The dependent variables Y and X are the variables in front and at the end of the arrow, respectively. The orange part indicates the actual existence of the current stage, and the white part is the part removed in the current stage.

4. Discussion

4.1. Different Sources of N

Different sources of N can provide bioavailable N for crop uptake [35,36], and together, these sources constitute the total N supply. When all sources of N are fully considered, achieving NUE together with sustainable development can be accomplished.

In north-central China, smallholder farmers often apply excessive amounts of N fertilizer to ensure high yields, and the overuse of N fertilizer leads to lower NUEs and higher mineral N accumulation levels in the soil [5,37]. In this study, the average RE_N (28.5%), AE_N (6.2 kg kg^{-1}), PE_N (22.3 kg kg^{-1}), and PFP_N (31.9 kg kg^{-1}) of FP treatment were below the common values, which were 30–60%, 10–30 kg kg^{-1}, 30–50 kg kg^{-1}, and 40–70 kg kg^{-1}, respectively [29]. Our data also showed that much greater mineral N accumulation occurred within the 0–100 cm soil profile under the FP_{3N} treatment (168–448 kg ha^{-1}) compared with the other treatments, which agrees with Lu et al. [11]. The soil N accumulation level was strongly correlated with nitrate leaching and is a valuable indicator of leaching tendency [4,38]. Moreover, the study region is characterized by sudden heavy rains and irrigation events (including flood irrigation) during the summer maize growing season, increasing the risk of N leaching [13,39]. Thus, any accumulated deposits of mineral N need to be depleted to reduce leaching, and the most effective method for achieving this is absorption by crops [40,41]. Thus, the cumulative soil N is an important N source.

Precipitation and irrigation are other N sources. Our field data showed that maize received a mean of 28 kg N ha^{-1} from these sources during the growing period. Researchers have reported that increasing amounts of N deposition occurred in China (from 13.2 kg N ha^{-1} in the 1980s to 21.1 kg N ha^{-1} in the 2000s) [42], and north-central China is a hotspot, as it currently has the greatest N deposition rate of 52.2 kg N ha^{-1} year^{-1} [22]. Returned N from crop residue can be utilized after decomposition by soil microorganisms. Returned crop residue N accounts for 37.4% of the total N needed for maize in China [24]. However, few studies have calculated crop residue N when recommending N fertilizer application rates.

N_{soil} represents the end-product of mineralization and immobilization of soil organic matter, crop residue, environmental N, or previously applied fertilizer. Nitrogen accessibility depends on N mineralization and immobilization after N enters the soil, which can strongly affect N management [14,43]. Therefore, the TN_{supply} also includes N remaining from the previous growing season, in combination with N_{soil}.

4.2. Essence of the Suitable Total N Supply

The TN_{supply} is a representation of all the sources of N available in a cropping system and an indicator of the N supply capacity. In this study, the TN_{supply} provides an improved way for better understanding crop system N supply capacity. Correlations between the TN_{supply} and RY, N input, and N output are shown in Figure 4. The TN_{supply} is a mixture of environmental, soil, crop residue, and fertilizer N, and indicates the support capacity for the system. With TN_{supply} values above 361 kg ha^{-1}, the RY values were relatively high. Additionally, we observed a linear-plateau dependency between RY and TN_{supply}. In addition, 63.4% of the TN_{supply} (as N input) entered the crops. Additionally, not all N input was assimilated by the crops: some proportion was lost or converted to the organic N pool, which affected the NUE. The N input/output linear-plateau correlation with the 55.4% linear slope was the lower-limit target NUE. We then estimated the sustainable TN_{supply} to be 325–497 kg ha^{-1}.

The EU Nitrogen Expert Panel suggested a NUE target value of 50–90% [32]. In fact, the compositions of the N supply in China and Europe were different. In Europe, manure is used more, which is different from that of the current maize system in China [44]. The lower-limit target NUE should be higher in the current system due to the lower N availability in manure than in inorganic fertilizer. Zhang et al. [15] also reported that the optimal NUE in the winter wheat–summer maize rotation system should be 60% according to a similar quantification method of NUE. In this study, at N input below 160 kg ha^{-1}, the

NUE was stably maintained at 55.4% (the slope), except for the intercept term. As N input increases, the NUE gradually decreases [16]. Therefore, it is acceptable that 55.4% is used as the lower-limit NUE.

4.3. N Fertilizer Application Recommendations under Suitable N Supply Levels

To achieve a balanced N supply and crop demand, the TN_{supply} indicator should be used to manage N balance. However, full use of this indicator to provide recommendations is somewhat challenging.

All four N sources should be considered when the TN_{supply} is used to make fertilizer recommendations. Residual N accumulation should be above 100 kg ha^{-1} (the soil buffer capacity level) in summer maize–winter wheat rotations, over which the nitrate leaching increases exponentially [10,16,25,38]. This value could be a recommended one for mineral N contents during N management in soils. Moreover, the environmental N should be 28 kg ha^{-1}, which is close to the value reported by Liu et al. [22] in the same region. Additionally, the previous wheat residue N content ranged from 2.9 to 143 kg ha^{-1} [45]. The specific value was influenced by the N delivery conditions [25,30,41]. We chose the upper quartile (48 kg ha^{-1}) and the median (37 kg ha^{-1}) of 2142 observations for the wheat residue N contents under excessive and suitable supply conditions based on suggestions provided by Chuan et al. [45]. Based on the above information and the appropriate TN_{supply} level, the fertilization recommendation was determined under different N supply conditions by measuring N_{soil} levels, which are shown in Figure 5 and explained below:

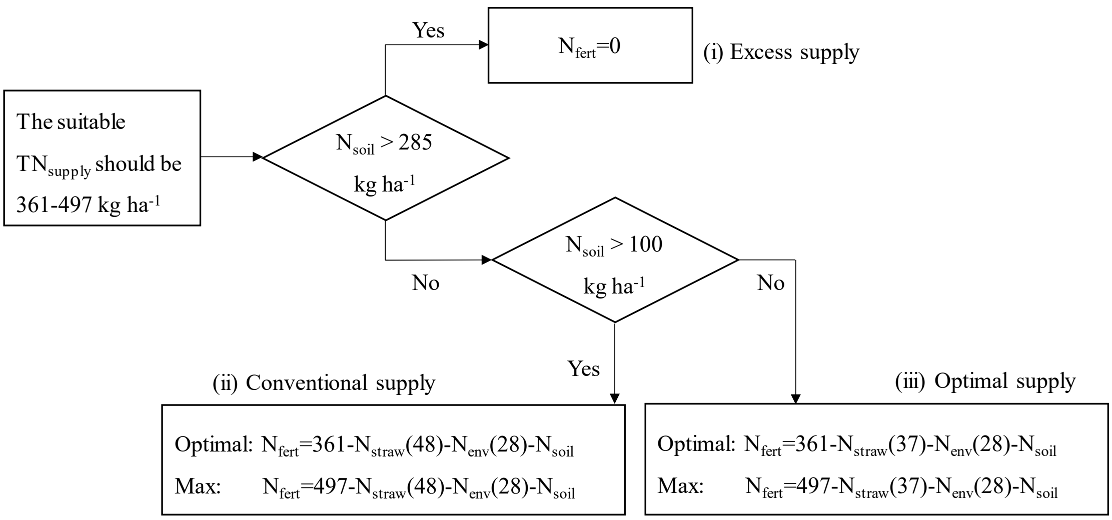

Figure 5. Flowcharts showing the use of suitable total nitrogen supply levels to make fertilizer recommendations. Kilograms per hectare was the unit of the values.

(i) Excess supply condition: The N_{soil} plus N_{straw} (48 kg ha^{-1}) and N_{env} (28 kg ha^{-1}) surpassed the minimum TN_{supply} requirements (equal to 361 kg ha^{-1}). Thus, N_{soil} needs to be above 285 kg ha^{-1}. Under this condition, N_{fert} should be zero, and the priority of the N management strategy is to deplete the accumulated residual N by crops.

(ii) Conventional supply condition: The N_{soil} ranged from 100 to 285 kg ha^{-1}, and the N_{straw} should be 48 kg ha^{-1} under this situation. The optimal N_{fert} rate should equal to the minimum TN_{supply} (361 kg ha^{-1}) minus the N_{straw}, N_{env}, and N_{soil}. In addition, the maximum N_{fert} rate cannot exceed the maximum TN_{supply} (497 kg ha^{-1}) minus the N_{straw}, N_{env}, and N_{soil}. Under these conditions, the goal of the N management strategy is to reduce the accumulated residual N to benign contents to maintain sufficient N.

(iii) Optimal supply condition: The N_{soil} level was below 100 kg ha^{-1}, and the N_{straw} level should be 37 kg ha^{-1} under this situation. The optimal N_{fert} should equal the minimum TN_{supply} (361 kg ha^{-1}) minus the N_{straw}, N_{env}, and N_{soil}. In addition, the maximum N_{fert} rate cannot exceed the maximum TN_{supply} (497 kg ha^{-1}) minus the N_{straw}, N_{env}, and N_{soil}. Thus, this is the minimum amount of synthetic N fertilizer to achieve high yields and high NUE with low soil N contents.

5. Conclusions

The TN_{supply}, including different N sources, is a robust indicator that can be used for synchronizing N supply and crop demand, which is valuable for guiding the scientific application of N fertilizer in the summer maize cropping system. In this study, the RY, N input, and N output plotted as functions of TN_{supply} values were fitted using linear-plateau, linear, and linear-plateau models, respectively. The suitable TN_{supply} ranged from 361 to 497 kg ha^{-1}, within which the crop can achieve higher grain yields, higher NUE, and less environmental N loss. Considering the high amounts of N accumulation in the soils of north-central China, sustainable N management should be considered, such as soil N, environmental N input, crop residue, and the minimum fertilizer applications, with regards to N for crop demand, and the residual soil N should be at a safe level. This research would provide a guideline for crop management involving crop residue post-utilization, improvements of soil quality, and environmental considerations.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/agronomy11071358/s1, Table S1: Variety, seed density, and fertilizer rate of summer maize in NE and FP treatments.

Author Contributions: S.H. conceived the study and wrote the manuscript; W.Y., L.J. (Liangliang Jia), and Y.Y. carried out the experiment and sample analysis; W.D., L.J. (Lingling Jiang), Y.L., and X.X. assisted with statistical analysis; P.H. and J.Y. revised the manuscript and were in charge of overall direction and planning. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key Research & Development Program of China (No. 2018YFD0200608, No. 2016YFD0200101), and the Scientific Research Project of Hebei Academy of Agriculture and Forestry Sciences (2021130201).

Data Availability Statement: Relevant data applicable to this research are within the paper.

Acknowledgments: We are grateful to the farmers in our study for their patience and support.

Conflicts of Interest: The authors declare no conflict of interest.

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