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Apparent Accumulated Nitrogen Fertilizer Recovery in Long-Term Wheat–Maize Cropping Systems in China

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Abstract: Recovery efficiency of nitrogen fertilizers has always been an important issue, especially for N fertilizer recommendation rate in cropping systems. Based on the equilibrium of N in the soil–plant system, apparent accumulated N fertilizer recovery (NRE_{ac}) was determined for long-term (15-years) experiments in wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) rotations at five field sites with various soils and climate characteristics in China. The result showed that the frequency of cropping and the content of soil clay affected NRE_{ac} positively and negatively, respectively. In the absence of nutrient deficiencies and other soil constraints (from NPK (nitrogen, phosphorus and potassium) in S2-CP (site2-Changping) in Beijing, S3-ZZ (site3-Zhengzhou) in Henan province and S4-YL (site4-Yangling) in Shaanxi province), NRE_{ac} had a narrow range from 70% to 78% with the highest average of 75% in wheat and maize cropping system. Meanwhile, the value 75% of NER_{ac} is a rational value proved by 3414 experiments. Additionally, the nitrate-N approach suggested that nitrate-N could be utilized by subsequent crops, the amount of which is calculated by the equation $-1.23 \times [(NO_3^{-}\text{-N}) - 87]$. Furthermore, another simpler and feasible method was proposed to maintain basic soil fertility while achieving a rational grain yield and maintaining a safe environmental upper threshold of nitrate. The present study provided a suit of methods for N fertilizer recommendations for the optimization of N applications in wheat and maize cropping system in China.

Keywords: apparent N recovery efficiency; fertilizer recommendation; wheat; maize

1. Introduction

The recovery efficiency of N fertilizers applied to crops (RE_N: the ratio of total N uptake by aboveground plant dry matter to the amount of fertilizer-N applied) has always been an important issue due to opposing goals [1]. On the one hand global food security must keep pace with an increasing world population, but at the same time there are legitimate concerns about environmental pollution caused by excess N applied to crops [1,2]. It is estimated that food demand will rapidly increase to 2.8×10^9 t in 2030 and the corresponding consumption of fertilizer-N is predicted to be 9.6×10^7 t compared with 7.8×10^7 t year^{-1} in 1995/1997 worldwide [3]. Especially in China, the total consumption of fertilizer-N has increased from 0.93×10^7 t in 1980 to 2.39×10^7 t in 2013 [4]. Fixen and West [5] reported that fertilizer-N supplies basic food needs for at least 40% of the global population and estimated that at least 60% of humanity will eventually owe its nutritional survival to fertilizer in the future. On the other hand, Chinese farmers always apply excess fertilizer-N to crops expecting to produce maximum yield. It is estimated that only 30–50% of applied N fertilizers are taken up by crops worldwide [6]. In China, Fixen and West [5] documented that AE_N (agronomic N use efficiency: kg grain per kg fertilizer-N) decreased from approximately 10–15 during 1958–1963 to 10 during 1981–1983 for wheat, and from 20–30 to 13.4 for maize. Consequently, environmental pollution due to excess N applied to crops is gradually becoming serious and a major cause for concern. Nitrate pollution in groundwater is one of the major pollution problems which have been reported in many countries such as the UK, Denmark, Belgium, France and India [7].

The need for food security and environmental protection is the paradox for fertilizer-N use [8,9]. Thus, a balancing between grain yield and the risk of nitrate-N loss is a common aim for both agronomists and environmentalists. Changes of RE_N, yield and soil NO_3^--N accumulation were subject to external factors, such as rate, place and time of applied N fertilizers, etc. As a result, Benbi and Biswas [10] reported that RE_N varied from 25 to 90% for both maize and wheat, which provided a possibility for mediating the paradox by improving fertilizer-N recommendation. The rate of N applied in the field was initially based on the theory of target yield fertilizer recommendation reported by Truog [11], and gradually improved with its widespread application [12–17], where determination of RE_N is the key. At present there are two methods, the difference and ^{15}N isotopic methods, to estimate RE_N [18]. However, both methods have some assumptions. The former assumes that soil N uptake by the crop is the same for both fertilized and unfertilized N treatments, while the latter assumes that the isotope composition of the tracer is constant, soil microbial populations make no distinction between the ^{14}N and ^{15}N isotopes, and the chemical identities of isotopes are maintained in biochemical systems. In general, the value determined by the former is lower than the latter on soils with higher available N, and the former is higher than the latter on soils with lower available N, which the elusive soil nitrogen-supplying capacity could account for. Unfortunately, approaches to measure RE_N are not widely accepted across a wide range of soils [19–21].

Therefore, a feasible method to estimate RE_N is an agenda for fertilizer-N recommendation, especially in wheat–maize cropping system in China, which is a dominant cropping system with excessive N rate and high level of residual soil nitrate-N [22]. Accordingly, a long-term experiment of national soil fertility and fertilizers in wheat–maize cropping system was used in the present study. The objectives were to: (i) discuss the factors affected NRE_{ac} (NRE_{ac}: apparent accumulated N recovery efficiency); (ii) determine NRE_{ac} on the condition of nitrogen equilibrium in the soil–plant system [23,24]; (iii) further complete target yield N recommendation with regulating the relationship between N fertilization and utilization of soil NO_3^--N in the wheat–maize cropping system in China.

2. Materials and Methods

The data involved in this study was derived from a network of experiments in China, which was set up in 1990 to determine the response of crops to fertilizers on various types of soil under different climatic conditions. The study was composed of five sites, distributed in five districts: Urumqi (in Xinjiang province, icon S1-WQ), Changping (in Beijing, icon S2-CP), Zhengzhou (in Henan province, icon S3-ZZ), Yangling (in Shaanxi province, icon S4-YL) and Qiyang (in Hunan province, icon S5-QY), which dominate soils and climates of wheat and maize growing regions in China. Initial properties of soils are briefly listed in Table 1 and more details can be found in Liu [25].

Table 1. The experiment sites and initial properties.

	Sites				
Items	**S1-WQ**	**S2-CP**	**S3-ZZ**	**S4-YL**	**S5-QY**
Location	Wulumuqi, Xinjiang	Changping, Beijing	Zhengzhou, Henan	Yangling, Shaanxi	Qiyang, Hunan
Longitude	87°25′58″ E	116°12′08″ E	113°39′25″ E	108°03′54″ E	111°52′32″ E
Latitude	43°58′23″ N	40°12′34″ N	34°47′02″ N	34°16′49″ N	26°45′12″ N
Mean annual temperature, °C	7.4	11.8	14.2	12.7	18.3
Annual rainfall, mm	247	577	644	542	1276
Cropping, per year	wheat or maize	wheat–maize	wheat–maize	wheat–maize	wheat–maize
Soil classification in China	Grey desert soil	Fluvo-aquic soil	Fluvo-aquic soil	Loessial soil	Red earth
Soil classification in FAO	Calcaric Cambisol	Haplic Luvisol	Calcaric Cambisol	Calcaric Regosol	Eutric Cambisol
Sand/Silt/Clay (%)	18.5/53.2/28.3	20.3/65.0/14.7	26.5/60.7/12.8	31.6/51.6/16.8	3.7/34.9/61.4
Soil pH (water/soil = 2.5)	8.1	8.2	8.3	8.6	5.7
Organic carbon (g kg^{-1})	8.8	7.1	6.7	6.3	6.7
Total N (g kg^{-1})	0.87	0.64	1.01	0.83	1.07
Total P (g kg^{-1})	0.67	0.69	0.65	0.61	0.45
Total K (g kg^{-1})	23	14.6	16.9	22.8	13.7

The present study included two cropping systems, one crop of wheat or maize per year in S1-WQ, another wheat–maize rotation per year at the other four sites. All experiments were unreplicated in a randomized design due to pressure on experiment land, where plot size varied between 100 and 468 m^2. Each experiment consisted of the following nine treatments: (1) CK (unfertilized), (2) PK (phosphorus and potassium), (3) N (nitrogen), (4) NK (nitrogen plus potassium), (5) NP (nitrogen plus phosphorus), (6) NPK (nitrogen, phosphorus plus potassium, (7) FS (NPK plus straw), (8) FM (NPK plus manure) and (9) HF (high NPK plus straw). Rates of fertilizers are shown in Liu et al. [25], in which the rates of manures or straw were based on N concentration, ratio of N from fertilizer to from manures or straws is 7:3, and the amounts of P and K were computed by P and K concentrations multiplied by the rates of applied manures or straw, respectively. Manures were applied after composting and straw was derived from corresponding treatments. All straw or manures were applied once-yearly as soon as the crop (wheat or maize) was harvested in S1-WQ, or wheat was harvested at the other four sites. The sources of N, P and K were urea, superphosphate and potassium chloride, respectively. Half of the N and all of the P and K were applied as basal fertilizer. The remainder of the N was applied as topdressing when needed. Irrigation was adjusted to annual precipitation when needed. When necessary, weeding by hand and pesticide applications were implemented.

2.1. Sampling and Analysis

Crops were harvested manually close to the ground with sickles at maturity and totally removed from the plots. Grain and straw were laid out in the sun on concrete slabs before threshing and then oven-dried at 65 °C to uniform moisture level before weighed, and then ground to pass a 0.15-cm sieve and stored for analysis. Plant samples to be tested were from the center of the plot in order to minimize marginal effects.

Soil samples were collected from the plough layer (0–20 cm) at the start of the experiment and between crop harvest and fertilizer application each autumn. At least five cores in each plot of each site were taken with a 5-cm diameter auger. Cores from the same plot were mixed thoroughly and air-dried, ground to pass through a 2.0-mm sieve and stored for analysis.

Plant samples were analyzed for total nitrogen using the micro-Kjeldahl digestion method, while soil samples were analyzed for total nitrogen, total phosphorus and total potassium using micro-Kjeldahl digestion, colorimetric analysis and a dissolution-flame photometer, respectively [26].

2.2. Calculation and Statistical Analysis

Based on mass balance theory, apparent accumulated N recovery efficiency ($NRE_{ac}\%$) was calculated as total N uptake (N_p, in kg ha^{-1}) by crops (grain and straw) divided by total N rate (N_f, in kg ha^{-1}) using the following equation:

$$NRE_{ac}\% = \frac{\sum_{i=1}^{i=n} N_{pi}}{\sum_{i=1}^{i=n} N_{fi}} \times 100 \quad (1)$$

where i is the number of cultivation years and the maximum value of n is 15 years in the present study. Np has been calculated in the companion paper [25] using the following equation:

$$N_P = Yield_{wheat} \times 2.73\% + Yield_{maize} \times 2.21\% \quad (2)$$

where $Yield_{wheat}$ and $Yield_{maize}$ represent the grain yields of wheat and maize (kg ha^{-1}), respectively, and 2.73% and 2.21% were the corresponding N concentrations in the aboveground biomass of wheat and maize, respectively. Moreover, on the principle of yield-based N recommendations [12,27], the following equation was used to compute a recommended N rate:

$$N_{f.opt} = \frac{N_p}{NRE_{ac.opt}\%} \quad (3)$$

where $NRE_{ac.opt}$ is an optimal NRE_{ac} with application of an economically optimal N rate ($N_{f.opt}$). In the present study, $NRE_{ac.opt}$ is the average of NRE_{ac} from NPK treatment in S2-CP, S3-YL and S4-ZZ, and the value is 75%.

In order to assess the reliability of N rate recommended by Equation (3), the experiment with '3414w design was introduced into the present study, which is one of D-optimal design for quadratic regression [28]. In the experiment of '3414′ design, 3 represents 3 factors (nitrogen, phosphorus and potassium), 4 represents 4 rates of factors (0, 50% normal rate, normal rate and 150% normal rate), and 14 represents 14 treatments. Since 2005, the "3414" experiment was carried out nationwide that is a standard method for fertilizer recommendation in China [29]. Four of the 14 treatments were selected in the present study and they were N0P2K2, N1P2K2, N2P2K2 and N3P2K2, where N0, N1, N2 and N3 represent nitrogen rates and P2 and K2 represent appropriate phosphorus and potassium rates in the locality, respectively. More details are shown in Appendix A and Appendix References. A quadratic curve fitted the data was as follows:

$$\mathrm{Yield} = \mathrm{a} \times {\mathrm{N_f}}^2 + \mathrm{b} \times \mathrm{N_f} + \mathrm{Yield_0} \quad (4)$$

where Yield is grain yield (kg ha^{-1}), N_f is the rate of applied N, $Yield_0$ is an intercept, defined as a basic grain yield (kg ha^{-1}) without applied N, a and b are two coefficients.

$N_{f.opt}$ is reached when

$$\frac{\partial \mathrm{Yield}}{\partial \mathrm{N_f}} = 2\mathrm{aN_{f.opt}} + \mathrm{b} = \mathrm{P} \quad (5)$$

where P equals the ratio of the cost of 1 kg fertilizer N to the price of 1 kg grain yield, and there are 2.33 (±0.28) and 2.76 (±0.50) for wheat and maize, respectively in the present study [30] and the variance of P does not make sense to the results of the study. Therefore, $N_{f.opt}$ was calculated by the following equation:

$$\mathrm{wheat}: \mathrm{N_{f.opt}} = \frac{2.33 - \mathrm{b}}{2\mathrm{a}};\ \mathrm{maize}: \mathrm{N_{f.opt}} = \frac{2.76 - \mathrm{b}}{2\mathrm{a}} \quad (6)$$

Based on the '3414′ design and Equations (4) and (6), the following equation fitted the relationship between $Yield_{opt}$ and $Yield_0$:

$$\mathrm{Yield_{opt}} = \alpha \times \mathrm{Yield_0} \quad (7)$$

where $Yield_{opt}$ is a grain yield at $N_{f.opt}$ and α is a coefficient.

Statistical analyses were performed using SPSS analytical software (SPSS Inc., Chicago, IL, USA; version 19). Linear regression was used to determine the relationship between $N_{f.opt}$ with estimatied by NRE_{ac} and measured in "3414" experiments, and correlation between $yield_{opt}$ and $yield_0$. A quadratic curve regression was used to fit the response of yield to N application in "3414" experiments. Analysis of variance (ANOVA) was used to test the differences of NRE_{ac}% among treatments and experiment sites.

3. Results

3.1. Factors Affecting NRE_{ac}

Apparent accumulated nitrogen recovery efficiencies (NRE_{ac}) for the whole years of cultivation (15 years) are shown in Table 2. Values of NRE_{ac} for all treatments have a wide variation that ranged from 24 to 161%. Except all treatments in S5-QY and S1-WQ1 during 1991–1994, and N in S2-CP and S4-YL, NRE_{ac} from the same treatment were always higher in the wheat–maize rotation per year (in S2-CP, S3-ZZ and S4-YL) than in the wheat–maize-maize rotation per 3 years (in S1-WQ2). And averages of the former were 40, 46, 71, 75, 62, 71 and 62 for N, NK, NP, NPK, FS, FM and HF treatments, respectively. When comparing NRE_{ac} among treatments combined application of N, P and K in all experimental sites, there were also discrepancies. NRE_{ac} from the NPK treatment were always higher than that from incomplete nutrients treatments, in which the values from NP were the highest followed by that from NK and N in all experiment sites (except from N and NK in S1-WQ2). Especially, NRE_{ac} from NPK was significant higher in S1-WQ1 with lower N input than in S1-WQ2 with normal N input. There were no significant differences among NRE_{ac} from NPK in the wheat–maize rotation per year (in S2-CP, S3-ZZ and S4-YL) and the average of NRE_{ac} was 75% with a standard deviation of 6% (Figure 1).

Table 2. Table 2. Average of NRE_{ac} during 15 years at all sites.

Treatment	Experiment Site (%)					
	S1-WQ1	**S1-WQ2**	**S2-CP**	**S3-ZZ**	**S4-YL**	**S5-QY**
N	149 [ab]	40 [b]	39 [e]	43 [f]	40 [c]	24 [e]
NK	115 [bc]	38 [bc]	47 [d]	50 [e]	42 [c]	30 [d]
NP	155 [ab]	58 [a]	66 [b]	77 [a]	70 [b]	39 [c]
NPK	161 [a]	62 [a]	70 [a]	78 [a]	77 [a]	43 [b]
FS	103 [c]	51 [ab]	48 [d]	64 [c]	74 [ab]	47 [ab]
FM	50 [d]	43 [b]	65 [b]	70 [b]	78 [a]	49 [a]
HF	31 [d]	26 [c]	58 [c]	56 [d]	71 [b]	47 [ab]

Note: different letters indicate significance at 0.05 levels in a column; S1-WQ1 was an experiment at S1-WQ from 1990 to 1994 and S1-WQ2 from 1995 to 2004.

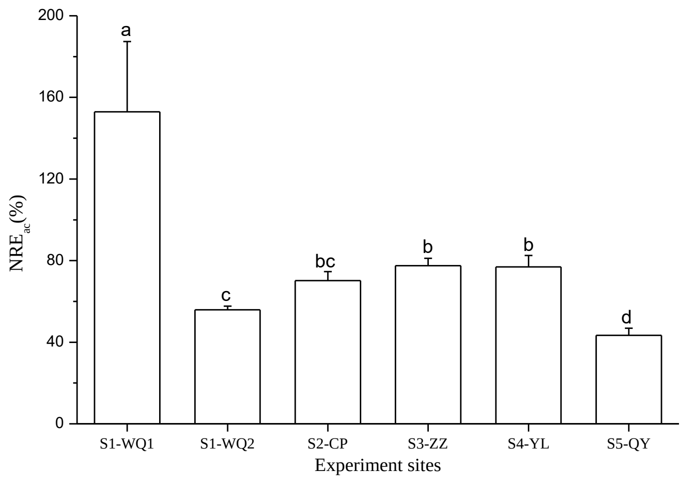

Figure 1. NRE_{ac} from NPK in all sites. Note: Different letters indicate significant differences at 0.05 levels; NRE_{ac} is apparent accumulated N recovery efficiency; S1-WQ1 is an experiment at Urumqi during 1991–1994; S1-WQ2 is an experiment at Urumqi during 1995–2005.

On the other hand, NRE_{ac} was also affected by N rates. The higher N rates (HF) are always lower than normal N rates in NRE_{ac} in all sites except S5-QY. Due to its location in the subtropical humid climate zone characterized by higher temperature (mean annual temperature 18.3 °C) and intensive precipitation (the sum of precipitation from Mar. to Aug. accounting for 70% of precipitation in a whole year), values of NRE_{ac} from inorganic N treatments (N, NK, NP and NPK) are the lower than the combined treatments of inorganic and organic N in S5-QY. These results were mainly attributed to decreasing soil pH. At the start of experiment, the initial soil pH in S5-QY was 5.7, where the growth of wheat and maize might be restricted. Furthermore, N fertilization accelerated soil acidification. In 2005, soil pH decreased approximately to 4.

3.2. Assessment of $N_{f.opt}$ and Relationship between $Yield_{opt}$ and $Yield_0$

Using 3414 data, correlations between $N_{f\cdot opt}$ estimated by NRE_{ac} and $N_{f\cdot opt}$ measured with a quadratic curve are illustrated in Figure 2. For both of wheat and maize, the values of r^2 are above 0.9 with significant relationships ($p < 0.01$) which suggested that NRE_{ac} of 75% from NPK in S2-CP, S3-ZZ and S4-YL is an optimal NRE_{ac}. Meanwhile, relationships between $Yield_{opt}$ and $Yield_0$ were illustrated in Figure 3, where values of r^2 are 0.62 and 0.73 for wheat and maize, respectively. And both correlations are significant ($p < 0.01$).

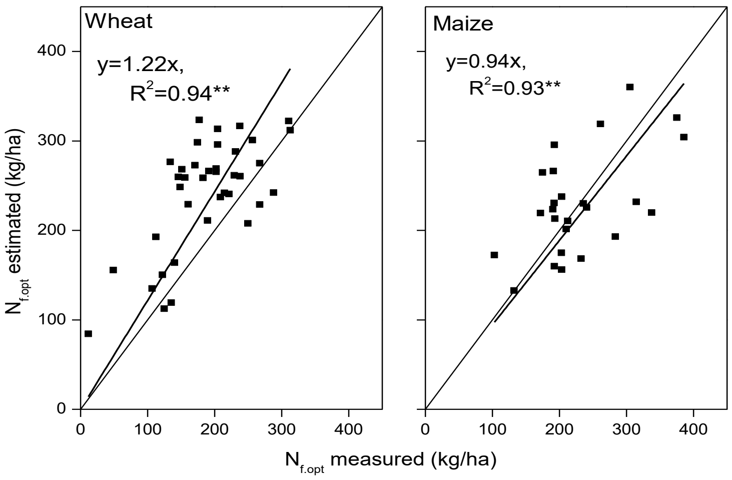

Figure 2. Correlation between $N_{f.opt}$ estimated using NRE_{ac} (75%) and $N_{f.opt}$ measured using 3414 experiments with a quadratic curve fitting for wheat and maize. Note: ** indicates significance at 0.01 level; $N_{f.opt}$ is an economically optimal N rate; NRE_{ac} is an apparent accumulated N recovery efficiency.

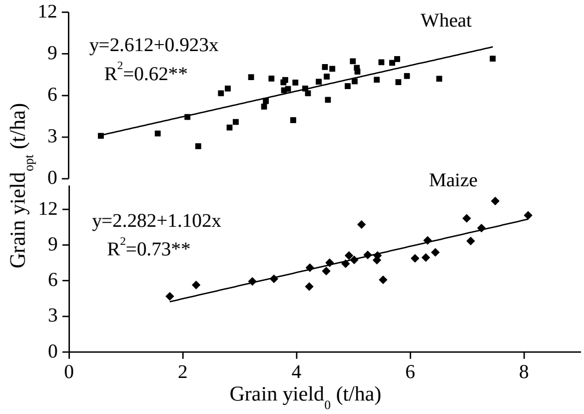

Figure 3. Relationships between grain $yield_{opt}$ and $yield_0$ for wheat and maize based on 3414 experiments. Note: ** indicates significance at 0.01 levels; grain $yield_{opt}$ is a grain yield at $N_{f.opt}$; grain $yield_0$ is a grain yield without N input.

4. Discussion

NRE_{ac} are affected by cropping, soil properties and the environment, etc. Usually, crop rotation has higher nutrients recovery efficiency than monoculture. Long-term studies showed that crop rotation contributed to maintaining higher production levels [31]. Furthermore, the present study proved that the frequency of crop rotation could strengthen the trend outlined by Peterson and Varvel [32–34]. Without nutrient deficiency (from NPK, FS, FM and HF), NRE_{ac} in a three-year rotation (S1-WQ2) was always far lower than from a one-year rotation except in S5-QY (Table 2 and Figure 1). Moreover, soil texture might have an effect on mineralization and immobilization of soil nitrogen that finally influenced NRE_{ac}. In the present study, clay content in S1-WQ and S5-QY were higher than in the other three sites (Table 1). Consequently, all NRE_{ac} from sufficient nutrients were lower in S1-WQ2 and S5-QY than that in the other sites (Table 2 and Figure 1). This result was consisted with Hassink [35], who found that there was a significant negative relationship between clay content and the N mineralization rate. Soil pH is another soil property that affected NRE_{ac}. There was an initial lower soil pH of 5.7 (Table 1) and gradual acidification due to continuous N fertilization in S5-QY. Liu et al. [25] discussed the determinant for plant growth due to decreasing pH, and eventually a lower NRE_{ac} irreversibly occurred. In general, providing enough nutrients without other soil limitations in the same cropping period (S2-CP, S3-ZZ and S4-YL), NER_{ac} from NPK had a narrow variation with a range of 6 and maintained a higher level (average of 75%) (Table 2 and Figure 1).

The response of grain yield to applied N from NPK treatments is classically illustrated in Olfs et al. [8]. Grain yield increased with gradually increasing rate of applied N, which followed by an inflection point called an economically optimal yield ($Yield_{opt}$) when the profit from an increased yield of added N equalled zero. The corresponding applied N rate is called the economically optimal N rate ($N_{f.opt}$). Especially in the present study, grain yields were not significantly different between NPK and high N fertilization (HF) [25]. Therefore, based on the responses of grain yield to applied N [8], it was inferred that grain yield from NPK could be the $Yield_{opt}$ and the corresponding N rate was equal to $N_{f.opt}$. Furthermore, there is a good correlation of $N_{f.opt}$ between estimated by NRE_{ac} (75%) and measured using a quadratic curve-fitting with data from the '3414′ design (Figure 2), which reconfirmed that the inference is correct. Therefore, the present study concluded that NRE_{ac} of 75% could be equivalent to $NRE_{ac \cdot opt}$ and Equation (3) could be used to estimate $N_{f.opt}$ in wheat–maize cropping systems in China.

When the N rate exceeds crop N requirement, there is an accumulation of NO_3^--N in the soil profile [36,37] as shown in Olfs et al. [8]. Moreover, the accumulated trend could be strengthened gradually with a further increasing N rate [8,38]. Previous research found that the content of NO_3^--N from the NPK treatment used in the present study were lower in the 0–90 cm soil profile (approximate 100, 30 and 60 kg ha^{-1} in S2-CP, S3-ZZ and S4-YL, respectively) [39–41] which did not exceed the critical value of soil nitrate-N (a range of 66–118 kg ha^{-1}) in the top 90 cm of the soil profile for high yield in the wheat–maize cropping system [22,42]. Moreover, nitrate accumulation did not occur in the deeper soil profile [39–41]. All of these observations suggested that N rates from the NKP treatment would be the rational N rates again and further confirmed that the N rates could maintain the apparent N balance of a soil–plant system in the three sites.

However, accumulation of NO_3^--N in soil profile and nitrate leaching into ground water were serious and prevalent in wheat–maize cropping system in China [43]. Initially, agronomist have focused on NO_3^--N accumulation mostly for environment pollution [44] and gradually utilized them by the subsequent crop [22,42,45]. Cui et al. [42] reported that NO_3^--N content in the top 90 cm soil should be maintained at a level of about 87 kg ha^{-1} after maize harvest. Furthermore, the numerical relationship between residual soil-N and applied N was that 1 kg soil NO_3^--N in the 0–90 cm soil profile was equivalent to 1.23 kg fertilizer-N [42]. The right side in Equation (3), therefore, should add N_s to utilize the abundant NO_3^--N using the following equation:

$$N_s = -1.23 \times \left[\left(NO_3^- - N\right) - 87\right] \quad (8)$$

where NO_3^--N means the nitrate-N content (kg ha^{-1}) in the top 90 cm soil profile, where 87 kg ha^{-1} is a critical value of soil NO_3^--N balancing the benefits between the economy and the environment. In other words, neither the nitrate leaching risk nor depletion of NO_3^--N happens in a soil profile while the content of soil NO_3^--N is maintained at the critical value.

The nitrate-N approach, however, would already provide a method to utilize the abundant soil residual N, but implementation of the method is a challenge. One of the reasons is that the interval between the growth of maize and wheat is too short to determine soil nitrate in the wheat–maize cropping system in China. Additionally, the extension of the soil test at the farm level would be insurmountable due to the number of small farms involved. Therefore, a more feasible way for using N_s was needed in the present study. Fortunately, Cui [22,42] reported that the relationship between grain yield of wheat and maize and initial soil NO_3^--N content in the top 90 cm of the soil profile before sowing were fitted by the following equations:

$$RY_{wheat}(\%) = 0.16 \times NO_3^- - N + 67.8 \quad (9)$$

$$RY_{maize}(\%) = 0.21 \times NO_3^- - N + 60.4 \quad (10)$$

where RY_{Wheat} and RY_{Maize} are the relative yields to the local highest yields of wheat and maize, respectively. And 0.16 and 0.21 were numerical relationships between relative grain yield and initial NO_3^--N (0–90 cm soil profile) for wheat and maize, respectively.

To maintain yields at a rational level, the content of soil NO_3^--N has to keep up with the critical value. Combining of Equations (8)–(10) and Figure 3, N_s could be calculated, called a basic soil productivity approach, using the following equations:

$$N_s = -1.23 \times \left(\frac{\left((\text{Yield}_{opt} - 2615) / (0.923 \times \text{Yield}_{opt}) \right) \times 100 - 81.7}{0.16} \right) \quad (11)$$

$$N_s = -1.23 \times \left(\frac{\left((\text{Yield}_{opt} - 2282) / (1.102 \times \text{Yield}_{opt}) \right) \times 100 - 78.7}{0.21} \right) \quad (12)$$

where 81.7(%) and 78.7(%) are two critical values of RY_{wheat} and RY_{maize}, respectively. Exceeding the values means that N rate should be reduced in order to crop unitizing N from the abundant soil NO_3^--N. Yield_{opt} is a goal yield that was estimated by an average of recently five-year yields multiplied by 1.1 [46]. Therefore, the abundant soil NO_3^--N could be utilized by a basic soil productivity approach more easily than a nitrate-N approach.

In general, yield-based N fertilizer recommendations were not completely accepted by agronomists and farmers at its inception due to limitations such as yield variability [47,48], uncertainty of N recovery efficiency estimated by the difference or isotopic methods [18] because of the complexity of the soil-supplying N capacity [19–21]. However, based on the present study, the theory of yield-based N fertilizer recommendation was further improved. Particularly, it could be adapted in the wheat–maize cropping areas in China.

5. Conclusions

Apparent accumulated nitrogen recovery (NRE_{ac}) was affected by a multitude of factors. The present result that the three-year rotation (S1-WQ2) was always far lower than from the one-year rotation in NRE_{ac} suggested that a frequent of crop rotation affected the N cycle. Moreover, soil texture also affected NRE_{ac}. In S1-WQ and S5-QY with higher soil clay contents, NRE_{ac} from all treatments were always lower than that in the other sites with lower soil clay contents. In general, from the NPK treatment in S2-CP, S3-ZZ and S4-YL, the nitrate contents were lower and its accumulation did not occur in the soil profile. In other words, the present study provided evidence that N applied from the NPK treatment maintained an apparent N balance in the soil–plant system in the three sites. Meanwhile, NER_{ac} had a narrow variation with a range of 6% and maintained a higher level (average of 75%). Furthermore, grain yield from NPK in the three sites were the Yield_{opt} where NRE_{ac} could be equal to that at $N_{f.opt}$. Additionally, based on the fact of accumulation of NO_3^--N in the soil profile being serious and prevalent in the wheat–maize cropping system in China, NO_3^--N should be utilized by subsequent crops. However, due to the logistical obstacle of determining profile NO_3^--N at the farm level, a basic soil productivity approach was advocated in the present study. A yield-based N fertilizer recommendation was proposed in the present study yet needs to be further evaluated. For example, the critical value of NO_3^--N is variable and should be adjusted in relation to soil type and management.

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

Appendix A

Table A1. 3414 data quoted from CSTJ (China Science and Technology Journal Database).

Sites	Treatments	Applied Rate (kg ha^{-1})			Grain Yield (kg ha^{-1})	r^2	References
Village, Province		N	P	K	Wheat		
Kaoshan, Anhui	$N_0P_2K_2$	0	72	150	4260	0.946	1
	$N_1P_2K_2$	90	72	150	5280		
	$N_2P_2K_2$	180	72	150	6645		
	$N_3P_2K_2$	270	72	150	6390		
Xinji, Anhui	$N_0P_2K_2$	0	26	75	2766	0.997	2
	$N_1P_2K_2$	98	26	75	4820		
	$N_2P_2K_2$	195	26	75	5852		
	$N_3P_2K_2$	293	26	75	6524		
Gupeizhen, Anhui	$N_0P_2K_2$	0	90	150	3178	0.997	3
	$N_1P_2K_2$	90	90	150	6392		
	$N_2P_2K_2$	180	90	150	7206		
	$N_3P_2K_2$	270	90	150	6321		
Hengshan, Anhui	$N_0P_2K_2$	0	90	150	4435	0.993	3
	$N_1P_2K_2$	90	90	150	5728		
	$N_2P_2K_2$	180	90	150	6826		
	$N_3P_2K_2$	270	90	150	6964		
Mingdong, Anhui	$N_0P_2K_2$	0	90	150	5195	0.940	3
	$N_1P_2K_2$	90	90	150	6818		
	$N_2P_2K_2$	180	90	150	8358		
	$N_3P_2K_2$	270	90	150	7318		
Nongkesuo, Anhui	$N_0P_2K_2$	0	90	150	4040	0.990	3
	$N_1P_2K_2$	90	90	150	5912		
	$N_2P_2K_2$	180	90	150	7070		
	$N_3P_2K_2$	270	90	150	6502		
Pancun, Anhui	$N_0P_2K_2$	0	90	150	5460	0.994	3
	$N_1P_2K_2$	90	90	150	7463		
	$N_2P_2K_2$	180	90	150	8160		
	$N_3P_2K_2$	270	90	150	8314		
Shaogang, Anhui	$N_0P_2K_2$	0	90	150	3847	0.984	3
	$N_1P_2K_2$	90	90	150	6084		
	$N_2P_2K_2$	180	90	150	7121		
	$N_3P_2K_2$	270	90	150	5630		
Shiba, Anhui	$N_0P_2K_2$	0	90	150	3551	0.999	3
	$N_1P_2K_2$	90	90	150	6027		
	$N_2P_2K_2$	180	90	150	7050		
	$N_3P_2K_2$	270	90	150	7022		
Zhaoxin, Anhui	$N_0P_2K_2$	0	90	150	5220	0.920	3
	$N_1P_2K_2$	90	90	150	6183		
	$N_2P_2K_2$	180	90	150	7878		
	$N_3P_2K_2$	270	90	150	7586		
Longkang, Anhui	$N_0P_2K_2$	0	52	124	2754	0.984	4
	$N_1P_2K_2$	98	52	124	4367		
	$N_2P_2K_2$	195	52	124	5987		
	$N_3P_2K_2$	293	52	124	6090		
Xiaolou, Anhui	$N_0P_2K_2$	0	43	81	5147	0.908	5
	$N_1P_2K_2$	98	43	81	5876		
	$N_2P_2K_2$	195	43	81	7209		
	$N_3P_2K_2$	293	43	81	6917		
Gaohuang, Anhui	$N_0P_2K_2$	0	33	81	4545	1.000	6
	$N_1P_2K_2$	113	33	81	6240		
	$N_2P_2K_2$	225	33	81	7200		
	$N_3P_2K_2$	338	33	81	7350		
Xuji, Anhui	$N_0P_2K_2$	0	26	75	4223	0.999	7
	$N_1P_2K_2$	90	26	75	5646		
	$N_2P_2K_2$	180	26	75	6198		
	$N_3P_2K_2$	270	26	75	5663		
Toupu, Anhui	$N_0P_2K_2$	0	39	62	3945	0.952	8
	$N_1P_2K_2$	83	39	62	5444		
	$N_2P_2K_2$	165	39	62	7314		
	$N_3P_2K_2$	248	39	62	6935		
Yonggu, Anhui	$N_0P_2K_2$	0	39	60	5475	0.972	9
	$N_1P_2K_2$	90	39	60	6375		

Table A1. *Cont.*

Sites	Treatments	Applied Rate (kg ha^{-1})			Grain Yield (kg ha^{-1})	r^2	References
	$N_2P_2K_2$	180	39	60	7238		
	$N_3P_2K_2$	270	39	60	7035		
Dazhuang (a), Gansu	$N_0P_2K_2$	0	39	87	3522	0.921	10
	$N_1P_2K_2$	60	39	87	4482		
	$N_2P_2K_2$	120	39	87	5460		
	$N_3P_2K_2$	180	39	87	4716		
Dazhuang (b), Gansu	$N_0P_2K_2$	0	39	87	1511	0.963	10
	$N_1P_2K_2$	60	39	87	2825		
	$N_2P_2K_2$	120	39	87	3021		
	$N_3P_2K_2$	180	39	87	3263		
Handian, Gansu	$N_0P_2K_2$	0	39	87	2883	0.898	10
	$N_1P_2K_2$	60	39	87	3294		
	$N_2P_2K_2$	120	39	87	3833		
	$N_3P_2K_2$	180	39	87	3512		
Nanhu, Gansu	$N_0P_2K_2$	0	39	87	3960	0.995	10
	$N_1P_2K_2$	60	39	87	4200		
	$N_2P_2K_2$	120	39	87	4095		
	$N_3P_2K_2$	180	39	87	3465		
Tonghua, Gansu	$N_0P_2K_2$	0	39	87	2129	0.990	10
	$N_1P_2K_2$	60	39	87	3458		
	$N_2P_2K_2$	120	39	87	4467		
	$N_3P_2K_2$	180	39	87	4322		
Yongning, Gansu	$N_0P_2K_2$	0	39	87	3020	0.855	10
	$N_1P_2K_2$	60	39	87	3455		
	$N_2P_2K_2$	120	39	87	4313		
	$N_3P_2K_2$	180	39	87	3932		
Yuebao, Gansu	$N_0P_2K_2$	0	39	87	2297	0.708	10
	$N_1P_2K_2$	60	39	87	2314		
	$N_2P_2K_2$	120	39	87	2409		
	$N_3P_2K_2$	180	39	87	2168		
Zhaodun, Gansu	$N_0P_2K_2$	0	39	87	834	0.728	10
	$N_1P_2K_2$	60	39	87	1536		
	$N_2P_2K_2$	120	39	87	3858		
	$N_3P_2K_2$	180	39	87	2505		
Gaocheng (City, a), Hebei	$N_0P_2K_2$	0	65	124	5805	0.998	11
	$N_1P_2K_2$	113	65	124	6795		
	$N_2P_2K_2$	225	65	124	6915		
	$N_3P_2K_2$	338	65	124	5985		
Gaocheng (City, b), Hebei	$N_0P_2K_2$	0	65	124	5685	0.967	11
	$N_1P_2K_2$	113	65	124	7545		
	$N_2P_2K_2$	225	65	124	7950		
	$N_3P_2K_2$	338	65	124	8715		
Gaocheng (City, c), Hebei	$N_0P_2K_2$	0	65	124	6555	0.925	11
	$N_1P_2K_2$	113	65	124	6915		
	$N_2P_2K_2$	225	65	124	7350		
	$N_3P_2K_2$	338	65	124	7140		
Gaocheng (City, d), Hebei	$N_0P_2K_2$	0	65	100	5910	0.980	11
	$N_1P_2K_2$	90	65	100	7275		
	$N_2P_2K_2$	180	65	100	7260		
	$N_3P_2K_2$	270	65	100	6570		
Wangguaying, Henan	$N_0P_2K_2$	0	31	60	4886	0.995	12
	$N_1P_2K_2$	81	31	60	6270		
	$N_2P_2K_2$	162	31	60	6615		
	$N_3P_2K_2$	243	31	60	6324		
Xieqiaozhen, Jiangsu	$N_0P_2K_2$	0	39	87	3810	0.989	13
	$N_1P_2K_2$	105	39	87	5745		
	$N_2P_2K_2$	210	39	87	6270		
	$N_3P_2K_2$	315	39	87	6345		
Liutao, Jiangsu	$N_0P_2K_2$	0	33	50	4503	0.930	14
	$N_1P_2K_2$	135	33	50	5623		
	$N_2P_2K_2$	270	33	50	5558		
	$N_3P_2K_2$	405	33	50	5367		
Sitaocun, Jiangsu	$N_0P_2K_2$	0	33	50	3420	0.979	15
	$N_1P_2K_2$	135	33	50	5145		
	$N_2P_2K_2$	270	33	50	5445		
	$N_3P_2K_2$	405	33	50	5400		
Qianshan,	$N_0P_2K_2$	0	37	31	4770	0.946	16

Table A1. *Cont.*

Sites	Treatments	Applied Rate (kg ha^{-1})			Grain Yield (kg ha^{-1})	r^2	References
Qinghai	$N_1P_2K_2$	59	37	31	5760		
	$N_2P_2K_2$	117	37	31	7571		
	$N_3P_2K_2$	176	37	31	7650		
Chengguan, Shaanxi	$N_0P_2K_2$	0	120	90	7464	1.000	17
	$N_1P_2K_2$	75	120	90	8122		
	$N_2P_2K_2$	150	120	90	8543		
	$N_3P_2K_2$	225	120	90	8671		
Chuanyuan, Shaanxi	$N_0P_2K_2$	0	52	100	4458	0.993	18
	$N_1P_2K_2$	90	52	100	6568		
	$N_2P_2K_2$	180	52	100	7442		
	$N_3P_2K_2$	270	52	100	8111		
Qili, Sichuan	$N_0P_2K_2$	0	28	60	3750	0.992	19
	$N_1P_2K_2$	59	28	60	5040		
	$N_2P_2K_2$	117	28	60	5622		
	$N_3P_2K_2$	176	28	60	6260		
Qixiang, Xinjiang	$N_0P_2K_2$	0	90	30	5760	0.973	20
	$N_1P_2K_2$	98	90	30	6690		
	$N_2P_2K_2$	195	90	30	7980		
	$N_3P_2K_2$	293	90	30	8175		
Zepu (County), Xinjiang	$N_0P_2K_2$	0	39	25	5000	1.000	21
	$N_1P_2K_2$	93	39	25	7046		
	$N_2P_2K_2$	186	39	25	8182		
	$N_3P_2K_2$	279	39	25	8455		
					Maize		
Caozhuang, Anhui	$N_0P_2K_2$	0	589	75	5562	0.895	22
	$N_1P_2K_2$	113	589	75	5926		
	$N_2P_2K_2$	225	589	75	6176		
	$N_3P_2K_2$	338	589	75	5548		
Sanshipu, Anhui	$N_0P_2K_2$	0	47	119	5259	0.999	23
	$N_1P_2K_2$	150	47	119	7069		
	$N_2P_2K_2$	300	47	119	8112		
	$N_3P_2K_2$	450	47	119	8108		
Gengzhuang, Liaoning	$N_0P_2K_2$	0	52	100	10869	0.967	24
	$N_1P_2K_2$	105	52	100	12300		
	$N_2P_2K_2$	210	52	100	12401		
	$N_3P_2K_2$	315	52	100	12134		
Sandu(a), Guangxi	$N_0P_2K_2$	0	26	124	6204	0.967	25
	$N_1P_2K_2$	105	26	124	8898		
	$N_2P_2K_2$	210	26	124	9102		
	$N_3P_2K_2$	315	26	124	8726		
Caohai, Guizhou	$N_0P_2K_2$	0	380	274	8266	0.988	26
	$N_1P_2K_2$	235	380	274	9942		
	$N_2P_2K_2$	470	380	274	9845		
	$N_3P_2K_2$	705	380	274	10614		
Shazi(a), Guizhou	$N_0P_2K_2$	0	52	149	5369	0.967	27
	$N_1P_2K_2$	90	52	149	7204		
	$N_2P_2K_2$	180	52	149	7604		
	$N_3P_2K_2$	270	52	149	7437		
Shazi(b), Guizhou	$N_0P_2K_2$	0	65	199	6503	0.998	27
	$N_1P_2K_2$	113	65	199	7637		
	$N_2P_2K_2$	225	65	199	8571		
	$N_3P_2K_2$	338	65	199	8071		
Tianping, Guizhou	$N_0P_2K_2$	0	59	174	8199	1.000	28
	$N_1P_2K_2$	105	59	174	8653		
	$N_2P_2K_2$	210	59	174	8639		
	$N_3P_2K_2$	315	59	174	9204		
Lejian(a), Guizhou	$N_0P_2K_2$	0	52	149	1766	0.987	29
	$N_1P_2K_2$	90	52	149	4295		
	$N_2P_2K_2$	180	52	149	4467		
	$N_3P_2K_2$	270	52	149	2298		
Lejian(b), Guizhou	$N_0P_2K_2$	0	59	174	4176	0.996	29
	$N_1P_2K_2$	105	59	174	6392		
	$N_2P_2K_2$	210	59	174	6902		
	$N_3P_2K_2$	315	59	174	6854		
Zhuping (County, a), Henan	$N_0P_2K_2$	0	39	75	4886	1.000	30
	$N_1P_2K_2$	120	39	75	6683		
	$N_2P_2K_2$	240	39	75	7518		

Table A1. *Cont.*

Sites	Treatments	Applied Rate (kg ha^{-1})			Grain Yield (kg ha^{-1})	r^2	References
	$N_3P_2K_2$	360	39	75	6828		
Zhuping (County, b), Henan	$N_0P_2K_2$	0	39	75	5423	0.995	30
	$N_1P_2K_2$	120	39	75	7265		
	$N_2P_2K_2$	240	39	75	8100		
	$N_3P_2K_2$	360	39	75	7857		
Zhuping (County, c), Henan	$N_0P_2K_2$	0	33	62	4962	0.999	30
	$N_1P_2K_2$	105	33	62	7203		
	$N_2P_2K_2$	210	33	62	8255		
	$N_3P_2K_2$	315	33	62	7322		
Zhuping (County, d), Henan	$N_0P_2K_2$	0	33	62	4590	0.964	30
	$N_1P_2K_2$	105	33	62	6713		
	$N_2P_2K_2$	210	33	62	7560		
	$N_3P_2K_2$	315	33	62	6870		
Zhuping (County, e), Henan	$N_0P_2K_2$	0	33	62	3311	0.997	30
	$N_1P_2K_2$	105	33	62	4658		
	$N_2P_2K_2$	210	33	62	6102		
	$N_3P_2K_2$	315	33	62	5778		
Zhuping (County, f), Henan	$N_0P_2K_2$	0	26	50	4806	0.998	30
	$N_1P_2K_2$	90	26	50	5429		
	$N_2P_2K_2$	180	26	50	6228		
	$N_3P_2K_2$	270	26	50			
Jiaohe (City), Jilin	$N_0P_2K_2$	0	26	62	7275	0.993	31
	$N_1P_2K_2$	75	26	62	9030		
	$N_2P_2K_2$	150	26	62	10230		
	$N_3P_2K_2$	225	26	62	10395		
Shuangdian, Jiangsu	$N_0P_2K_2$	0	21	102	5054	0.941	32
	$N_1P_2K_2$	150	21	102	8607		
	$N_2P_2K_2$	300	21	102	9970		
	$N_3P_2K_2$	450	21	102	10813		
Wangji, Jiangsu	$N_0P_2K_2$	0	39	100	5130	0.998	33
	$N_1P_2K_2$	165	39	100	6375		
	$N_2P_2K_2$	330	39	100	8025		
	$N_3P_2K_2$	495	39	100	7620		
Gengzhuang (b), Liaoning	$N_0P_2K_2$	0	52	100	6245	0.986	34
	$N_1P_2K_2$	90	52	100	7620		
	$N_2P_2K_2$	180	52	100	8349		
	$N_3P_2K_2$	270	52	100	8100		
Yezhai, Ningxia	$N_0P_2K_2$	0	65	50	6905	0.999	35
	$N_1P_2K_2$	113	65	50	9944		
	$N_2P_2K_2$	225	65	50	10779		
	$N_3P_2K_2$	338	65	50	11219		
Huangguan, Ningxia	$N_0P_2K_2$	0	52	50	4268	0.994	36
	$N_1P_2K_2$	248	52	50	7016		
	$N_2P_2K_2$	495	52	50	8577		
	$N_3P_2K_2$	743	52	50	8129		
Gongu (County), Xinjiang	$N_0P_2K_2$	0	72	49	12330	0.994	1
	$N_1P_2K_2$	48	72	49	13140		
	$N_2P_2K_2$	97	72	49	13350		
	$N_3P_2K_2$	145	72	49	14820		
Wenyaer, Xinjiang	$N_0P_2K_2$	0	42	25	11700	0.994	38
	$N_1P_2K_2$	113	42	25	14588		
	$N_2P_2K_2$	225	42	25	16538		
	$N_3P_2K_2$	338	42	25	12278		
Jiucheng, Yunnan	$N_0P_2K_2$	0	33	50	4553	0.970	39
	$N_1P_2K_2$	113	33	50	5654		
	$N_2P_2K_2$	225	33	50	6603		
	$N_3P_2K_2$	338	33	50	6804		
Luoxiong, Yunnan	$N_0P_2K_2$	0	52	90	6326	0.960	40
	$N_1P_2K_2$	138	52	90	7268		
	$N_2P_2K_2$	276	52	90	8111		
	$N_3P_2K_2$	414	52	90	7808		
Zhongcun, Zhejiang	$N_0P_2K_2$	0	24	75	3510	0.986	41
	$N_1P_2K_2$	86	24	75	5444		
	$N_2P_2K_2$	173	24	75	5734		
	$N_3P_2K_2$	259	24	75	6240		

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