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Influence of nitrogen fertilizer application on maize yield and nitrogen use efficiency in China

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Abstract
Maize (Zea mays L.) is a staple crop in China however, the excessive application of nitrogen fertilizer by farmers beyond crop requirement has led to a reduction in nitrogen use efficiency and environmental problems. To better understand these problems, we explored the differences in maize nitrogen management in China, this study uses a two-season field experiment conducted to test the effect of nitrogen rate on maize growth, yield, and NUE at Quzhou Experimental Station in the North China Plain in 2020-2021. The main results are shown below:
Field experiment results indicated that the application of 200 kg N/ha led to a higher yield of 7685 kg/ha in 2021, while the application of 60 kg N/ha resulted in higher N use efficiency. Excessive application of N led to reduced Partial Factor Productivity (PFPN) and Agronomic Use Efficiency (AEN) when 200kg N/ha was applied compared to the application of 60 kg N/ha with a PFPN of 33.1 kg/kg and 128.1 kg/kg, respectively, in 2021.
In summary, the high application of nitrogen has been found to increase yield, however, the excessive application beyond crop requirement for maximum maize yield led to low partial factor productivity and agronomy use efficiency of N. Therefore, it is paramount to reduce nitrogen application rate as the application beyond the optimal rate does not guarantee a steady increase in yield but rather causes a decline in nitrogen utilization of maize. Overall, the result indicates that for China to sustain maize production and improve N use efficiency, application rate needs to be optimized.

Keywords: *nitrogen application rate, China, yield, maize, partial factor productivity, agronomic use efficiency, nitrogen use efficiency.*

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I. Introduction

One-third of China's grain production is from maize[1]. The common farming method practiced in the North China Plain is the wheat/maize system. Maize yield has increased significantly in recent decades in China and other mechanized parts of the world due to increased mineral fertilization, mechanization, and improvements in planting density [2]. The productiveness of any given plant is a feature of nutrient availability [3]. However, crops grown must efficiently utilize all or most of the nutrients applied [4], and as such, agricultural intensification for maximum food production necessitates holistic approaches in fertilizer management, particularly nitrogen [5].

Nitrogen (N) is an essential nutrient that influences agricultural ecosystem productivity. It is mostly supplied through chemical fertilizers [6]. Maize productivity responds positively to N availability. In 2019, China's chemical N fertilizer consumption was 26 million metric tons (MMT), followed by India (18 MMT), the USA (11 MMT), and the European Union (9 MMT), making China the top agricultural consumer of total N in the world [7]. The application level, method, and source of nitrogen, along with climate, affect maize production [8]. Increasing N application has been an important strategy in agricultural production for achieving high yields, yet there is not always a positive correlation between crop yield and N level [9]. Farmers in China apply N fertilizer >263 kg/ha, higher than the optimum rate practiced in the experimental field, which leads to low nitrogen use efficiency (NUE) and agronomic use efficiency (AEN) [10].

Nitrogen management has become a serious issue in China and other developed countries as the excessive application by farmers has led to the loss of profit, resource depletion, and environmental issues such as leaching, volatilization, and eutrophication. According to [11] the application of 172 kg N/ha affected grain yield and NUE of maize, and a further increase of fertilizer led to yield decline. Also, a Regression analysis by Yang showed a linear decrease in PFPN AEN with an increase in N application rates [10].

A large portion of fertilizer N is not used effectively in agriculture, and 50 % of the N applied is recovered from soil and plants [12]. The average NUE is around 30 %, resulting from N loss [13]. Therefore, effective and improved nitrogen management practices are required to enhance maize productivity, agronomic efficiency, and N utilization. Good nutrient management practices increase N use efficiency by applying agronomic rate, at the precise time and using the right method [14]. Optimum nitrogen management involves reducing N application and using a combination of slow-release and urea fertilizers, which leads to an increase in NUE and grain yield [15]. Deep placement of fertilizer with a combination of CRU and urea at a ratio of 2:1 can improve NUE and maize yield[16]. Many researchers have focused on the effect of different N levels on maize growth and yield, but the correlation between nitrogen application rate and nitrogen use efficiency needs to be addressed. Hence, the influence of N application rate on growth parameter, yield, and N utilization efficiency in China were instigated in this research. The objectives of this study were (i) to determine the impact of different N application rates on growth and yield parameters of maize, (ii) to ascertain how different N application rates affect nutrient uptake of maize, and (iii) to analyze the influence of N application rates on partial factor productivity of N and agronomic efficiency of N in China.

II. Materials And Method

Description of study area

The experiment was carried out from June 2020 to October 2021 at the China Agricultural University, Science and Technology Backyard (STB), Quzhou Experimental Station, Hebei Province, located on the North China Plain. Its geographical coordinates lie between 36°52´N and 115°01´E. The soil in this area is alkaline, and the cropping system practiced is the winter wheat/summer maize rotation. The study site has a warm-tempered monsoon zone with a mean yearly temperature of 14.4 °C and annual precipitation of 676 mm, of which 60 % occurs from July to September. The soil has a pH of 7.71, and the topsoil (0-20 cm) contains soil organic carbon of 17.1 g/kg, total N 1.22 g/kg, available P 103 mg/kg, and available K 144 mg/kg air-dried soil. Plant samples were dried and ground to powder form for nutrient analysis. The material was dissolved in a mixture of concentrated H_2SO^4 and H_2O^2 before determining N, P, and K content. Nitrogen content was determined by the micro–Kjeldahl method (KDY-9810, KETUO Instrument Co. Ltd., Beijing, China); P content was determined by the vanadomolybdate method (UV757T, Shanghai Instrument Co. Ltd., Shanghai, China); K content was measured by flame photometry (FP640, Shanghai Instrument Co. Ltd., Shanghai, China) [17].

Experimental design and treatment

A randomized block design (RBD) with four replicated treatments was used to conduct the experiment. Nitrogen treatment was set as (Control, N0, N200, and N60 kg/ha) with phosphorous (P) and potassium (K) at a constant rate of 75 kg/ha and 60 kg/ha, respectively, excluding control. Fertilizer was applied as a top dressing, and the sources of fertilizer used for the experiment were urea as N, single super phosphate (SSP) as phosphorus, and potassium chloride (KCL) as potassium. The size of each plot was 6 m long and 3 m wide (18 m^2).
Denghai 605, a high-yield maize variety, was sown on June 13, 2020, and May 25, 2021, using a planter and placing one seed per hole. The planting density was 66666 plants/ha in 2020 and 2021, using a planting spacing of 25 cm and a row spacing of 60 cm. The variety has an 88-90 % germination rate. Fertilizer was applied after emergence, using the furrow application method at a depth of 10 cm and 5 cm from the maize plant. Imazapyr, a non-selective herbicide, was used to control weeds, and *Bacillus thuringiensis* was used to control insects and pests.

Sampling and measurements

a) Basic soil fertility: Before planting, soil samples were taken from a depth of 0-20 cm, and after harvest, samples were taken from 0-20 cm and 20-40 cm using an auger. The samples were air-dried for 3 days and passed through a 2 mm sieve to remove debris. The soil samples were used to determine soil pH, organic carbon content, total N content, available N, Phosphorus, and Potassium content
b) Determination of plant traits: Measurements were taken at tasseling (VT) and harvest stage using a carpenter tape. Three plants from the middle row, excluding the right and left border row of each plot, were randomly selected to determine plant height, ear height, leaf length, leaf width, and aboveground dry matter. Fresh leaf, stem, and cob samples were cut, bagged separately, and oven-dried at 75°C. The final dry weight was recorded. Dried plant samples were then blended and sent to the laboratory for nutrient analysis. Green leaf area (LA) was determined using the length-width coefficient method [18].
c) The relative content of chlorophyll: Chlorophyll content was reflected by SPAD value, which was determined using a chlorophyll meter (SPAD-502) at the tasseling stage on 3 plants selected randomly from the three middle rows of each plot, and the average was calculated.
d) Yield and its component: At physiological maturity, a harvested area of 5.4 m^2 that has not been tampered with was selected. Cobs were harvested from the three middle rows of each plot, excluding the first and last borderline due to the influence of environmental factors. Total ear harvested were weighed and oven-dried at 75 ˚C, after which dry weight was recorded, five (5) maize cob with the most common trait from each plot were selected from the total harvested ear and weighed, then oven-dried at 75 ˚C and dried weight was recorded. The five ear samples were used to measure ear length, ear diameter, bald tip using a measuring tape, number of rows in an ear, number of grains in a row, and 1000 grain weight (TGW). Nitrogen use efficiency was calculated as AEN, PFPN and NUE.

Statistical formula

Green leaf area (GLA)
GLA = ∑ (leaf length × maximum width × 0.75) Equation (3-1)
Grain yield
Dry weight (kg/ha) = (dry weight of harvested area/ harvested area) Equation (3-2)
Dry weight of 1000 grain
100 grain weight = dry weight of grains/ number of grains *1000 Equation (3-3)
Dry matter (DM)
DM (kg/ha) = (dry matter sample per plant * harvest density) Equation (3-4)
Agronomic efficiency of N fertilizer (AEN)
AEN (kg/kg)= (maize output in fertilized treatment – maize output in control plot) / N rate (kg N/ha) [19]. Equation (3-5)
Partial factor productivity of applied N (PFPN)
PFPN (kg/kg)= GY_N /N where GY_N (kg/ha) is the maize grain yield from N treatment and N is the application rate [20]. Equation (3-6)
Plant nutrient uptake = nutrient content % in grain, leaf or stem * dry matter weight in kg/ha/100 [21] Equation (3-7)
Apparent utilization rate of N (NUE)
NUE (kg/kg) = (N uptake in N plot – N uptake in no N plot)/N input Equation (3-8)

Statistical analysis

Data were compiled in Excel 2019 and analyzed using R software version 4.0.2 to test a two-way ANOVA. At $p < 0.05$, the mean was compared using the least significant difference (LSD). Figures were constructed using Origin Pro 2021.

III. Result And Discussion

Influence of nitrogen application level on growth parameter of maize.

The following growth characteristics: plant height, leaf number, leaf area, and SPAD of summer maize during the two years were analyzed and shown in Table 1. The Table below shows no significant difference in plant height, number of leaves, leaf area, and chlorophyll content between treatment at the tasseling stage and harvest in 2020. In 2021, at ($P < 0.05$), a significant difference in plant height at the tasseling stage was recorded between the CK and N200 treatments. The control treatment had an average height of 255.2cm, while N200 had an average height of 264.8cm. At harvest, no significant difference was recorded in plant height between treatments. Similarly, leaf number, leaf area, and SPAD values were not significantly affected by treatment. However, CK treatment recorded the lowest plant height, leaf area at tasseling, and harvest in both years. The analysis of variance (ANOVA) at ($P < 0.05$) indicated that year had a significant effect on growth parameters. However, treatment and the interaction between treatment and year had no significant effect on plant height, leaf number, leaf area, and chlorophyll content.

Table 1. Influence of nitrogen application rate on growth parameter of maize at VT (tasseling stage and harvest) in 2020-2021

Year	Treatment (kg N/ha)	Plant height at VT (cm)	Plant height at Harvest (cm)	Number of green leaves at VT	Leaf area (cm^2)	SPAD at VT
2020	Ck	$209.8±2.8^a$	$221.5±13.0^a$	$12.2±0.8^a$	$525.1±28.0^a$	$60.3±3.0^a$
	N_0	$212.3±8.0^a$	$227.7±9.0^a$	$12.3±0.5^a$	$530.2±37.3^a$	$60.7±1.0^a$
	N_{60}	$212.1±12.5^a$	$230.2±4.2^a$	$12.5±0.3^a$	$530.5±34.8^a$	$60.7±2.1^a$
	N_{200}	$215.9±8.0^a$	$234.7 ±13.1^a$	$12.7±0.3^a$	$542.2±19.4^a$	$60.9±0.8^a$
2021	Ck	$255.2±6.0^b$	$236.7±1.9^a$	$13.2±0.7^a$	$479.9±9.6^a$	$57.0±0.5^a$
	N_0	$261.5±6.4^{ab}$	$240.0±16.8^a$	$13.3±0.0^a$	$502.0±40.2^a$	$57.0±1.9^a$
	N_{60}	$262.6±4.5^{ab}$	$240.8±5.9^a$	$13.3±0.5^a$	$505.6±21.2^a$	$57.1±0.9^a$
	N_{200}	$264.8±4.8^a$	$247.9±5.5^a$	$13.7±0.5^a$	$510.4±31.4^a$	$58.3±2.1^a$
Year (Y)		0.001	0.001	0.001	0.004	0.001
Treatment(T)		ns	ns	ns	ns	ns
T×Y		ns	ns	ns	ns	ns

* NB: N represents nitrogen, control (CK), 0, 60, and 200 kg N/ha represent the applied N rate. The values are presented as the mean ± standard deviation. Different letters in the same columns represent significant differences at the level of $P < 0.05$.

Influence of nitrogen application rate on maize yield and yield components in 2020-2021

Grain yield, ear height, cob diameter, and thousand-grain weight were significantly ($P < 0.05$) affected by year, kernel per ear was significantly influenced by the interaction between treatment and year (Table 2). The response of N rate on ear height, cob length, cob diameter, thousand-grain weight (TGW), and yield were not significant in both years. However, in 2021, a significant difference was recorded between CK and N200 treatments, with a kernel number of 581.8 and 656.3, respectively. No significant difference was found between the N0 and N60 treatments. In 2021, the highest grain yield was recorded in treatment N200 with a grain yield of 7685.1 kg/ha, and CK with the lowest yield of 6363.2 kg/ha, but no significant difference was recorded between treatments.

Table 2. Maize yield and its components as affected by N application in 2020-2021.

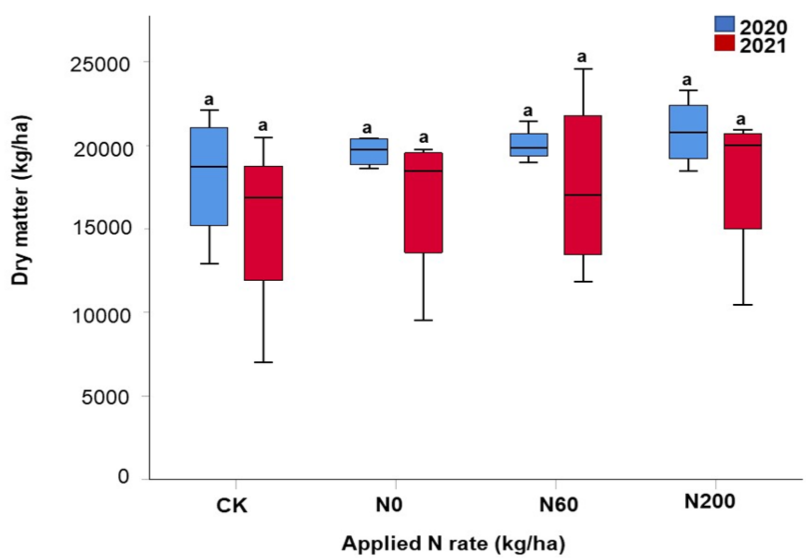
Year	Treatment	Ear height (cm)	Cob length (cm)	Cob diameter (cm)	Kernel per ear	1000 grain weight (g)	Yield (kg/ha)
2020	CK	83.3±7.1[a]	22.8±1.1[a]	5.7±0.1[a]	598.1±41.3[a]	352.0±13.1[a]	5189.9±567.3[a]
	N_0	83.9±3.3[a]	22.8±1.4[a]	5.7±0.1[a]	611.7±56.2[a]	363.3±9.5[a]	5243.9±119.9[a]
	N_{60}	85.4±3.7[a]	23.0±0.8[a]	5.7±0.4[a]	632.6±33.0[a]	368.0±11.0[a]	5575.7±38.5[a]
	N_{200}	87.1±9.8[a]	23.3±0.7[a]	5.8±0.3[a]	641.7±28.0[a]	369.3±15.1[a]	5654.7±278.3[a]
2021	CK	95.7±2.4[a]	22.0±1.3[a]	5.1±0.3[a]	581.8±46.2[b]	339.3±17.3[a]	6363.9±619.1[a]
	N_0	97.6±8.9[a]	23.0±1.3[a]	5.2±0.4[a]	654.3±36.0[a]	339.3±19.9[a]	6623.5±447.2[a]
	N_{60}	98.5±7.1[a]	23.4±0.6[a]	5.2±0.4[a]	633.1±22.3[ab]	344.7±14.5[a]	6755.7±798.4[a]
	N_{200}	98.8±8.8[a]	23.6±1.2[a]	5.2±0.3[a]	656.3±43.2[a]	352.3±24.5[a]	7685.1±383.8[a]
Year (Y)		0.001	ns	0.001	ns	0.001	0.001
Treatment (T)		ns	ns	ns	ns	ns	ns
T×Y		ns	ns	ns	0.04	ns	ns

* NB: N represents nitrogen, control (CK), 0, 60, and 200 kg N/ha represent the applied N rate. The values are presented as the mean ± standard deviation. Different letters in the same columns represent significant differences at the level of $P < 0.05$.

Effect of nitrogen rate on dry matter weight in 2020-2021 growing seasons

Figure 1 illustrates that dry matter weight ranged from 15330 - 20820 kg/ha, with the lowest biomass associated with treatment CK (18130 kg/ha) and the highest N200 (20820 kg/ha) in 2020. In 2021, there was no significant difference between treatments, CK had the lowest biomass weight of 15330 kg/ha, and N200 had a high biomass of 17850 kg/ha. However, at ($P > 0.05$) treatment, year, the interaction between year and treatment had no significant effect on dry matter weight.

Fig. 1. Effect of nitrogen rate on dry matter weight in 2020-2021 growing seasons.

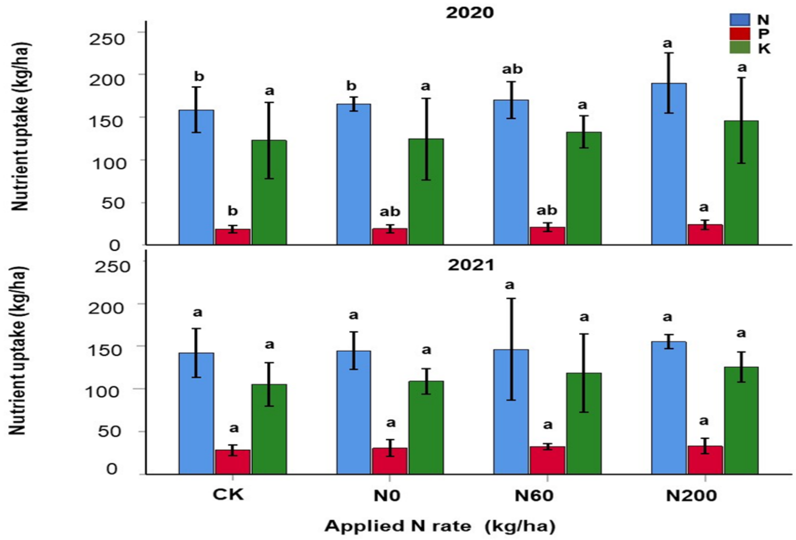


NB: N represents nitrogen, control (CK), 0, 60, and 200 kg N/ha represents the applied N rate. Values are means of four replicates of every treatment. Means followed by a common letter are not significantly (ns) different at ($P < 0.05$) probability level.

Influence of nitrogen application rate on Nutrient uptake of maize in 2020-2021

After harvest, the total NPK nutrient uptake, derived from stem, leaf, and grain was analyzed. As seen in Fig (2). The result shows application rate affected N uptake in 2020 planting season. A significant difference was observed between treatments with N200 having the highest N uptake of (190.0 kg/ha) and control (CK) having the lowest (158.5 kg/ha). Also, a significant difference was observed in P uptake between CK and N200.

However, treatment did not affect K uptake nutrients. In 2021 growing season N application rate did not affect the NPK nutrient of the plant. The highest NPK uptake was recorded in N200, while CK had the lowest nutrient uptake. Overall analysis shows that year had a significant effect on NPK uptake of maize, while treatment and the interaction between T×Y had no effect.



NB: N represents nitrogen, control (CK), 0, 60, and 200 kg N/ha represents the applied N rate. Values are means of four replicates of every treatment. Means followed by a common letter are not significantly (ns) different at ($P < 0.05$) probability level.

Effect of application rate on PFPN, AEN, and NUE

Table 3 shows that PFPN increased significantly with decreasing N application rate in 2020 and 2021. Overall analysis shows years, treatment and T×Y interaction had a significant effect on PFPN. No significant difference was recorded between year, treatment, and the interaction between T×Y of AEN. Treatment N200 had the lowest N agronomic use efficiency. As N rate increased from 60 kg N/ha to 200kg N/ha apparent utilization rate reduced in 2020 and 2021. Statistics show that year, treatment, and the interaction between T×Y had no significant effect on NUE.

Table 3. Effect of application rate on N agronomic efficiency (AEN), partial factor productivity of applied N (PFPN), and apparent utilization rate

Treatment	PFP (kg/kg)		AEN (kg/kg)		NUE (%)	
	2020	2021	2020	2021	2020	2021
CK	-	-	-	-	-	-
N_0	-	-	-	-	-	-
N_{60}	92.9±9.3a	128.1±12.8a	6.6±10.2a	6.5±3.8a	18.9±11.3a	10.2±29.7a
N_{200}	28.3±0.4b	33.1±4.5b	2.3±1.4a	6.5±33a	15.6±5.6a	6.6±2.6a
Year (Y)	0.001		ns		ns	
Treatment (T)	0.001		ns		ns	
T×Y	0.001		ns		ns	

* NB: N represents nitrogen, control (CK), 0, 60, and 200 kg N/ha represent the applied N rate. The values are presented as the mean ± standard deviation. Different letters in the same columns represent significant differences at the level of $P < 0.05$

Table 4 Soil chemical properties at depths 0-20 cm and 20-40 cm from 2020-2021 after harvest

Year	Treatment	Available N (%)		Available P (mg/kg)		Available K (mg/kg)		pH 1:2.5		SOC (%)	
		0-20 cm	20-40 cm	0-20 cm	20-40 cm	0-20 cm	20-40 cm	0-20 cm	20-40 cm	0-20cm	20-40cm
2020	CK	0.11±0.1^a	0.11±0.1^a	12±0.7^a	2±0.1^a	136±2.8^a	102±0.5^a	7.9±0.1^a	8.1±0.3^a	1.6±0.1^a	0.7±0.1^a
	N_0	0.11±0.1^a	0.10±0.1^a	10±0.3^a	2±0.1^a	143±2.3^a	102±0.6^a	8.0±0.0^a	8.2±0.1^a	1.7±0.2^a	0.7±0.0^a
	N_{60}	0.11±0.1^a	0.11±0.1^a	8±0.4^a	2±0.1^a	131±1.6^a	100±0.5^a	8.1±0.1^a	8.1±0.2^a	1.6±0.2^a	0.7±0.0^a
	N_{200}	0.11±0.1^a	0.12±0.1^a	8±0.2^a	2±0.1^a	142±1.4^a	101±0.6^a	7.9±0.1^a	8.2±0.1^a	1.6±0.1^a	0.7±0.0^a
2021	CK	0.11±0.1^a	0.11±0.1^a	9±0.4^a	6±0.2^a	141±1.9^a	109±1.1^a	7.9±0.4^a	8.1±0.2^a	1.5±0.1^a	0.9±0.1^a
	N_0	0.10±0.1^a	0.10±0.1^a	9±0.5^a	5±0.1^a	143±1.8^a	108±1.3^a	8.0±0.2^a	8.0±0.1^a	1.3±0.3^a	0.9±0.2^a
	N_{60}	0.11±0.1^a	0.12±0.1^a	10±0.3^a	6±0.1^a	151±1.7^a	119±1.2^a	8.0±0.1^a	8.1±0.1^a	1.5±0.2^a	1.1±0.0^a
	N_{200}	0.10±0.1^a	0.12±0.1^a	9±0.4^a	4±0.1^a	149±2.2^a	107±1.2^a	8.1±0.0^a	8.1±0.0^a	1.4±0.3^a	0.9±0.1^a
Year (Y)		ns	0.001	ns	0.001	ns	0.001	ns	ns	0.027	0.001
Treatment(T)		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
T×Y		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Note: Soil AK, AP, and AN at a depth of 0-20 cm and 20-40 cm in 2020 - 2021. The values are presented as the mean ± standard deviation.

Soil chemical properties as affected by nitrogen level in 2020 and 2021

After the harvesting of maize in 2020 and 2021, soil properties were tested and analyzed from a depth of 0-20 cm and 20-40 cm. The above table shows that N level did not affect available N, P, and K at a depth of 0-20 cm and 20-40 cm in 2020 and 2021. The summary of the analysis of variance shows that year had a significant effect on available N, P, and K at the depth of 20-40 cm. application rate had no influence on soil pH at the dept of 0-20cm and 20-40cm, analysis of variance shows that at a depth of 0-20 cm and 20-40cm year, treatment, and interaction between T×Y had no impact on soil pH. It was observed that as depth increased soil organic carbon reduced across both seasons. In 2021 treatment N0 and N60 had the lowest SOC at a depth of 0-20 cm, no significant difference was observed between treatments. ANOVA shows that years had a significant effect on soil organic carbon at the depth of 0-20 cm and 20-40 cm, treatment and interaction did not affect SOC at both depths.

Discussion

Effect of nitrogen application on maize yield and biomass

The effect of applying N on maize grain yield and yield parameters varies depending on the rate applied and soil physiochemical conditions. Several researchers have mentioned the importance of other managerial factors such as planting density, source of N, and variety, among others, as they interact with N in affecting maize yield. The results from this study showed a higher grain yield when N200 was applied with a planting density of 66666 plants/ha. Maize grain yield increased with time, with 2021 producing the highest yield. The result is in line with other researchers who reported that maize yield is at a maximum stage when application is N200 and with a density of 66666 plants/ha [22]. Nitrogen application rate did not significantly influence maize yield, however, yield increased as N application increased. The average grain yield was higher in the N200 application than in the N60 application (6630 and 6139 kg/ha, respectively). The lowest average grain yield (5776 kg/ha) was recorded in CK treatment. The result thereby implied that soil residual availability of N meets or exceeds the crop's nutritional demand. This indicates that the application of N fertilizer beyond its optimum rate may reduce yield, thereby causing loss of profit and resources [23]. A higher yield in cereal-based systems was recorded when no external fertilizer was used [24]. This was mostly attributed to the improvement of soil-related parameters, as the yield of long-term experiment control plots did not vary significantly. Similar findings were observed, where no N was applied, higher yields of 9894 kg/ha were realized than when 350kg N /ha was applied 9352 kg/ha [25]. This further proves that additional N supply in maize cropping systems should be minimized and may bring several environmental benefits in continuous maize systems. In one study, it was observed that average grain yield increased and then decreased with increasing N rate. The result also shows an average high yield of 13.366 kg/ha when 180 kg N/ha was applied, compared to 9,859 when no N was applied [26]. Meta-analytic studies in China review that maize yields can be increased by applying 146-180 kg N/ha, with soil pH less than 8 [27]. Researchers have reported that applying an average of 225 kg N/ha is positively linked with high yield driven by high radiation, water, and N use efficiency [28]. Identifying an optimum rate of N which facilitates high yields while reducing environmental repercussions remains a challenge in China.

However, overall analysis shows that time affected growth and yield parameters this could be as a result of environmental factors such as rainfall, and temperature [29], [30] or management factors such as early planting. Early planting significantly increases yield which is reasonable as the maize was also planted at the right time [31]. Maize yields observed in this study were generally higher, even though they were affected by flooding in the second year of the experiment. Research has shown that grain yield increases with an increase in precipitation, up to a point where it starts declining [32]. Despite the observed effects of year and potential environmental challenges, high yields were observed across all treatments, including the control, suggesting that other factors may have mitigated an impact. On average, maize grain yield was lower in 2020 than in 2021. The reason might be that, besides different levels of N applied, maize residue retention was carried out soon after harvesting. This affects N levels in the soil, as all the nutrients are retained in the soil and become available through mineralization to the next crop. Residue retention in China has become a common practice and has been reported to inhibit N leaching while increasing maize yields [33]. At the same time, strategies to increase fertilizer use efficiency while maintaining high grain yields and economic benefits should be encouraged, such as the use of controlled-release urea [34]. Higher grain yields have been reported with conventional urea when applied at the right time and in the right amount [35]. Achieving high yields with minimum N application as seen in this study could also be linked to the high genetic efficiency of the variety in N utilization. As such, future studies which focus on varieties that efficiently utilize residual nutrients and ensure minimum application of external fertilizers should be promoted [36]. Furthermore, despite high grain yields in China, continued efforts are needed to close the yield gap and achieve the zero-hunger goal by 2030. Consequently, further scientific examination of efficient and sustainable nitrogen fertilizer application methods is crucial for policymakers, researchers, and farmers [37].

Effect of nitrogen application on nitrogen nutrient uptake of maize

Crop nutrient uptake is dependent on the nutrient concentration in the soil, and crop yield is directly affected by this uptake [11]. Residual N from fertilizer remaining in the soil after harvest can be available to plants in subsequent growing seasons in the following ways: as mineral N, in roots, immobilized into microbial biomass [38], or integrated into other soil organic matter pools [39]. It was observed from this study that N uptake increased as application rate increased this aligns with previous researchers who recorded an increase in N uptake with increased nitrogen application, followed by a decline at excessive N application [40], [41]. This further indicates that the application of N fertilizer at an optimum rate is required for high crop uptake, as excessive application leads to a decline [42]. Increased root branching has been linked to N fertilizer application, especially when applied close to the surface where P levels are highest [43]. The result from this study shows that as N increased, P Uptake reduced. This aligns with previous research that indicates additional application of N affects plant metabolism and root surface absorption of phosphorus. This suggests that excessive nitrogen residue due to the over-application of N leads to a change in P absorption by the plant [44], despite sufficient phosphorus supply in the soil, which has significant implications for fertilizer management practices in maize production. Excessive application of N by farmers needs to be addressed as it can result in the decrease of N use efficiency and influence other nutrients uptake by plants such as phosphorus, which could be yield-limiting [45]. Furthermore, N application has been shown to increase P uptake in alkaline soil [46] and an increase in N can promote the uptake of K in grain as well as stover. Therefore, optimal levels of N application are needed to balance nutrient uptake and obtain optimal crop yield.

Effect of nitrogen application rate on N fertilizer use efficiency

A key indicator used in reflecting the productivity of N fertilizer is N partial factor productivity (PFPN). Research has shown that PFPN reduces as N input increases [47], [48]. Consistent with this, Table 3 demonstrates that as N rate input increased, partial factor productivity of N (PFPN) reduced. In 2020, a significant difference in PFPN was observed between N60 and N200, with values of 28.3 and 92.9 kg/kg, respectively. Similar results were recorded in 2021, with PFPN of 33.1 kg/kg for N200 and 128.1 kg/kg for N60. An increase in PFPN was recorded as N rate increased and declined when N exceeded the optimum rate [20], [49], [50]. This proves that an excessive N application rate >200 certainly poses a reasonably high risk of N loss due to leaching, denitrification of nitrate N, and ammonia volatilization [51].

Agronomic efficiency (AEN) and nitrogen use efficiency (NUE) are indices of N use efficiency that show the grain yield production per unit of N applied [52]. In this study, the application rate of N had no significant effect on AEN and NUE, nor did year or the interaction between year and treatment. In 2020 AEN values for N200 and N60 were 2.3 kg/kg and 6.6 kg/kg, respectively, while in 2021, the values were 6.5 kg/kg and 6.6 kg/kg. Nitrogen utilization declined as N rate increased. A decline in AEN was recorded as N increased from 150 to 300 kg N/ha with an AEN of 3.9 - 2.1 kg/kg [20]. Treatment N60 had a higher AEN however, it was lower than the recommended value of 25-30 kg/kg for good management of AEN [53]. As N application rate reduced, AEN and NUE increased, indicating that the application rate was higher than optimal. A 20-40 % reduction in N fertilizer can increase nitrogen utilization efficiency while maintaining soil nitrogen concentration [53]. For nitrogen application requirement ≥180 kg/ha, split application of 2 or 3 with N requirement is recommended for lower NUE [54].

Effect of different nitrogen applications on soil chemical properties

Soil pH in China is an area that has received a lot of attention in the past few decades due to soil degradation concerns. Previously around the 1980s to 2000 researchers found high soil acidification due to excessive N application [55]. However, more scientific experiments show that soil pH in many parts of the country has changed to more alkaline conditions [56]. In China, maize production strives in neutral and alkaline soil, however, from the research it was observed that soil pH had no significant effect on treatment, year, and interaction. Furthermore, results across two years indicated that the overall levels of available N, P, K, and soil organic carbon increased in the 20-40 cm soil depth. Having larger values of residual soil nutrients might be an area that China needs to explore by incorporating heavy crop-feeding species. In maize cropping systems, alternating maize with legumes or other cereals that maximize the use of residual fertilizer may lead to reduced fertilizer application and limit excessive fertilizer application.

Conclusion

In this study, four treatments were used to assess the effect of N application rate on maize yield and N use efficiency. Results from the research show that China is faced with a problem of over-application of N fertilizer by smallholder farmers, which does not necessarily translate to further yield increase. The application of N60 kg/ha resulted in higher AEN, PFPN, and NUE in both seasons than in N200 kg/ha. Therefore, to increase use efficiency, China needs to reduce N application. The average yield of N200 6630 kg/ha was higher than N60 6139 kg/ha compared to CK with an average yield of 5776 kg/ha. This further implies that maize grain yield and N use efficiency are not increased with high N application.

Therefore, it is suggested that an optimized application rate be used to reduce wastage of fertilizer and increase N use efficiency as the soil in China has a great residual nutrient content after harvesting. In conclusion, future studies which focus on varieties that efficiently utilize residual nutrients and ensure minimum application of external fertilizers should be promoted also, and intercropping with high nitrogen fixation crops should be practiced in China.

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