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Research article

Effects of nitrogen reduction rates on grain yield and nitrogen utilization in a wheat-maize rotation system in yellow cinnamon soil

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Abstract: Excessive nitrogen (N) fertilizer application severely degrades soil and contaminates the atmosphere and water. A 2-year field experiment was conducted to investigate the effects of different N fertilizer strategies on wheat-summer corn rotation systems in yellow-brown soil areas. The experiment consisted of seven treatments: no N fertilization (CK), conventional fertilization (FP), optimized fertilization (CF), reduced N rates of 10% (90% FP), 20% (80% FP), 30% (70% FP), and a combination of controlled release with conventional urea at 7:3 ratio (CRU). The results indicate that under the condition of 80% FP, both CF and CRU treatments can increase the yield of wheat and corn for two consecutive years. Compared with FP treatment, the wheat yield of CF and CRU treatments increased by 3.62–2.57% and maize yield by 3.53–1.85% with N fertilizer recovery rate (NRE) of crops by 46.2–37.8%. The agronomic N use efficiency (aNUE) under CF treatment increased by 35.4–37.7%, followed by CRU, which increased by 30.5–33.9%. Moreover, compared with FP treatment, both CF and CRU treatment increased the content of organic matter (OM), total N (TN), and hydrolyzed N (HN) in the topsoil layer, and 70% FP treatment significantly reduced the HN content. Both CF and CRU treatments significantly increased the NO_3 concentrations in the 0–20 cm soil depth during the wheat and maize season at maturity stages and decreased the residual inorganic N below the plow layer (40–60 cm). During the corn season, the CF and CRU treatments significantly reduced the NO_3 concentration in the 40–60 cm soil layer from seedling to jointing. Considering various factors, CRU treatment under 80% FP conditions would be the best fertilization measure for wheat-corn rotation in yellow-brown soil areas.

Keywords: yellow cinnamon soil; wheat-maize rotation system; nitrogen fertilizer rate reduction; grain yield; soil nutrient

1. Introduction

The nitrogen (N) fertilizer management practices are crucially important to increase crop yield while protecting the environment by decreasing losses [1–4]. Among nutrients, the N contributes the most to increasing grain yield in cereal crops by 40% [5]. The fertilizers used in China since the 1980s have resulted in a nearly 85% increase in grain yield. However, the amount of fertilizer has increased 4.5 times, far exceeding the rate of grain yield increase [6]. The excessive use of N fertilizer is common; approximately 20% of the area in a wheat-maize rotation suffers from excessive N fertilizer applications [7]. Consequently, over-fertilization resulted in soil compaction, soil acidification, and other types of soil degradation, as well as ecological and environmental problems, such as residual NO_3 pollution [8,9]. The loss of N fertilizer in farmland is 40–50% [10–12]. Agricultural non-point source pollution caused by fertilizer residue has threatened the sustainable development of agriculture [13,14].

Appropriate applications of N fertilizer can increase grain yield and N utilization while reducing environmental pollution risks [15,16]. Many studies have investigated the effects of reducing fertilizer use and increasing efficiency on grain yield and N utilization. Nie [17] showed that reducing N applications in wheat by 10% or 20% in a vertical rotary tillage system reduced fertilizer waste and increased grain yield without significantly affecting grain quality. Li et al. [18] found that reducing N fertilizer applications by 10% and incorporating straw residue combined with bacterial residue (60 m^3/hm^2) increased wheat yield and N utilization efficiency, resulting in optimal economic benefits. Xiao et al. [19] found that a 30% reduction in controlled-release N fertilizer increases maize yield and N utilization efficiency. Liu et al. [20] reduced N fertilizer under 40% lower wheat planting density and 42.9% higher maize planting density and recommended fertilizer amount of 180 kg/hm^2.

Most studies on N fertilizer reduction and increased fertilizer efficiency focused on a single crop, with limited research on the annual reduction in N fertilizer use in different crop rotations. The wheat-maize rotation system is the main grain cropping system in Henan Province, with wheat accounting for 27.58% of the total national production and maize accounting for 8.38% [21,22]. High and stable yields of wheat and maize in this region are critical for ensuring national food security. Yellow cinnamon soil is the dominant soil in Henan Province, accounting for 15.38% of the soil in the province's cultivated land [23]. The aim of the study was to assess the potential for N fertilizer reduction in this rotation system and provide guidance for N fertilizer applications to achieve efficient and environmentally friendly production of grain crops and utilize nutrients efficiently while increasing grain yields.

2. Material and methods

2.1. Experimental site

The field experiment was conducted from October 2018 to October 2020 in Lizhuang Village, Shunhe Office, Yicheng District, Zhumadian City, Henan Province, China (33º01'16" N, 114º 07'27" E), a yellow cinnamon soil region. The soil at the experimental site exhibited the following physicochemical properties: pH value of 5.03, organic matter (OM) content of 22.5 g/kg, total nitrogen (TN) content of 1.31 g/kg, hydro-lytic nitrogen (HN) content of 126 mg/kg, available phosphorus (P) content of 50.1 mg/kg, available potassium (K) content of 114 mg/kg, exchangeable calcium (Ca) content of 8.2 cmol/kg, and exchangeable magnesium (Mg) content of 1.25 cmol/kg.

2.2. Experimental design

The Zhengmai7698 wheat and Zhengdan958 maize varieties were grown under seven different fertilizer management practices: no fertilization (CK); conventional fertilization (FP); optimized fertilization (CF); and 10% (90% FP), 20% (80% FP), and 30% (70% FP) reductions in N fertilizer application rate from conventional amount and made of mixture of urea with a nitrification inhibitor and urea at a ratio of 7:3 (CRU). The fertilizer rates and application methods are listed in Table 1. The urea fertilizers with a nitrification inhibitor (N, 43.6%) were produced by Henan Xinlianxin Fertilizer Co., Ltd. Regular urea (N, 46.0%), superphosphate (P_2O_5, 44%), and K chloride (K_2O, 60%) were purchased from the local agricultural market. In each treatment, the P and K fertilizers were applied as basal fertilizers once for wheat and during the seedling stage for maize. The N fertilizers were applied as basal fertilizers or as top-dressing according to the requirements for wheat during the tillering or elongation stages and for maize during the seedling or tasseling stages. Each treatment was replicated three times in a randomized complete block design (RCBD). Each plot was 10.0 m long and 3.0 m wide, with an area of 30 m^2. The row spacing for wheat was 0.2 m, with an interval of 0.6 m between plots. The interval between the rows was 0.4 m for maize, and the plot size was 20 m^2. A distance of 1.0 m was left between replications, and protective rows were established around the plots. The sowing rate for wheat was 180.0 kg/hm^2, and the planting density for maize was 67,500 plants/hm^2. Trained workers carried out all field management practices on the same working day.

2.3. Sample collection and analytical methods

2.3.1. Sample collection

The soil samples from the 0–20 cm plow layer was collected using the Mei flower method before sowing to measure initial soil properties. Samples were air dried, ground, and sieved, and then the pH value and the organic matter, alkaline hydrolysis N, available P, and available K contents were determined. After sowing, soil samples were collected from the 0–20 cm, 20–40 cm, and 40–60 cm layers of each plot during the seedling, elongation, heading, and maturation stages of wheat and the elongation, tasseling, and maturation stages of maize to determine the NO_3 content. A portion of the 0–20 cm soil sample was reserved after partial air-drying for laboratory analysis. The 2–3 plant samples were obtained from each plot, and their fresh weight was measured. After drying, their dry weight was measured, and representative samples were reserved for subsequent laboratory analysis. Plant samples were also collected during the maturation stage.

Table 1. Fertilization and application methods in the wheat-maize crop rotation.

Treatments	Fertilization method	Wheat (NPK)	Maize (NPK)
T1 = CK	No N fertilizer	0–90–60	0–60–90
T2 = FP	One-time N fertilization	225–90–60	225–60–90
T3 = CF	Recommended fertilization at intervals	180–90–60	180–60–90
T4 = $FP_{90\%}$	Reduced N rate by 10%	202.5–90–60	202.5–60–90
T5 = $FP_{80\%}$	Reduced N rate by 20%	180–90–60	180–60–90
T6 = $FP_{70\%}$	Reduced N rate by 30%	157.5–90–60	157.5–60–90
T7 = CRU	Controlled-release urea mixed with ordinary urea at 7:3 ratio	180–90–60	180–60–90

Strategy: The ratio of base to top N fertilizer during the wheat period was 6:4, the seedling stage: the trumpet stage during maize period is 4:6 in the treatment (T3); Other test treatments: One-time application of wheat base fertilizer, One-time application in seedling stage of maize.

2.3.2. Yield measurement and planting evaluation

Representative plants were selected from each plot for conventional yield assessment. After wheat maturity, the number of spikes per plant, number of grains per spike, and thousand–grain weight were statistically analyzed. Before the maize harvest, 10 cobs of each plot were air–dried to a standard moisture content (14%), and the cob length and diameter, length of the tip without kernels, number of rows per cob, and thousand-grain weight were measured. The plot yields were recorded, and the plant and grain samples were preserved for further analysis.

2.3.3. Parameters and lab analysis

The soil OM was determined using the potassium dichromate volumetric method with external heating. The TN content was obtained using the Kjeldahl method. The HN was analyzed using the alkaline diffusion method. Soil NO_3 concentration was measured by calcium chloride extraction and a flow analyzer. The available P was determined using the Olsen method, and the available K concentration was measured using ammonium acetate extraction with flame photometry. In the case of plant sample analysis, the plant samples were boiled in concentrated sulfuric acid and hydrogen peroxide after pulverization. The TN contents in the straw and seeds were determined with conventional analytical methods. The N fertilizer recovery rate (NRE), agronomic N efficiency (aNUE), and N fertilizer partial productivity (NPFP) of crops were calculated as follows:

$$NRE = \frac{Crop\ N\ uptake_{Fertilized\ plot} - Crop\ N\ uptake_{None\ fertilized\ plot}}{N\ input} \times 100 \quad (1)$$

$$aNUE = \frac{Crop\ yield_{Fertilized\ plot} - Crop\ yield_{None\ fertilized\ plot}}{N\ input} \quad (2)$$

$$NPFP = \frac{Crop\ yield_{Fertilized\ plot}}{N\ input} \quad (3)$$

where *NRE* is N fertilizer recovery rate, %; *aNUE* is agronomic N efficiency, kg/kg; *NPFP* is N fertilizer partial productivity, kg/kg; *N input* is N fertilizer applied in fertilized plot, kg/hm^2; $Crop\ N\ uptake_{Fertilized\ plot}$ is Crop N uptake in fertilized plot, kg/hm^2; $Crop\ N\ uptake_{None\ fertilized\ plot}$ is Crop N uptake in none fertilized plot, kg/hm^2; $Crop\ Yield_{Fertilized\ plot}$ is Crop yield in fertilized plot, kg/hm^2; and $Crop\ Yield_{None\ fertilized\ plot}$ is Crop yield in none fertilized plot, kg/hm^2.

2.4. Statistical analysis

Soil Analysis of variance (ANOVA) was performed using SPSS 22 to determine the effects of different N fertilizer management practices on wheat and maize yields, NRE, aNUE, NPFP, OM, TN, HN, and soil N distributions at different growth stages. The differences between N fertilizer treatments were detected using Duncan's multiple range test at $p < 0.05$. The MS Excel 2019 (Microsoft, USA) origin 2023b (Origin Lab, USA) were used to visualize data graphically.

3. Results

3.1. Wheat and maize yields

The wheat yield was lower in 2020 than in the previous year, while the maize yield was higher (Table 2). This result was mainly attributed to the prolonged duration of the spring drought in the local area in 2020 resulting in a water imbalance. However, there was sufficient rainfall in the autumn of 2020. The CF involved a split application of fertilizers for wheat and maize, which significantly increased the yields of both crops. The CF treatment produced the highest annual wheat and maize yields, with 8630 kg/hm^2 and 6458 kg/hm^2 for wheat and 7835 kg/hm^2 and 8555 kg/hm^2 for maize. The CRU treatment resulted in slightly lower wheat and maize yields, but there was no significant difference compared to the CF treatment. The wheat yield was 3.62% and 2.57%, respectively, and the maize yield was 3.53% and 1.85% higher in the CF and CRU treatments than in the 80% FP treatment. However, the yield was lower in the 70% FP treatment.

Table 2. Wheat-maize crop yield under different treatments.

Treatments	2018–2019		2019–2020	
	wheat（kg/hm^2）	maize（kg/hm^2）	wheat（kg/hm^2）	maize（kg/hm^2）
CK	5103.5c	4427.5d	3927.0c	5247.5c
FP	8369.0ab	7559.0ab	6203.0ab	8274.0ab
CF	8630.0a	7835.0a	6458.0a	8555.0a
90% FP	8465.5a	7484.5ab	6273.5ab	8090.5ab
80% FP	7649.5b	7074.0b	5879.5ab	7625.5b
70% FP	6858.5b	6338.5c	5277.5b	6809.0bc
CRU	8534.0a	7674.0a	6398.0a	8454.0a

Note: Different lowercase letters in the same column indicate significant differences among treatments at 0.05 level. CK is no fertilization; FP is conventional fertilization; CF is optimized fertilization; 90% FP, 80% FP, and 70% FP are applications of reduced N fertilizer by 10%, 20%, and 30%, respectively. CRU is the application rate from conventional amount and a mixture of urea with a nitrification inhibitor and urea at a ratio of 7:3.

The three N reduced treatments (90% FP, 80% FP, and 70% FP) had lower wheat and maize yields than the FP treatment in both years, with the following order: 90% FP > 80% FP > 70% FP. There was no significant difference in the winter wheat yield between the 90% FP and 80% FP treatments and between these two treatments and the FP treatment. However, the winter wheat yield was significantly different between the 70% FP treatment and the FP treatment in the second year. No significant difference in the maize yield was observed between the three N reduction treatments and the FP treatment in the second year, but the yields of the 80% FP and 70% FP treatments were significantly lower than that of the CF treatment. The maize yield of the 70% FP treatment was significantly lower than that of the FP and CF treatments in the first year. However, the 30% reduction resulted in a lower yield. Compared to the FP treatment, the wheat yield was 18.05% and 14.92% lower (average of 16.49%), and the maize yield was 16.15% and 17.71% lower (average of 16.93%) than FP treatment.

3.2. Yield attributes of wheat and maize

Results showed spikelet number was significantly higher in all fertilizer treatments than CK (Table 3). The three N reduced treatments (90% FP, 80% FP, and 70% FP) exhibited a decreasing trend in the spikelet number. The spikelet number was significantly lower in the 70% FP treatment than FP treatment. It was higher in the CRU treatment, but there was no significant difference compared to the FP treatment. The effective spikelet number and thousand-grain weight were significantly higher in the CF, 90% FP, and CRU treatments than CK, while there was no significant difference in these parameters between the different fertilizer treatments. The maize cob number was significantly higher in all fertilizer treatments than CK. All reduced N fertilizer treatments showed a decrease in cob number. The cob number was significantly lower in the 80% FP, followed by 70% FP treatments than FP treatment. The cob number was higher in the CRU treatment than FP treatment, but there was no significant difference. The hundred-grain weight in the first year was significantly higher in all fertilizer treatments than CK. The hundred-grain weight was significantly lower in the 70% FP treatment than FP treatment, while there was no significant difference between the X treatment and the other fertilizer treatments. In the second year, the hundred-grain weight was significantly higher in the FP, CF, 90% FP, and CRU treatments than CK, whereas there was no significant difference between the 80% FP and 70% FP treatments and the CK.

3.3. The nitrogen (N) uptake and utilization of wheat and maize

The total N uptake in wheat and maize was significantly higher in all N fertilizer treatments than CK in both rotation (Table 4). No significant difference was observed in the total N uptake between all N fertilizer treatments and the FP treatment, except for a higher value in the 70% FP treatment. The three N reduction treatments (90% FP, 80% FP, and 70% FP) exhibited a decreasing trend in total N uptake. The total N uptake in wheat and maize was 18.32% and 16.56% lower (statistically significant) in the 70% FP treatment than FP treatment. The total N uptake in the two rotation years was 7.26% and 3.67% (4.48% and 5.63%) higher in the CF treatment (CRU treatment) than FP treatment.

Table 3. Crop yield components in the wheat-maize rotation under different treatments.

Year	Treatments	wheat			maize		
		Effective number of panicles （x 1000 ears/hm^2）	Grain number per ear （ear）	1000–grain weight （g）	Effective number of panicles （x 1000 ears/hm^2）	Grain number per ear （Grain number/ear）	100–grain weight （g）
2018–2019	CK	32.4b	30.7c	38.5b	6.695a	267.4c	26.5c
	FP	44.1ab	36.4ab	42.1a	6.735a	410.1a	29.6a
	CF	45.4a	37.6a	42.7a	6.740a	417.8a	30.9a
	90% FP	44.9a	37.2a	42.5a	6.730a	407.0ab	28.9ab
	80% FP	41.7ab	33.1b	40.5ab	6.715a	350.6b	28.4ab
	70% FP	39.7ab	31.8b	39.9ab	6.685a	307.9b	27.9bc
	CRU	44.3a	37.1a	42.3a	6.740a	413.8a	30.2a
2019–2020	CK	29.6b	22.6c	43.7b	6.575a	304.8c	24.3b
	FP	40.6ab	37.6ab	43.5ab	6.695a	439.8ab	26.5a
	CF	42.4a	39.4a	45.8a	6.695a	453.9a	27.1a
	90% FP	42.0a	38.6a	45.5a	6.720a	435.8ab	26.2a
	80% FP	40.2ab	35.8ab	45.1a	6.705a	397.2b	25.2ab
	70% FP	39.2ab	33.4b	44.0ab	6.690a	357.9b	25.0ab
	CRU	41.8a	38.9a	45.2a	6.735a	454.1a	26.9a

Note: CK is no fertilization; FP is conventional fertilization; CF is optimized fertilization; 90% FP, 80% FP, and 70% FP are applications of reduced N fertilizer by 10%, 20%, and 30%, respectively. CRU is the application rate from conventional amount and a mixture of urea with a nitrification inhibitor and urea at a ratio of 7:3.

Table 4. Annual N use efficiency of wheat-maize under different treatments.

Year	Treatment	N uptake (kg/hm^2)	*NRE* (%)	*aNUE* (kg/kg)	NPFP (kg/kg)
2018–2019	CK	165.4 c	/	/	/
	FP	290.4 a	27.8bc	14.22bc	35.40b
	CF	311.5 a	40.6a	19.26a	45.74a
	90% FP	289.6 ab	30.7b	15.85b	39.38b
	80% FP	278.9 ab	31.5b	14.42bc	40.90ab
	70% FP	237.2 b	22.8c	11.64c	41.90ab
	CRU	303.4 a	38.3ab	18.55ab	45.02a
2019–2020	CK	229.1 c	/	/	/
	FP	343.0 a	25.3bc	11.78bc	32.17b
	CF	355.6 a	35.1ab	16.22a	41.70a
	90% FP	356.5 a	31.5ab	12.81b	35.47b
	80% FP	336.5 a	29.8b	12.03bc	37.51ab
	70% FP	286.2 b	18.1c	9.24c	38.37ab
	CRU	362.3 a	37.0a	15.77ab	41.26a

Note: CK is no fertilization; FP is conventional fertilization; CF is optimized fertilization; 90% FP, 80% FP, and 70% FP are application of reduced N fertilizer by 10%, 20%, and 30%, respectively. CRU is the application rate from conventional amount and a mixture of urea with a nitrification inhibitor and urea at a ratio of 7:3.

The NRE, aNUE, and NPFP rates were higher in the CF and CRU treatments than in FP treatment in both rotation cycles. The NRE was 46.0% and 38.7% (37.8% and 46.2%) higher in the CF treatment (CRU treatment) than FP treatment. The aNUE was 35.4% and 37.7% (30.5% and 33.9%) higher in the CF treatment (CRU treatment) than FP treatment. The NPFP was 29.2% and 29.6% (27.2% and 28.3%) higher in the CF treatment (CRU treatment) than FP treatment. The three N reduced treatments (90% FP, 80% FP, and 70% FP) exhibited a decrease in the NRE and aNUE and an increase in the NPFP. The NPFP rate and aNUE were 18.0% and 28.5% and 18.1% and 21.6% lower in the 70% FP treatment than FP treatment in both rotation cycles, respectively.

3.4. Soil organic matter (OM) content during wheat and maize maturity

The soil OM content was higher in all N fertilizer treatments than CK during the maturity stage of wheat and maize (Figure 1). Significantly higher soil OM contents of wheat field were observed in the FP, CF, and CRU treatments than CK in both rotation cycles. Also, significantly higher soil OM contents of maize fields were observed in FP, CF, and CRU treatments in the first year and in the FP, CF, 90% FP, and CRU treatments in the second year than CK. However, there was no significant difference in this parameter between different N fertilizer treatments. The soil OM content was higher in the CF and CRU treatments than FP treatment. The OM was 2.87% and 5.64% higher at wheat maturity stage and 8.33% and 1.83% higher at maize stage in the CF treatment than FP treatment in the two rotation cycles, respectively. Whereas, OM was 1.72% and 1.02% higher at wheat maturity and 5.09% and 2.28% higher at maize maturity stage in the CRU treatment than FP treatment in the two rotation cycles, respectively. The three N reduction treatments (90% FP, 80% FP, and 70% FP) exhibited a decrease in the soil OM content during the wheat-maize rotation.

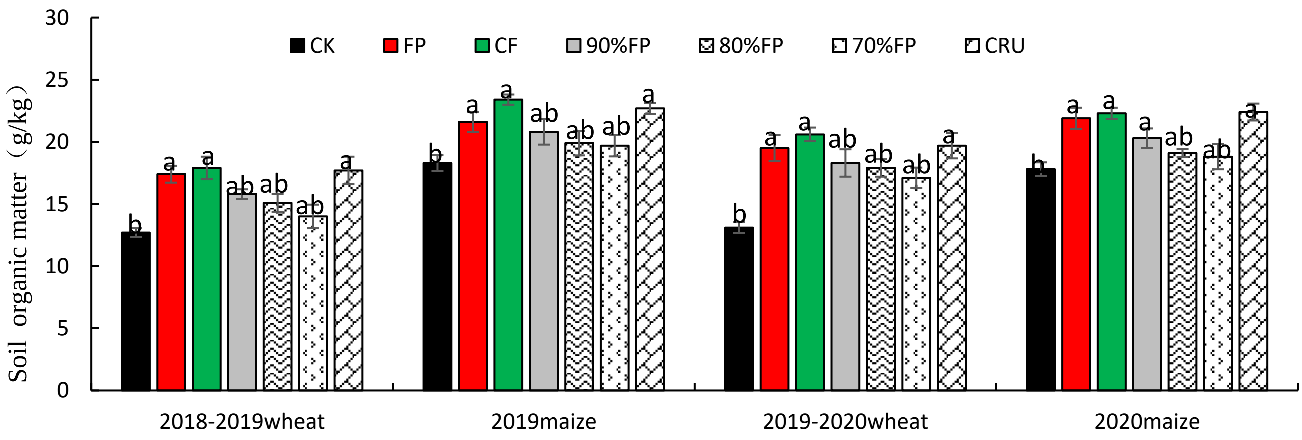

Figure 1. Soil organic matter content in the plough layer in different treatments at the maturity stage of wheat-maize. CK is no fertilization; FP is conventional fertilization; CF is optimized fertilization; 90% FP, 80% FP, and 70% FP are application of reduced N fertilizer by 10%, 20%, and 30%, respectively. CRU is the application rate from conventional amount and a mixture of urea with a nitrification inhibitor and urea at a ratio of 7:3.

3.5. Total nitrogen (TN) content during wheat and maize rotation

Figure 2 shows that the TN content in the soil at maturity stage of wheat in both rotation cycles was slightly higher in all N fertilizer treatments than CK. However, this effect was not significant in all N treatments and in both rotation years. The TN content was significantly lower in the 70% FP treatment than FP treatment, but there was no significant difference in this parameter among the other N fertilizer treatments. The TN content of mature maize in both rotation cycles was higher in all N fertilizer treatments than CK. The CRU treatment resulted in a significantly higher soil TN content than the CK. The TN content at maize maturity stage was 14.77% and 13.48% higher in the CRU treatment than FP treatment in the two rotation cycles, respectively. The three N reduced treatments (90% FP, 80% FP, and 70% FP) exhibited a decrease in the soil TN content during the wheat season but no consistent pattern in the maize season.

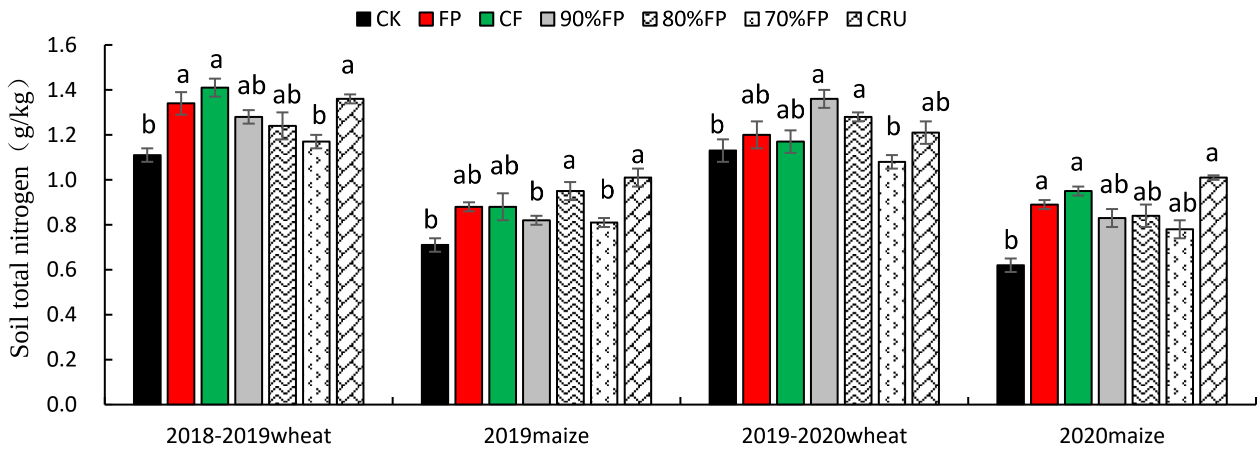

Figure 2. The total N content in the plough layer soil of different treatments at the maturity stage of wheat-maize. CK is no fertilization; FP is conventional fertilization; CF is optimized fertilization; 90% FP, 80% FP and 70% FP are application of reduced N fertilizer by 10%, 20%, 30%, respectively. CRU is the application rate from conventional amount and a mixture of urea with a nitrification inhibitor and urea at a ratio of 7:3.

3.6. Available soil nitrogen content (aSNC) during wheat-maize rotation

Figure 3 indicates that the treatments substantially affected the aSNC during wheat-maize rotation. The aSNC at the crop maturity stage was higher in all N fertilizer treatments than CK. In the first year of the wheat-maize rotation, the aSNC was significantly higher in the FP, CF, and CRU treatments than CK. In the second year of the wheat-maize rotation, the aSNC was significantly higher in the CF and CRU treatments than CK and FP treatments. On average, aSNC in wheat was 6.40% higher in the CF treatment than CK in both rotation cycles. It was 2.57% and 10.43% higher in maize in the two rotation cycles, respectively. The aSNC in the wheat was 15.29% higher in the CRU treatment than FP treatment. It was 7.85% and 5.45% higher in maize in the two rotation cycles, respectively. The three reduced N treatments (90% FP, 80% FP, and 70% FP) exhibited a decrease in the aSNC during the wheat-maize rotation.

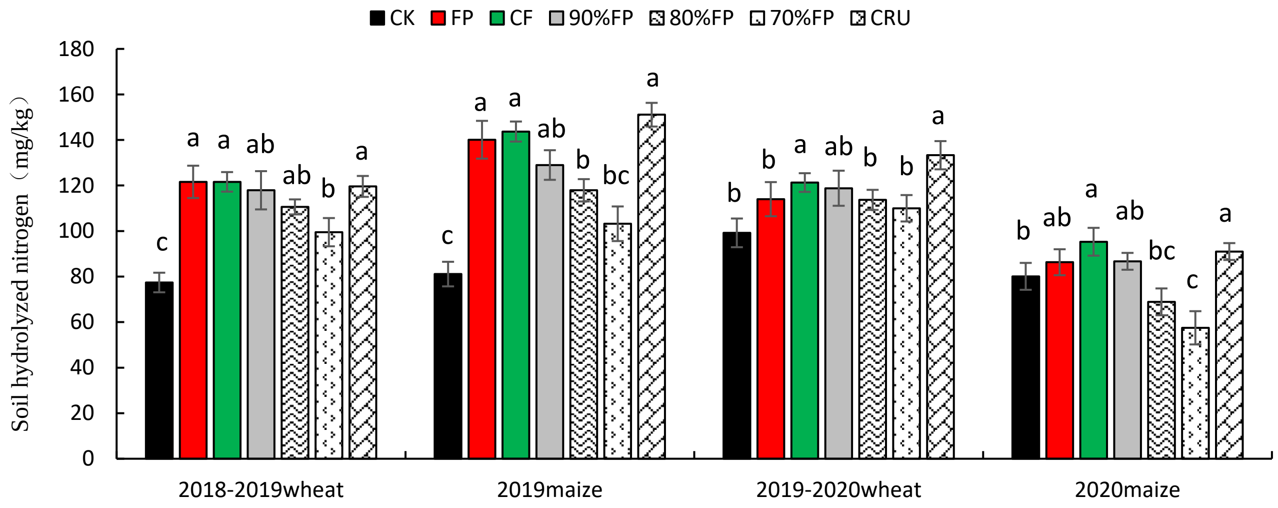

Figure 3. The content of hydrolyzed N in tilth soil of different treatments at the maturity stage of wheat-maize. CK is no fertilization; FP is conventional fertilization; CF is optimized fertilization; 90% FP, 80% FP, and 70% FP are application of reduced N fertilizer by 10%, 20%, and 30%, respectively. CRU is the application rate from conventional amount and a mixture of urea with a nitrification inhibitor and urea at a ratio of 7:3.

3.7. Nitrate (NO_3^-) distribution in different soil layers during different crop growth stages of wheat and maize

The NO_3 distributions in different soil depths at different growth stages of wheat and maize are visualized in Table 5 and Table 6. The Tables show that the NO_3 concentration was low in the CK in different soil layers during the wheat and maize seasons in different growth stages. The NO_3 concentration was higher in all N fertilizer treatments than CK in different soil layers.

The NO_3 concentration in the 0–20 cm soil layer of wheat from the seedling to the heading stages was not significantly lower in the three reduced N treatments (90% FP, 80% FP, and 70% FP) than FP treatment. However, it was significantly lower at the maturity stage, with no significant differences between the three treatments. The NO_3 concentration in the 20–40 cm soil layer of wheat was not significantly lower in the reduced N treatments from the seedling to the elongation stages but was significantly lower from the heading to the maturity stages, with no significant differences between the three treatments. A significant difference in the NO_3 concentration was observed in the 40–60 cm soil layer from the seedling to the heading stages. However, there was no significant reduction at the maturity stage, with no significant differences between the three treatments.

For maize, NO_3 concentration in the 0–20 cm soil layer was significantly lower in the 90% FP and 80% FP treatments from the tasseling to maturity stages and in the 70% FP treatment at all growth stages. The NO_3 concentration in the 20–40 cm soil layer was significantly lower in the 90% FP treatment at maturity stage and from the tasseling to the maturity stages in the 80% FP treatment, and from the elongation to the maturity stages in the 70% FP treatment. No significant differences occurred in the NO_3 concentration in the 40–60 cm soil layer in all growth stages, but the three reduced N treatments showed a decrease in the NO_3 concentration with decreasing N fertilizer input.

The NO_3 concentration in all soil layers during the wheat season at the seedling stage was significantly lower in the CF treatment than FP treatment. The NO_3 distributions were 110.61% and 51.60% higher in the 0–20 cm soil layer at the maturity stage and 16.37% and 44.53% lower in the 20–40 cm soil layer during the two rotation cycles, respectively. In contrast, NO_3 was no significant difference in the 40–60 cm soil layer. During the maize season, the NO_3 concentration was significantly lower in the CF treatment in the 0–20 cm soil layer at the seedling stage. It was 38.41% and 70.23% higher in the elongation to the maturity stages. There were no significant differences in the 20–40 cm soil layer, but a significant decrease occurred in the NO_3 concentration from the seedling to the elongation stages in the 40–60 cm soil layer, with decreases of 57.20–49.32% and 28.21–35.57%, respectively, during the two rotation cycles. No significant differences were observed from the tasseling to the maturity stages.

Table 5. NO_3 concentration in the soil profile during the wheat growth period in two cropping systems.

Treatments	Layers (cm)	2018–2019 NO$_3$ concentration (mg/kg)				2019–2020 NO$_3$ concentration (mg/kg)			
		Seedling stage	Jointing stage	Heading date	Maturity	Seedling stage	Jointing stage	Heading date	Maturity
CK	0–20	6.48c	6.01c	3.93c	2.39d	6.92d	5.69b	3.30c	3.21d
	20–40	5.19c	4.63c	1.18c	0.40c	4.05d	3.67ab	1.78c	2.40c
	40–60	4.30c	3.97d	0.57c	0.19c	3.76c	2.14ab	0.20d	0.72c
FP	0–20	29.69a	11.84b	8.31b	10.46b	37.83a	6.62b	7.37ab	11.86b
	20–40	26.16a	9.36ab	5.52a	5.07a	11.21b	4.01a	6.63a	7.77a
	40–60	11.21a	7.75ab	4.54a	1.74a	10.06a	3.34a	2.92a	2.01a
CF	0–20	18.59b	18.15a	10.54a	22.03a	10.43c	9.60a	8.91a	17.98a
	20–40	14.21b	5.91bc	3.01bc	4.24ab	7.45c	3.53ab	5.87a	4.31b
	40–60	5.79c	5.43c	1.65b	1.75a	4.39c	1.34bc	1.72b	1.60ab
90% FP	0–20	26.34a	13.15b	6.33b	4.48c	30.33b	6.59b	8.36a	7.65c
	20–40	14.06b	10.60a	3.36b	2.15b	13.59ab	2.93b	5.79a	2.15c
	40–60	8.35ab	9.58a	1.46b	1.86a	5.12b	1.33bc	1.08c	1.74a
80% FP	0–20	24.10ab	9.77b	4.16c	6.01c	30.49b	3.85c	7.93a	7.24c
	20–40	22.99a	6.75bc	2.19bc	3.48b	12.22ab	2.36b	4.71b	2.59c
	40–60	9.15ab	4.94cd	1.27b	1.52ab	6.04b	1.63b	1.49bc	1.83a
70% FP	0–20	26.63a	10.48b	3.47c	7.79bc	29.35b	5.79b	5.68b	7.70c
	20–40	21.68a	9.32ab	1.37c	5.28a	15.04a	2.06b	2.70c	1.84c
	40–60	7.30b	6.61bc	1.21b	1.81a	6.92b	1.37bc	1.72b	1.29b
CRU	0–20	17.21b	16.45ab	9.38ab	17.78a	11.51c	8.36ab	7.90a	15.42a
	20–40	13.61b	7.02b	2.80bc	5.26a	10.30b	3.38ab	5.68ab	6.07a
	40–60	6.33bc	5.38c	1.15b	1.27b	4.73c	1.05c	1.87b	1.28b

Note: CK is no fertilization; FP is conventional fertilization; CF is optimized fertilization; 90% FP, 80% FP, and 70% FP are applications of reduced N fertilizer by 10%, 20%, and 30%, respectively. CRU is the application rate from a conventional amount and a mixture of urea with a nitrification inhibitor and urea at a ratio of 7:3. Different lowercase letters in the same growth period and soil layer indicate significant differences at 0.05 level.

Table 6. NO_3 concentration in the soil profile during maize growth period in two cropping systems.

Treatments	Layers (cm)	2019 NO_3 concentration (mg/kg)				2020 NO_3 concentration (mg/kg)			
		Seedling stage	Jointing stage	Male withdrawal period	Maturity	Seedling stage	Jointing stage	Male withdrawal period	Maturity
CK	0–20	10.61d	8.09d	7.90f	1.42d	8.08d	5.37d	4.95d	1.50d
	20–40	4.85d	5.68c	6.73ab	0.97d	4.94d	3.69d	2.11c	0.85c
	40–60	1.30d	1.18c	1.02c	0.64c	1.37d	1.25d	1.18b	0.48c
FP	0–20	76.08a	22.07b	15.75b	23.85c	52.27a	17.32b	10.43b	15.45b
	20–40	14.94bc	8.93b	7.92a	14.50a	15.99a	12.94b	4.51ab	12.91a
	40–60	9.37a	5.90a	4.36a	3.08ab	3.90a	5.82ab	2.47a	2.98ab
CF	0–20	43.55c	35.39a	22.36a	33.01a	41.68c	31.81a	17.32a	26.30a
	20–40	19.78ab	18.34a	6.09b	15.38a	12.09b	18.06a	4.35b	14.91a
	40–60	4.01c	2.99b	2.26b	2.80b	2.80b	3.75c	2.51a	2.15b
90% FP	0–20	64.24b	11.30cd	11.24c	20.29d	47.75ab	16.49bc	5.26cd	11.67bc
	20–40	15.57b	6.79bc	6.64ab	8.15b	16.92a	5.56c	2.92c	4.18b
	40–60	5.72bc	5.65a	3.84ab	3.55a	3.36ab	5.28b	2.46a	3.09a
80% FP	0–20	57.03b	12.21c	12.36c	15.60e	45.99b	15.62bc	6.15c	10.15c
	20–40	12.57c	6.76bc	6.30b	8.78b	10.19bc	6.57c	2.95c	4.41b
	40–60	9.41a	2.32b	3.89ab	3.30a	1.90cd	6.71a	2.17ab	3.14b
70% FP	0–20	57.65b	12.37c	12.84bc	12.65e	39.75c	14.98c	6.25c	8.74c
	20–40	23.17a	5.01c	5.24b	4.67c	8.52c	7.73c	2.78c	4.04b
	40–60	7.53ab	2.38b	3.29b	2.17bc	1.12d	6.76a	2.03ab	2.28b
CRU	0–20	40.31c	23.06b	19.45ab	27.10b	39.67c	30.30a	14.14ab	23.69a
	20–40	16.14b	7.05b	6.94ab	14.85a	10.37bc	19.60a	5.15a	14.68a
	40–60	7.47b	2.95b	4.43a	3.28ab	2.47bc	3.05c	2.29a	1.99b

Note: CK is no fertilization; FP is conventional fertilization; CF is optimized fertilization; 90% FP, 80% FP, and 70% FP are applications of reduced N fertilizer by 10%, 20%, and 30%, respectively. CRU is the application rate from a conventional amount and a mixture of urea with a nitrification inhibitor and urea at a ratio of 7:3. Different lowercase letters in the same growth period and soil layer indicate significant differences at 0.05 level.

Compared to FP treatment, the NO_3 concentration was significantly lower in the CRU treatment in all soil layers during the wheat season at the seedling stage. It was 69.98% and 30.02% higher in the 0–20 cm soil layer at the maturity stage during the two rotation cycles, respectively. There were no significant differences in the 20–40 cm soil layer but a significant decrease in the 40–60 cm soil layer. The NO_3 concentration was 27.01% and 36.32% lower during the two rotation cycles, respectively. During the maize season, the NO_3 concentration was significantly lower in the CRU treatment in the 0–20 cm soil layer at the seedling stage. However, it significantly increased from elongation to maturity by 13.63% and 55.33%. There were no significant differences in the NO_3 concentration between the treatments in the 20–40 cm soil layer, but a significant decrease occurred from the seedling to the elongation stages in the 40–60 cm soil layer, with decreases of 20.28–50.00% and 36.67–47.59% during the two rotation cycles, respectively. No significant differences occurred in the NO_3 concentration from the tasseling to the maturity stages.

4. Discussion

4.1. Effects of reduced N fertilizer applications on wheat and maize yields

Appropriate amounts of N fertilizer can substantially increase the effective spike number, grain number, and grain weight per unit area of crops. A moderate reduction in the N fertilizer application can increase the yield and improve fertilizer utilization efficiency. However, an excessive reduction in the N fertilizer amount can reduce the yield [24–26]. This is true for most types of soil. We found N fertilizer application was reduced by 20%, and a split fertilizer application under optimized conditions using controlled-release urea would increase wheat and maize yields by promoting yield attributes. While 30% reduced N fertilization showed an obvious decline in yield. The N is an essential nutrient for wheat growth and has a significant impact on wheat yield [27–29]. Results of this study are consistent with previous research works conducted in the Huang-Huai-Hai wheat region have shown that reducing the N amount from 240 kg/hm^2 to 180 kg/hm^2 did not significantly decrease the wheat yield, but a substantial yield loss occurred when the N application was further reduced to 120 kg/hm^2 [30]. The most common N reduction management practices include deep placement and controlled-release fertilizers for one-time application to reduce fertilizer dosage and increase efficiency [31–33]. Jianjun et al. [34] observed that using controlled-release N fertilizer increased maize biomass accumulation and significantly increased maize grain yield compared to using urea. Li et al. [35] demonstrated a significant increase in maize yield when the N fertilizer amount was reduced by 35% (N195 kg/hm^2). The N fertilizer input in the wheat-maize rotation system in the North China Plain is 588 kg/hm^2 per year, significantly higher than in other countries [36]. Qin et al. [37] showed that reducing the N fertilizer amount by 150 kg/hm^2 did not decrease wheat and maize yields compared to conventional fertilization when only chemical fertilizer or a 10% proportion of biogas slurry were used as substitutes.

4.2. Effects of reduced N fertilizer applications on N uptake and utilization of wheat and maize

The uptake and utilization efficiency of N fertilizer are critical indicators of effective fertilizer management practices. This study indicates that the optimized fertilization under CF treatment and the controlled-release urea under CRU significantly increased. However, the TN accumulation in the crop plants, the N utilization and aNUE rates were lower, and the NPFP was higher in the 90% FP, 80% FP, and 70% FP treatments compared to control. Results are consistent with previous studies that have shown that an appropriate reduction in chemical N fertilizer combined with controlled-release N fertilizers or organic fertilizers can produce high yields by improving aNUE in a wheat-maize rotation system. Liping et al. [38] demonstrated that a one-time application of controlled-release N fertilizer (180 kg/hm^2 N, with conventional fertilizer application of 280 kg/hm^2) significantly improved wheat yield and aNUE. Li et al. [39] found that reducing the N fertilizer application by one-third (compared to a conventional N application rate of 288 kg/hm^2) and combining it with organic fertilizer significantly improved aNUE and WUE in maize.

4.3. Effects of reduced N fertilizer applications on OM content of wheat and maize fields

The soil nutrient content reflects fertility and is crucial for crop growth and yield [40–42]. Studies have shown that long-term inappropriate N fertilizer applications can decrease soil OM content. These adverse effects can be mitigated by incorporating organic and inorganic fertilizers, such as straw [43], or increasing the application of organic fertilizers [44] to enrich OM content in soil. This study also showed that the OM, TN content and HN in the topsoil were higher in the CF and CRU treatments than FP treatment, whereas the TN content was significantly lower in the 30% N reduced treatment. This result indicates that excessive N reduction reduces crop yield and decreases the N supply in the soil, consistent with the findings of Zhang [47]. Liu et al. [45] found that reducing the N amount by 15% and applying humic acid increased the TN and alkaline N content in the soil significantly. Zeng et al. [46] reported that the N, P and K nutrients in maize fields significantly increased after reducing the N amount by 20% and plowing under winter green manure.

4.4. Effects of reduced N fertilizer on soil NO_3 *concentration in wheat and maize fields at different growth stages*

The soil NO_3 concentrations in different soil depths at different growth stages indicate how much applied N fertilizer is utilized and unutilized by the crop. Generally, higher NO_3 accumulation below the root zone or in an ineffective soil layer is considered a loss, leading to the risk of leaching [50-52]. Subsequently, groundwater is contaminated through drainage after heavy doses of irrigation [48,49]. This study showed that the NO_3 concentration in the topsoil, middle and bottom layers were significantly lower in the three N reduction treatments of 90% FP, 80% FP, and 70% FP than FP at the maturity stage of wheat from the heading stage to the maturity stage, and from the seedling stage to the heading stages, respectively. In the maize growing season, the NO_3 concentration was significantly lower in the 90% FP and 80% FP treatments in the 0–20 cm soil layer from the tasseling stage to maturity and in the 70% FP treatment at all growth stages. The NO_3 concentration was significantly lower in the 90% FP treatment at the maturity stage, in the 80% FP treatment from the tasseling stage to the maturity stage, and in the 70% FP treatment from the elongation stage to the maturity stage in the 20–40 cm soil layer. At the same growth stage, the NO_3 concentration in the 40–60 cm soil layer decreased as the N fertilizer input decreased. These results are consistent with Jiang et al. [53] who observed that reducing the N amount by 25% for three consecutive years did not significantly affect maize yield, nutrient quality, or N uptake. It improved the N fertilizer utilization efficiency and significantly reduced the accumulation of NO_3 concentration in the soil profile. Lu et al. [54] found that reducing N applications by 25–45% maintained the crop yield and reduced the accumulation of NO_3 in the deep soil layer. Cao Bing et al. [55] demonstrated a 10–20% reduced N fertilizer, resulting in increased summer maize yield and reduced residual NO_3 in deep soil layers. The finding of present study indicates that an appropriate N reduction can significantly reduce the residual inorganic N concentration in the soil below the plow layer and reduce the probability of leaching.

5. Conclusions

We assessed the potential reduction in N fertilizer amounts in a wheat-maize rotation system in the yellow cinnamon soil region. The wheat and maize yields were significantly lower in the 80% FP and CRU treatments than CK for two consecutive years. The wheat yields were 3.62–2.57% higher and maize yields were 3.53–1.85% higher in the CF and CRU treatments than 80% FP treatment. However, a substantial yield reduction occurred when N fertilizer was reduced by 30%. The NRE, aNUE and NPFP were significantly higher in the CF and CRU treatments than FP treatment. Specifically, the NRE rate was 46.0% and 38.7% higher in the CF treatment and 37.8% and 46.2% higher in the CRU treatment in the two years. The OM, TN, and HN content in the topsoil were higher in the CF and CRU treatments than FP treatment. In addition, the NO_3 concentration in the 0–20 cm soil layer during the wheat growing season was significantly higher in the CF and CRU treatments. These same treatments increased NO_3 concentration from the elongation stage to the mature stage. In both treatments, the NO_3 concentration in the 40–60 cm soil layer decreased significantly from the seedling to the elongation stage. Considering all factors, the CRU treatment with a 20% N reduction would be optimal fertilization for the wheat-maize rotation system in the yellow cinnamon soil region. However, further research is needed to investigate the long-term effects of N reduction.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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