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Optimized fertilizer recommendation method for nitrate residue control in a wheat–maize double cropping system in dryland farming

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ABSTRACT

The recommendations for soil fertilization based on soil testing are time-critical and labor-intensive for farmers in the winter wheat–summer maize double cropping system. Understanding the relationships between the crop yield, nitrogen requirement, and nitrate residue level under the combined N and P fertilizer application is necessary to optimize the fertilizer recommendation method in order to reduce the nitrate residue levels. In 2009, we established a long-term field fertilization experiment with five N application rates and four P application rates in the winter wheat-summer maize double cropping system. The grain yield, N requirement, and soil nitrate residue were determined during 2016–2019 to optimize the N inputs for nitrate residue control. The crop yield was increased by N application and it increased further when combined with P fertilizer. The N requirement of crops increased by N application but decreased when combined with P. The calculated maximum winter wheat yield was 7235 kg ha^{-1} and the theoretical N requirement for 1000 kg grain formation (N_R) was 28.68 kg Mg^{-1}. The maximum summer maize yield was 7866 kg ha^{-1}, and the theoretical N_R was determined as 23.43 kg Mg^{-1}. The residual nitrate-N was increased by N application but decreased by combined P fertilizer. The correlation between the nitrate-N content in 0–20 cm top soil (S_{NC}) and nitrate-N residue in 0–100 cm soil (S_{NR}) was linear at the winter wheat harvest but exponential at the summer maize harvest. Thus, the S_{NR} can be predicted by the S_{NC} according to their correlation at the harvest. The predicted S_{NR} at the harvest of the previous crop, the target yield and N_R for the subsequent crop obtained from long-term in-situ observations can be used to guide the fertilizer amounts applied to the following crop. Therefore, we developed a convenient method to optimize the fertilizer recommendation method for the winter wheat–summer maize cropping system.

1. Introduction

The winter wheat–summer maize double cropping system is a critical food production system in the North Central Plain (Zhao et al., 2018) and it has an important role in ensuring food security in China (Li et al., 2019). However, the excessive pursuit of high yields and profits by farmers have led to the intensive use of N fertilizer (Chen et al., 2021; Lu et al., 2019), which is then lost through complex routes such as hydrological and gaseous pathways (De Notaris et al., 2018; Kuypers et al., 2018; Wang et al., 2020a). Furthermore, nitrate leaching caused by excessive N application is considered the main reason for the increased nitrate concentration in groundwater, and it leads directly to the eutrophication of ecosystems and water quality degradation (Delin and Stenberg, 2014; Huang et al., 2017a,b; Ju et al., 2009). Therefore, maintaining high grain yields and reducing nitrate pollution are essential for sustainable food production (Yang et al., 2014; Zhang et al., 2015a; Chen et al., 2021).

Previous studies indicate that optimum N fertilizer management methods can significantly reduce the residual soil nitrate level (De Notaris et al., 2018; Ju et al., 2009). In particular, in order to optimize the nitrogen fertilizer input (N_{fer}, kg ha^{-1}), Ju and Christie (2011) proposed that the theoretical N rate should be equal to the aboveground

Abbreviations: S_{NC}, nitrate-N content in 0–20 cm top soil; S_{NR}, nitrate-N residue in 0–100 cm soil; N_R, N requirement for 1000 kg grain formation; N_{fer}, N fertilizer input; GNu, grain N uptake; ANu, aboveground N uptake; ADM, aboveground dry matter.

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N uptake (ANu, kg ha^{-1}) by analyzing the quantitative relationships between the N fertilizer, soil nitrogen, and crop nitrogen absorption, thereby obtaining a reasonable N application rate as: $N_{fer} \approx$ Target Yield/1000 × N_R, where N_R (kg Mg^{-1}) is the N requirement for 1000 kg grain formation. Using this method, farmers can easily and quickly determine a reasonable N application amount for actual production. Since the development of this method, many researchers have noted that it does not consider the actual residual nitrate-N problem (Huang et al., 2017a,b; Zhang et al., 2019a,b). Fertilizer recommendation methods based on soil testing can maximize the use of local soil nutrients while maintaining the crop yield and improving the nutrient utilization efficiency from fertilizers (Chuan et al., 2016; Cui et al., 2008). According to Huang et al. (2017a,b), nitrate-N readily accumulates in dryland soil. They deduced a formula for determining the appropriate amount of N to apply for winter wheat production in dryland farming: $N_{fer} \approx$ Target Yield/1000 × $N_R + 55 - S_{NR}$, where 55 (kg ha^{-1}) is the safety threshold for soil nitrate-N residue in the 0–100 cm soil layer at crop harvest and S_{NR} (kg ha^{-1}) is the residual soil nitrate-N in the 0–100 cm soil layer at crop harvest. Zhang et al. (2019a,b) observed that this method requires the determination of the residual nitrate-N in the 0–100 cm soil layer by sampling the soil from 0 to 100 cm at wheat harvest, which is difficult and impractical for farmers and agricultural service agents. Therefore, they showed that the nitrate-N content in the 0–20 cm top soil (S_{NC}, mg kg^{-1}) is linearly correlated with S_{NR}, and they employed the regression relationship between S_{NC} and S_{NR} in order to predict S_{NR}, which makes it easier and quicker to monitor the residual nitrogen in deep soil. However, despite convenience, this method has been rarely applied in winter wheat–summer maize double-cropping systems in dryland farming due to the applicability of parameters.

The winter wheat–summer maize double cropping system is highly intensive in China (Li et al., 2019; Zhao et al., 2018). In this system, testing the soil in a short time after harvesting winter wheat or summer maize is time-critical and labor-intensive for farmers (Huang et al., 2017a,b; Zhang et al., 2019a,b). Therefore, determining N_{fer} for subsequent crop by N_R and S_{NR} can not only save time and money, but also control soil nitrate-N residue. However, the application of this convenient method in the double cropping system is strongly governed by the target yield, N_R, and S_{NR}. The local production level limits the target yield, and if the relationship between the amount of fertilizer applied and grain yield is established by collecting field data for a specific region, the estimation of this parameter will be accurate (Ju and Christie, 2011; Zhang et al., 2018). N_R is affected by both the amount of N supplied and the grain yield (Yue et al., 2012), but the combined application of both N and P fertilizer can effectively promote crop growth and nutrient absorption, and thus improve the crop yield (Savini et al., 2016; Tang et al., 2008; Zhu et al., 2012). Therefore, the application of N and P fertilizer may affect N_R, which needs to be explored further. Previous studies have shown that excessive N fertilizer accumulates in the soil profile, but the balanced application of NP fertilizer can significantly reduce the accumulation of nitrate-N compared with only applying N fertilizer (Wen et al., 2016; Zhang et al., 2019a,b; Guo et al., 2010). Thus, S_{NR} may also be affected by the combined application of N and P fertilizer. In addition, the accumulated nitrate-N is readily leached (Huang et al., 2018; Lu et al., 2019; Wang et al., 2020b), which may be another factor that affects S_{NR}. In the winter wheat–summer maize double cropping system, 65 % of the rainfall occurs during the summer maize growing season (June to September), and it is usually characterized by short-term heavy rainfall. By contrast, little rainfall occurs during the winter wheat growing season (October to June in the following year) (Fang et al., 2021; Sun et al., 2015). This may greatly change the regression relationship between S_{NC} and S_{NR}. In summary, little is known about how combined N and P fertilizer application affects the target yield, N_R, and S_{NR} under the winter wheat–summer maize cropping system in dryland farming.

Therefore, we conducted a long-term in situ experiment in a winter wheat and summer maize cropping system to test the effects of the combined application of N and P fertilizer on the crop yield, N_R, and S_{NR} in the soil. In particular, we aimed: (1) to estimate the crop yield and N_R under different N and P fertilizer treatments in this cropping system; (2) to determine the relationship between S_{NC} and S_{NR} at the winter wheat and summer maize harvests; and (3) to explore the possibility of modifying the N fertilizer (N_{fer}) recommendation method by replacing S_{NR} with S_{NC} at the winter wheat and summer maize harvests.

2. Materials and methods

2.1. Site description

The field experiments were initiated in October 2009 at the research station on the North Campus of Northwest A&F University, Yangling, Shaanxi, China (34°29′N, 108°06′E; and 520 m a.s.l.). The area has a semi-humid climate and is prone to drought, with an annual average air temperature of 12.9 °C, mean precipitation of 631 mm (61.8 % of the rainfall is concentrated in the summer between June and September) during 1957–2019, and potential evaporation of 1400 mm. Fig. 1 shows the distribution of the precipitation between October 2016 and October 2019. According to the USDA system, the soil at this site is classified as calcareous EumOrthic Anthrosol (UdicHaplustalf according to the USDA system), with a loamy texture and bulk density of 1.20–1.38 g cm^{-3} in the top 0–40 cm soil layer. The other main properties of the initial topsoil are shown in Table 1. Winter wheat–summer maize is the major local cropping system in this area. Winter wheat is usually sown in early October and harvested in late May or early June in the following year. The period from the harvest until the next sowing of winter wheat is the summer maize growing season.

2.2. Experimental design and cultivation practices

The field experiment had a split-plot design with five different N rates and four P fertilizer rates under each N fertilizer rate, and three replicates, where N was the main treatment and P was the secondary treatment. The fertilization treatments and application amounts are shown in Table 2. Plots were fertilized with nitrogen as urea [$(NH_2)_2CO$; 46 % N] and phosphate as superphosphate [$Ca_2PH_4O_8$; 16 % P_2O_5]. The area of each plot was 40 m^2 (4 × 10 m). Each year, all fertilizer was broadcast evenly by hand over the soil surface on each plot as a basal fertilizer at sowing before plowing immediately into the top 20 cm soil layer using a rotavator. Winter wheat was sown at a rate of 150 kg ha^{-1}, with a row space width of 20 cm and sowing depth of 5 cm. After the winter wheat harvest, fertilizer was applied again by evenly manually broadcasting over the soil surface on each plot as a basal fertilizer at the same amount used for winter wheat sowing before plowing immediately into the top 20 cm soil layer for the second time using a rotavator. Summer maize was sown at a density of 67500 plants ha^{-1}, with a row spacing width of 60 cm, plant spacing 20 cm, and sowing depth of 5 cm. The varieties, sowing dates, and harvest dates for winter wheat and summer maize in different years are shown in Table 3. Supplemental irrigation was not provided during the crop growing season, and thus water from natural precipitation was the only water resource available for winter wheat and summer maize growth. The prominent pests of wheat and maize in the experimental region were *Sitodiplosis mosellana*, aphids, and *Mythimna separata*, and the main diseases were wheat stripe rust and maize *Curvularia* leaf spot. During the experiment, pests and diseases were fully controlled by the application of chemicals such as cyhalothrin, thiophanate-methyl etc. Weeds were controlled by manual hoeing. In addition, other common cropping management practices were employed.

2.3. Sample collection and analysis

2.3.1. Crop yield, biomass, and N concentration

Samples of winter wheat and summer maize were collected at

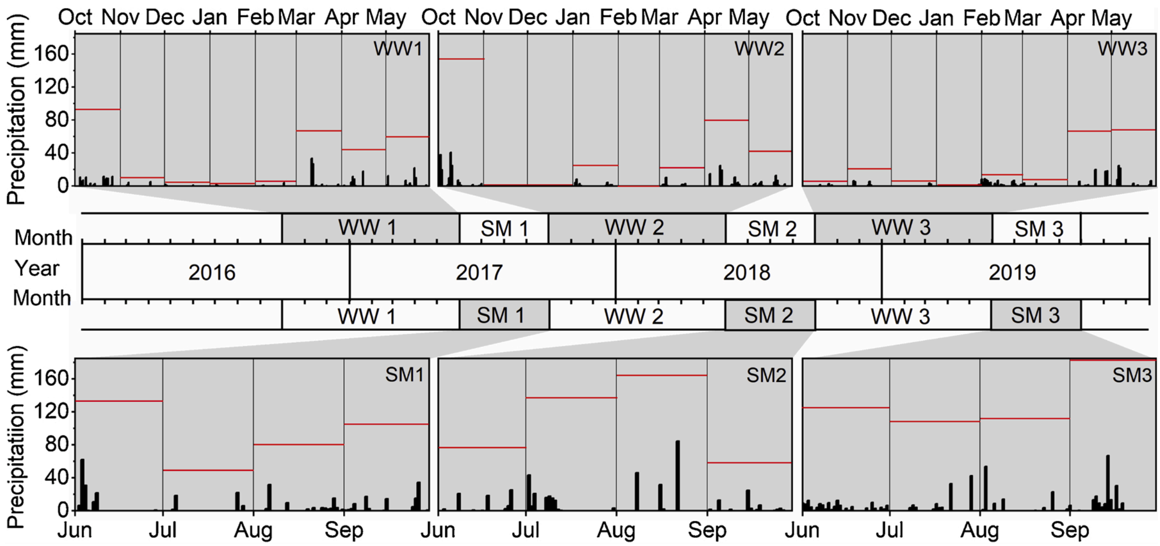


Fig. 1. Rainfall distribution at the test site from October 2016 to October 2019.
Note: WWi is the i-th (i = 1–3) winter wheat growing season, SMi is the i-th (i = 1–3) summer corn growing season, and the red horizontal line is the monthly rainfall. Meteorological data were recorded near the experimental site by Yangling District Meteorological Bureau in Shaanxi Province. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 1
Chemical properties of the soil (0–100 cm layer) before the experiment started in 2009.

Soil properties	Soil layers (cm)				
	0–20	20–40	40–60	60–80	80–100
Bulk density (g cm^{-3})	1.20	1.38	1.49	1.51	1.58
pH (H_2O)	8.40	8.43	8.41	8.53	8.50
Organic matter (g kg^{-1})	14.26	10.04	6.82	7.35	7.3
Total nitrogen (g kg^{-1})	1.20	0.62	0.56	0.57	0.54
Available phosphorus (mg kg^{-1})	15.3	9.98	4.51	4.55	4.46
Available potassium (mg kg^{-1})	188	132	124	115	128
Nitrate-N (mg N kg^{-1})	6.14	6.89	3.40	2.77	3.08
NH_4-N (mg N kg^{-1})	2.54	2.37	0.85	0.45	0.38

maturity. Twenty maize plants or three 1 m-long rows of wheat plants at the center of each plot were harvested randomly by hand to measure the grain yield and biomass. Enzymes were deactivated in the wheat and maize plants, and the plants were then dried at 70 °C. The total N concentrations in the grain and aerial plant parts were analyzed using a standard Kjeldahl Autoanalyzer (Kjeltec 8400; FOSS, Denmark).

The harvest index (HI, %) was expressed as the ratio of the grain yield relative to the aboveground dry matter (ADM, kg ha^{-1}). The N requirement for 1000 kg grain formation (N_R, kg Mg^{-1}) was calculated as the ratio of crop N uptake in the aboveground biomass relative to the grain yield and multiplied by 1000.

2.3.2. *Soil nitrate-nitrogen*

After harvesting the crop, soil samples were collected by obtaining soil cores from five different sites in each subplot to a depth of 100 cm at intervals of 20 cm with an auger (inner diameter = 4 cm). Soil nitrate-N was extracted with 1.0 mol L^{-1} KCl solution and determined using a colorimetric method with a Continuous Flow Analytical System (AA3, SEAL Company, Germany). The soil bulk density was measured with the volumetric ring method (using a core sampler with a volume of 100 cm^3).

Table 2
Fertilizer treatments and application amounts used in the field experiment.

Treatment	Winter wheat fertilization		Summer maize fertilization		Annual fertilization	
	N fertilizer (kg N ha^{-1})	P fertilizer (kg P_2O_5 ha^{-1})	N fertilizer (kg N ha^{-1})	P fertilizer (kg P_2O_5 ha^{-1})	N fertilizer (kg N ha^{-1})	P fertilizer (kg P_2O_5 ha^{-1})
N0P0	0	0	0	0	0	0
N0P1	0	60	0	60	0	120
N0P2	0	120	0	120	0	240
N0P3	0	180	0	180	0	360
N1P0	75	0	75	0	150	0
N1P1	75	60	75	60	150	120
N1P2	75	120	75	120	150	240
N1P3	75	180	75	180	150	360
N2P0	150	0	150	0	300	0
N2P1	150	60	150	60	300	120
N2P2	150	120	150	120	300	240
N2P3	150	180	150	180	300	360
N3P0	225	0	225	0	450	0
N3P1	225	60	225	60	450	120
N3P2	225	120	225	120	450	240
N3P3	225	180	225	180	450	360
N4P0	300	0	300	0	600	0
N4P1	300	60	300	60	600	120
N4P2	300	120	300	120	600	240
N4P3	300	180	300	180	600	360

Table 3
Crop planting information for the experiment in different years.

Year	Winter wheat			Summer maize		
	Cultivars	Sowing date	Harvest date	Cultivars	Sowing date	Harvest date
2016–2017	Xinong 506	2016-10-08	2017-06-11	Zhengdan 958	2017-06-16	2017- 10-02
2017–2018	Xinong 979	2017-10-07	2018-06-10	Zhengdan 958	2018-06-15	2018-10-08
2018–2019	Xinong 979	2018-10-11	2019-06-09	Zhengdan 958	2019-06-16	2019-10-07

The residual nitrate-N in the 0–100 cm soil layer (S_{NR}) was calculated with the following equation:

$$S_{NR}\ (\text{kg N ha}^{-1}) = \sum_{i=20}^{100} (\text{Di} \times \text{Ti} \times S_{NC-i} \times 10^{-1}),$$

where Di is the soil bulk density (g cm^{-3}), Ti is the soil layer thickness (cm), and S_{NC-i} is the soil nitrate-N content (mg kg^{-1}) in different soil layers, i.e., i = 0–20, 20–40, 40–60, 60–80, 80–100 cm soil layers.

2.4. Statistical analysis

Data analysis and chart processing were conducted using SPSS 20.0, Origin 2018, and Excel 2019. Duncan's method for multiple comparisons was used with the analysis of variance (ANOVA). The least significant difference (LSD) method was used for split zone ANOVA. N, P, and year were all treated as fixed factors. Significant differences were accepted at levels of $P < 0.05$, $P < 0.01$ and $P < 0.001$.

A 1:1 histogram was also established between the simulated values and observed values to evaluate model's accuracy. Performance was evaluated using the root mean square error (RMSE) and relative root mean square error (RRMSE):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(o_i - p_i)^2}$$

$$RRMSE = \frac{RMSE}{\overline{O}} \times 100\%,$$

Table 4
Aboveground dry matter (ADM), yield, and harvest index (HI) for winter wheat and summer maize under different N and P fertilizer treatments.

Treatment		Winter wheat			Summer maize		
		ADM (kg ha^{-1})	Yield (kg ha^{-1})	HI (%)	ADM (kg ha^{-1})	Yield (kg ha^{-1})	HI (%)
Combined treatment	N0P0	7371 b	2222 b	30.62 b	11766 a	3529 a	30.00 a
	N0P1	8002 ab	2510 ab	31.36 a	12321 a	3868 a	31.54 a
	N0P2	8715 a	2828 a	32.23 a	12228 a	3978 a	32.47 a
	N0P3	8504 a	2788 a	32.71 a	12270 a	3739 a	30.48 a
	N1P0	9994 c	3573 c	35.80 c	13493 c	4904 c	36.40 b
	N1P1	12282 b	5401 b	44.01 a	15477 b	6016 b	38.90 a
	N1P2	13699 a	5915 a	43.20 ab	16446 a	6645 a	40.41 a
	N1P3	14231 a	5985 a	42.17 b	16198 ab	6672 a	41.25 a
	N2P0	10512 b	3942 b	37.47 c	14327 c	5172 c	36.15 c
	N2P1	15844 a	7170 a	45.26 a	16506 b	7234 b	43.81 a
	N2P2	15443 a	7086 a	45.90 a	17863 a	7636 a	42.74 ab
	N2P3	15527 a	6925 a	44.61 b	17452 ab	7352 b	42.14 b
	N3P0	10517 c	3779 c	36.12 b	14196 c	5084 c	35.87 c
	N3P1	15734 a	6865 a	43.64 a	16975 b	7413 b	43.71 ab
	N3P2	15044 a	6499 b	43.12 a	17807 a	7918 a	44.46 a
	N3P3	14484 b	6287 b	43.40 a	16731 b	7009 b	41.85 b
	N4P0	10089 b	3599 b	35.74 c	14183 c	5020 c	35.45 c
	N4P1	14200 a	6240 a	43.93 a	16902 b	7624 a	45.14 a
	N4P2	14578 a	6249 a	42.86 b	16743 b	7084 b	42.44 b
	N4P3	15104 a	6411 a	42.45 b	17701 a	7144 ab	40.48 b
Average	N0	8148 E	2587 E	31.73 C	12146 C	3779 D	31.12 C
	N1	12551 D	5219 D	41.30 B	15403 B	6059 C	39.24 B
	N2	14332 A	6281 A	43.31 A	16537 A	6849 A	41.21 A
	N3	13945 B	5857 B	41.57 B	16427 A	6856 A	41.47 A
	N4	13493 C	5625 C	41.24 B	16382 A	6718 B	40.88 A
	P0	9697 C	3423 B	35.15 B	13593 C	4742 C	34.77 C
	P1	13212 B	5637 A	41.64 A	15636 B	6431 B	40.62 A
	P2	13496 A	5716 A	41.46 A	16217 A	6652 A	40.50 A
	P3	13570 A	5679 A	41.07 A	16070 A	6383 B	39.24 B
	Y1	12541 B	5121 B	39.74 A	14999 B	5923 B	38.69 A
	Y2	12919 A	5284 A	39.90 A	16117 A	6346 A	38.74 A
	Y3	12021 C	4937 C	39.85 A	15022 B	5888 B	38.93 A
ANOVA	Factor	F-value			F-value		
	Y	51.7***	35.1***	0.2^{ns}	72.7***	88.8***	0.1^{ns}
	N	967.2***	1492.6***	410.2***	409.5***	1413.0***	256.4***
	P	667.3***	1107.2***	236.4***	218.8***	795.6***	126.8***
	Y × N	21.3***	10.4***	8.5***	4.0***	35.8***	20.1***
	Y × P	29.2***	20.6***	9.0***	24.3***	20.1***	4.8***
	N × P	35.5***	54.1***	10.2***	12.1***	50.8***	9.7***
	Y × N × P	4.5***	5.9***	4.4***	5.7***	6.6***	2.4**

Note: Y1 represents the year from 2016 to 2017, Y2 represents the year from 2017 to 2018, and Y3 represents the year from 2018–2019. ADM values, yields, and HI values under the combined treatments are the average values for the three years. Lowercase letters following values within columns indicate significant differences among the P fertilizer under the same N level, and uppercase letters within columns indicate significant difference among averages of the main factors at $P < 0.05$ according to the LSD test. ns: $P > 0.05$, *: $P < 0.05$, **: $P < 0.01$, ***: $P < 0.001$.

where Oi and Pi are the simulated values and measured values, respectively, n is the number of data, and $\overline{o}$ is the average of the measured data. In general, if RRMSE < 10 %, the performance of the simulation model is considered excellent. If 10 % ≤ RRMSE < 20 %, the simulation model's performance is considered good. If 20 % ≤ RRMSE < 30 %, the performance of the simulation model is considered to be adequate. If RRMSE ≥ 30 %, the performance of the simulation model is poor.

3. Results

3.1. Winter wheat and summer maize yields and nitrogen requirement

3.1.1. Winter wheat and summer maize yields under combined N and P fertilizer

The crop yield and ADM varied among N and P fertilizer treatments and years, and the trends were similar in winter wheat and summer maize (Table 4). Taking winter wheat yield as an example, the application of N fertilizer significantly increased the average yields by 101.7 %, 142.8 %, 126.4 %, and 117.4 % at N rates of N1, N2, N3, and N4, respectively, compared with N0. On the basis of 150 kg N ha^{-1}, the yields were further improved by 81.9 %, 79.8 %, and 75.7 % at P rates of P1, P2, and P3, respectively, compared with P0. These results indicate that the crop yields were increased by N application and they increased further when combined with P fertilizer. N2P1 and N2P2 obtained the highest yield for winter wheat with an average of 7128 kg ha^{-1}, while N3P2 and N2P2 produced the maximum results for summer maize with an average of 7777 kg ha^{-1}. Due to the effects of combined N and P fertilizer application on the yield and ADM, HI exhibited a parabolic trend under both N and P rates, and the average HI was highest under N2 for winter wheat but highest under N3 for summer maize. Under P fertilizer, the maximum HI values for winter wheat and summer maize were obtained under P1. Thus, insufficient or excessive N and P fertilizer decreased HI, which was not conducive to enhancing the crop yield.

3.1.2. Nitrogen uptake and requirements under combined N and P fertilizer treatments

The ANOVA results showed that the crop ANu and GNu also varied among N and P fertilizer applications treatments and years, but especially N and P fertilizer (Table 5). ANu for winter wheat increased initially and then decreased as the N application level increased, where it was highest under N3. ANu for summer maize increased gradually, where it was highest under N4. The ANu values for winter wheat and

Table 5
Aboveground N uptake (ANu), grain N uptake (GNu), and N requirement for 1000 kg grain formation (N_R) for winter wheat and summer maize under different N and P fertilizer treatments.

Treatment		Winter wheat			Summer maize		
		ANu (kg ha^{-1})	GNu (kg ha^{-1})	N_R (kg Mg^{-1})	ANu (kg ha^{-1})	GNu (kg ha^{-1})	N_R (kg Mg^{-1})
Combined treatment	N0P0	45.4 a	22.7 c	20.6 a	72.9 a	38.7 a	20.9 a
	N0P1	51.4 a	26.6 b	20.7 a	74.4 a	44.2 a	19.6 b
	N0P2	52.0 a	28.3 a	18.8 c	74.1 a	44.2 a	18.7 c
	N0P3	54.2 a	29.0 a	19.9 b	79.6 a	43.3 a	21.5 a
	N1P0	101.6 d	65.4 c	28.4 a	125.2 b	80.6 c	25.5 a
	N1P1	116.4 c	78.6 b	21.5 c	125.2 b	89.8 bc	20.8 b
	N1P2	133.2 b	94.7 a	22.5 c	129.0 b	99.9 ab	19.5 c
	N1P3	156.5 a	98.4 a	26.2 b	143.3 a	110.4a	21.4 b
	N2P0	127.4 c	87.3 d	32.2 a	153.0 b	98.9 c	29.6 a
	N2P1	177.6 b	145.7 c	24.8 c	158.3 b	133.7 b	21.9 d
	N2P2	201.4 a	160.2 a	28.4 b	179.7 a	144.6 a	23.6 c
	N2P3	204.2 a	153.0 b	29.5 b	192.6 a	141.7 a	26.2 b
	N3P0	139.7 b	93.3 c	36.8 a	155.6 c	102.7 c	30.6 a
	N3P1	213.4 a	159.8 a	31.1 c	175.6 b	139.8 b	23.8 d
	N3P2	215.1 a	158.2 a	33.2 b	192.4 a	148.4 a	24.4 c
	N3P3	208.9 a	149.1 b	33.2 b	194.5 a	133.1 b	27.9 b
	N4P0	146.6 b	89.9 c	40.7 a	168.8 c	97.1 b	33.6 a
	N4P1	206.0 a	150.4 a	33.0 b	188.6 b	144.8 a	24.7 c
	N4P2	207.0 a	144.2 b	33.1 b	187.6 b	137.4 a	26.4 b
	N4P3	209.2 a	143.2 b	32.6 b	192.0 a	142.5 a	26.9 b
Average	N0	50.8 D	26.7 E	20.0 E	75.2 E	42.6 C	20.2 E
	N1	126.9 C	84.3 D	24.7 D	130.7 D	95.2 B	21.8 D
	N2	177.7 B	136.6 B	28.7 C	170.9 C	129.7 A	25.3 C
	N3	194.3 A	140.1 A	33.6 B	179.5 B	131.0 A	26.7 B
	N4	192.2 A	132.0 C	34.8 A	184.3 A	130.4 A	27.9 A
	P0	112.2 D	71.7 D	31.7 A	135.1 D	83.6 C	28.1 A
	P1	153.0 C	112.2 C	26.2 D	144.4 C	110.5 B	22.2 C
	P2	161.7 B	117.1 A	27.2 C	152.6 B	114.9 A	22.5 C
	P3	166.6 A	114.6 B	28.3 B	160.4 A	114.2 A	24.8 B
	Y1	148.9 A	106.5 B	28.4 A	142.2 B	102.8 B	24.2 A
	Y2	150.8 A	108.6 A	28.1 A	157.3 A	114.4 A	24.5 A
	Y3	145.4 B	96.7 C	28.7 A	144.9 B	100.1 C	24.4 A
ANOVA	Factor	F-value			F-value		
	Y	6.6**	93.2***	2.6^{ns}	67.5***	122.2***	0.9 ^{ns}
	N	1986.2***	3315.0***	635.1***	1322.4***	1873.6***	241.1***
	P	410.4***	808.1***	120.0***	93.0***	352.6***	207.2***
	Y × N	8.7***	45.0***	11.1***	15.4***	15.8***	16.5***
	Y × P	26.2***	21.2***	9.2***	18.9***	18.7***	13.3***
	N × P	34.0***	71.6***	12.6***	10.5***	31.7***	11.7***
	Y × N × P	7.0***	8.5***	3.8***	5.4***	6.0***	3.4***

Note: Y1 represents the year from 2016 to 2017, Y2 represents the year from 2017 to 2018, and Y3 represents the year from 2018–2019. The ANu, GNu, and N_R values under the combined treatments are the average values for the three years. Lowercase letters following values within columns indicate significant difference among the P fertilizer under the same N level. Uppercase letters within columns indicate significant difference among averages of the main factors at $P < 0.05$ according to the LSD test. ns: $P > 0.05$, *: $P < 0.05$, **: $P < 0.01$, ***: $P < 0.001$.

summer maize increased gradually as the P application level increased, and the application of P fertilizer significantly enhanced the N uptake by crops. The GNu values increased initially and then decreased as the N and P application rates increased, where the highest values were obtained under N3 and P2, thereby indicating that the application of suitable amounts of N and P could significantly increase the transport of nitrogen to the grain. N_R was mainly affected by N and P fertilizer, where a higher N application level led to greater values of N_R. However, N_R tended to decrease initially before then increasing with different P fertilizer amounts under the same N level. These results demonstrate that the application of an appropriate combination of N and P fertilizers ensured sufficient N uptake and reduced ineffective N uptake, which was advantageous for decreasing N_R.

3.1.3. Maximum yields corresponding to N_R for winter wheat and summer maize

In order to calculate the maximum yields corresponding to N_R for winter wheat and summer maize, we treated the crop yield and N_R as dependent variables, and the amounts of N and P fertilizer applied as independent variables, and conducted regression analysis to obtain binary quadratic polynomials describing the mathematical relationships among the yield, N_R, and fertilizer (Fig. 2). By calculating the partial derivative of Eq. (1), the optimal N application amount corresponding to the highest yield was determined as 185 kg N ha^{-1}, the optimal P application amount as 113 kg P_2O_5 ha^{-1}, and the maximum winter wheat yield as 7235 kg ha^{-1}. By calculating the partial derivative of Eq. (3), the optimal N and P application amounts were determined as 197 kg N ha^{-1} and 103 kg P_2O_5 ha^{-1}, respectively, and the maximum summer maize yield 7850 kg ha^{-1}. After substituting the amounts of N and P fertilizer applied into Eqs. (2) and (4), respectively, the theoretical N_R for winter wheat at the highest yield was determined as 28.68 kg Mg^{-1}, and the theoretical N_R for summer maize at the highest yield was determined as 23.43 kg Mg^{-1}.

3.2. Nitrate-N content and residual nitrate-N in soil

3.2.1. Soil nitrate-N at winter wheat harvest

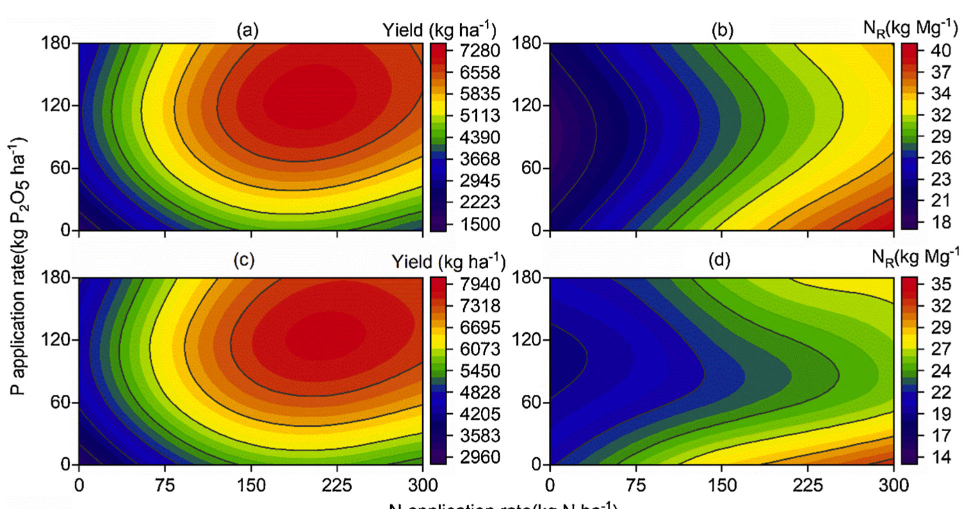
The S_{NC} (Fig. 3) and S_{NR} (Fig. 4) at winter wheat harvest were mainly affected by N and P fertilizer. The S_{NC} value at winter wheat harvest was 2.49–72.03 mg kg^{-1} and the range of S_{NR} was 19.94–609.96 kg N ha^{-1}. The trend in S_{NR} was similar to that in S_{NC} under different N and P fertilizer treatments. Both S_{NC} and S_{NR} increased gradually according to the N fertilizer treatment level. Applying P fertilizer under the same N fertilizer treatment, S_{NC} and S_{NR} tended to decrease initially before then increasing. For example, with the different N fertilizer treatment levels, the average S_{NR} values under N4 (388 kg N ha^{-1}), N3 (283 kg N ha^{-1}), N2 (114 kg N ha^{-1}), and N1 (42 kg N ha^{-1}) changed by +748 %, +516 %, +147 %, and −8%, respectively, compared with that under N0 (47 kg N ha^{-1}). At the N2 level, the S_{NR} values under N2P1 (103 kg N ha^{-1}), N2P2 (86 kg N ha^{-1}), and N2P3 (112 kg N ha^{-1}) were 32 %, 44 %, and 26 % lower, respectively, compared with that under N2P0 (152 kg N ha^{-1}). In summary, the application of N fertilizer significantly increased S_{NR} but the combined application of N with an appropriate amount of P fertilizer significantly reduced S_{NR}.

3.2.2. Soil nitrate-N at summer maize harvest

The S_{NC} values at summer maize harvest ranged from 3.97 to 22.65 mg kg^{-1}, which were significantly lower than the S_{NC} values at winter wheat harvest. In addition, the S_{NR} values ranged from 22.75 to 869.97 kg N ha^{-1}, which were slightly higher than the S_{NR} values at winter wheat harvest. The ANOVA results showed that the application of N and P fertilizer significantly affected the S_{NC} (Fig. 5) and S_{NR} (Fig. 6) values at the summer maize harvest. The changes in S_{NC} and S_{NR} were similar to the trends at the winter wheat harvest. The increases in S_{NC} were significantly lower than those in S_{NR} under different N and P fertilizer treatments. For example, the average S_{NC} values under N4 (17.3 mg kg^{-1}), N3 (14.9 mg kg^{-1}), N2 (11.1 mg kg^{-1}), and N1 (7.7 mg kg^{-1}) were 184 %, 145 %, 82 %, and 27 % higher, respectively, compared with that under N0 (6.1 mg kg^{-1}). The average S_{NR} values under N4 (423 kg N ha^{-1}), N3 (273 kg N ha^{-1}), N2 (134 kg N ha^{-1}), and N1 (50 kg N ha^{-1}) were 926 %, 563 %, 228 %, and 21 % higher, respectively, compared with that under N0 (41 kg N ha^{-1}).

3.3. Relationship between S_{NC} and S_{NR}

After comprehensively considering the yields, N uptake, and residual nitrate-N at the winter wheat and summer maize harvest in this study, the P1 and P2 fertilizer levels were selected to determine the regression



Winter wheat:

$$\text{Yield} = 1518 + 33.98N + 35.45P - 0.092N^2 - 0.156P^2 + 0.027NP \quad (R^2 = 0.85^{**}, n = 180)\ (1)$$

$$N_R = 21.54 + 0.083N - 0.084P - 0.762N^2 \times 10^{-4} + 0.459P^2 \times 10^{-3} + 0.959NP \times 10^{-4} \quad (R^2 = 0.83^{**}, n = 180)\ (2)$$

Summer maize:

$$\text{Yield} = 2969 + 28.19N + 29.54P - 0.071N^2 - 0.136P^2 + 0.023NP \quad (R^2 = 0.83^{**}, n = 180)\ (3)$$

$$N_R = 22.57 + 0.045N - 0.108P - 0.373N^2 \times 10^{-4} + 0.571P^2 \times 10^{-3} - 0.734NP \times 10^{-4} \quad (R^2 = 0.73^{**}, n = 180)\ (4)$$

Fig. 2. Contour map showing the grain yield and N requirement for 1000 kg grain formation (N_R) for winter wheat (a, b) and summer maize (c, d) under different N and P fertilizer treatments.

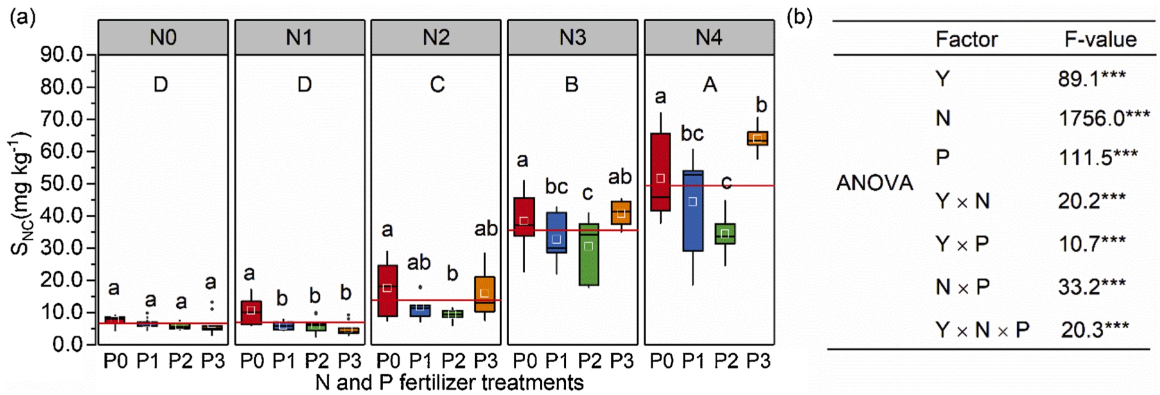


Fig. 3. (a) Nitrate-N content in 0–20 cm soil depth (S_{NC}) at winter wheat harvest under different N and P fertilizer levels. (b) Analysis of variance (ANOVA) results. Red lines denote the average S_{NC} value at the same N level. Lowercase letters indicate significant difference among the P fertilizer under the same N level. Uppercase letters indicate significant difference among averages of the N fertilizer at $P < 0.05$ according to the LSD test. *: $P < 0.05$, **: $P < 0.01$, ***: $P < 0.001$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

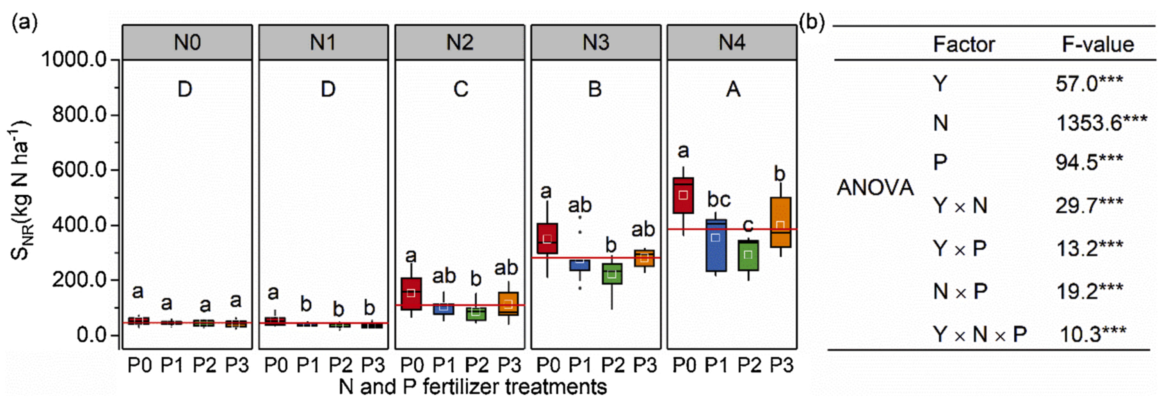


Fig. 4. (a) Nitrate-N residue in the 0–100 cm soil depth (S_{NR}) at winter wheat harvest under different N and P fertilizer levels. (b) Analysis of variance (ANOVA) results. Red lines denote the average S_{NR} value at the same N level. Lowercase letters indicate significant difference among the P fertilizer under the same N level. Uppercase letters indicate significant difference among averages of the N fertilizer at $P < 0.05$ according to the LSD test. *: $P < 0.05$, **: $P < 0.01$, ***: $P < 0.001$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

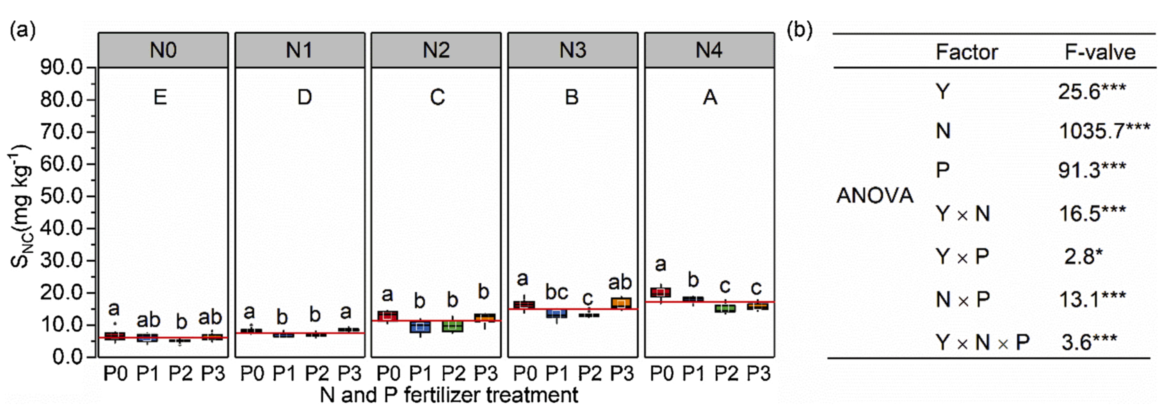


Fig. 5. (a) Nitrate-N content in 0–20 cm soil depth (S_{NC}) at summer maize harvest under different N and P fertilizer levels. (b) Analysis of variance (ANOVA) results. Red lines denote the average S_{NC} value at the same N level. Lowercase letters indicate significant difference among the P fertilizer under the same N level. Uppercase letters indicate significant difference among averages of the N fertilizer at $P < 0.05$ according to the LSD test. *: $P < 0.05$, **: $P < 0.01$, ***: $P < 0.001$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

relationships with S_{NC} and S_{NR} because these levels resulted in relatively higher yields (Table 4) and greater ANu values (Table 5), as well as relatively lower residual nitrate-N contents (Figs. 4, 6). The relationship between S_{NC} and S_{NR} at the winter wheat harvest had a significant linear correlation (Fig. 7a), whereas the relationship between S_{NC} and S_{NR} at the summer maize harvest had a significant exponential growth trend (Fig. 7b). Furthermore, the R^2 values greater than 0.90 indicated strong relationships between S_{NC} and S_{NR}. The relationships between S_{NC} and S_{NR} at the winter wheat harvest and summer maize harvest differed significantly.

In order to further verify the accuracy and the suitability of the model under different P fertilizer levels, the independent validation data

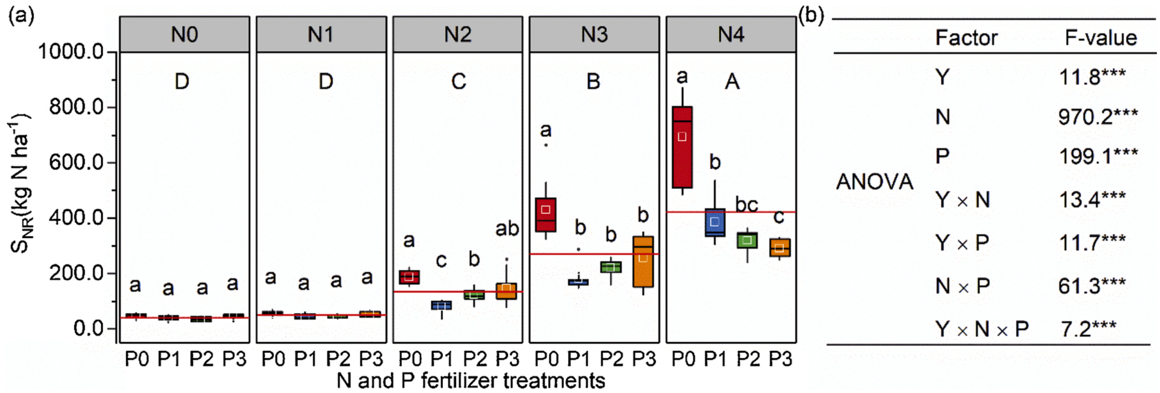


Fig. 6. (a) Nitrate-N residue in 0–100 cm soil depth (S_{NR}) at summer maize harvest under different N and P fertilizer levels. (b) Analysis of variance (ANOVA) results. Red lines denote the average S_{NR} value at the same N level. Lowercase letters indicate significant difference among the P fertilizer under the same N level. Uppercase letters indicate significant difference among averages of the N fertilizer at $P < 0.05$ according to the LSD test. *: $P < 0.05$, **: $P < 0.01$, ***: $P < 0.001$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

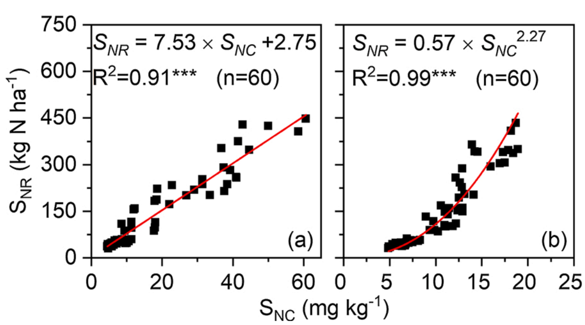


Fig. 7. Regression relationships between nitrate-N content in 0–20 cm soil depth (S_{NC}) and nitrate-N residue in 0–100 cm soil depth (S_{NR}) at winter wheat harvest (a) and at summer maize harvest (b).

sets under P0 (n = 45), P1 (n = 15), P2 (n = 15), and P3 (n = 45), and the modeling data sets under P1 (n = 30) and P2 (n = 30) level were selected to verify the accumulated nitrate-N in the soil at the winter wheat harvest and summer maize harvest, respectively. The results showed that the simulated and observed values under different P fertilizer levels had good 1:1 relationships (Fig. 8). Overall, the RRMSE values under P1 and P2 were close to 20–30 %, and thus the performance of the models was adequate. In addition, the RRMSE values were ≥ 30 % under P0 and P3, suggesting that the performance of the models was poor, but the overall deviation was less than 50 %, which indicates a certain degree of credibility. Thus, we demonstrated that it is feasible to predict S_{NR} at the winter wheat harvest and summer maize harvest by using S_{NC}, and the accuracy of the predictions obtained using these models can vary under different P fertilizer application levels.

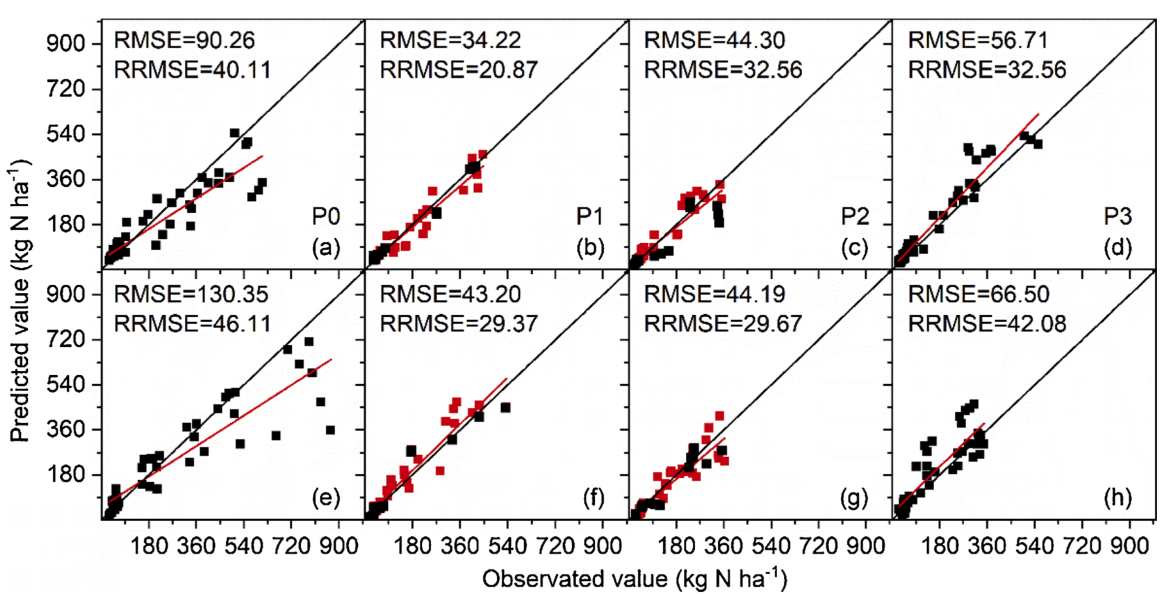


Fig. 8. The 1:1 relationships between the observed S_{NR} (Nitrate-N residue in 0–100 cm soil depth) and predicted S_{NR} values, where (a), (b), (c), and (d) show the predicted and observed values at winter wheat harvest, and (e), (f), (g), and (h) show the predicted and observed values at summer maize harvest. The red solid lines represent the best linear fits. The black solid lines represent 1:1 and they indicate that the observed value is equal to the predicted value. The red dots denote the modeling data set and the black dots indicate the independent validation data set. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

4. Discussion

4.1. Crop yield and nitrogen uptake

Determining the optimal nutrient management practices requires knowledge of the target yield and crop nutrient requirements (Ju and Christie, 2011; Yin et al., 2019). In order to accurately estimate the N requirements of crops in practice, we should consider different fertilizer treatments and the grain yield levels (Yue et al., 2012; Ju, 2015). The results obtained in the present study showed that the reasonable application of a combination of N and P fertilizer could significantly promote the absorption of nitrogen by winter wheat and summer maize to increase the crop yield. However, applying excessive or insufficient amounts of N and P was not conducive to enhancing the absorption of nitrogen and the accumulated yields of winter wheat and summer maize (Tables 4 and 5). These findings are consistent with the results obtained in most fertilizer trials (Yang et al., 2006, 2017; Zhang et al., 2018). Considering the maximum yield obtained by fitting models under different N and P fertilizer combinations, we recommend that the target yield for winter wheat is 7235 kg ha^{-1} and the optimal N_R is 28.68 kg Mg^{-1}. The target yield for summer maize was determined as 7850 kg ha^{-1} and N_R as 23.43 kg Mg^{-1} (Fig. 2). The recommended yield levels are basically consistent with previously reported data and field trials under similar planting conditions (Liu et al., 2016; Zhang et al., 2015a). The recommended N_R values obtained in this study are equivalent to the recommended N_R for wheat (28 kg Mg^{-1}) and maize (23 kg Mg^{-1}) based on various previous studies under the current production conditions and yield levels (Ju, 2015). Thus, the target yield and N_R for winter wheat and summer maize are generally relatively stable when the other production conditions (such as the plant varieties, irrigation, and management techniques) do not change significantly in a specific area.

However, although N_R was generally stable, the value tended to vary to differing extents under the combined application of N and P fertilizer. For winter wheat and summer maize, N_R increased as the N application level increased under the same P fertilizer level (Table 5). Thus, the yield increase caused by the greater supply of N in the soil possibly led to a much higher increase in ANu than the grain yield, thereby increasing N_R (Zhang et al., 2019a,b). N_R decreased initially and then increased as the amount of P applied increased at the same N fertilizer level. Thus, the yield increase caused by the higher supply of P in the soil possibly led to a much greater increase in the grain yield than that in ANu initially. However, N_R then decreased as the amount of P applied increased because excessive P fertilizer leads to physiological dysfunction and the vigorous vegetative growth of crops, and the nitrogen absorbed by the crops cannot be fully transferred into the grain (Barneix, 2007; Savini et al., 2016; Tang et al., 2008). Therefore, there was a much greater increase in ANu than the grain yield, and N_R increased. The results showed that applying an appropriate combination of N and P fertilizer was advantageous for reducing N_R, which means that when the same yield level was reached, the amount of N fertilizer or P fertilizer in a single application was greater than that of the combined application of N and P.

4.2. Residual nitrate-N in soil

In contrast to the response of the yield to the increasing application of N, the residual nitrate-N in the 0–100 cm soil layer increased slowly initially but then increased more rapidly, which is consistent with the findings of most previous N application field experiments (Wang et al., 2017; Zhang et al., 2015b). The requirement for soil N by winter wheat and summer maize did not increase as the amount of N applied increased. If the applied N exceeds the crop's requirement, it accumulates in the soil over time (Hartmann et al., 2014; Ju and Christie, 2011). We found that the accumulated nitrate-N in the soil decreased initially and increased as the P application rate increased at the winter wheat and summer maize harvests. A similar phenomenon has been observed in many P fertilization experiments (Dai et al., 2016; Guo et al., 2010; Yang et al., 2006). However, the mechanism responsible for this effect of P is not fully understood. The decrease in the accumulation of nitrate in the soil the receiving P fertilizer can be explained partly by an increase in the crop N uptake (Table 5) because the rational application of P fertilizer can increase the uptake of N to promote the growth of crops and improve the crop yield (Savini et al., 2016; Tang et al., 2008; Zhu et al., 2012), thereby reducing the residual soil nitrate content. However, the residual nitrate-N content increased in the soil when excessive N and P fertilizer was applied, mainly because adding excessive N and P fertilizer limits the growth of crops to reduce the uptake and utilization of nitrogen, and thus the risk of nitrate leaching increases (Guo et al., 2010; Ju et al., 2009; Yang et al., 2015).

In dryland farming, the migration of nitrate from the topsoil into deeper soil is a water-driven process (Huang et al., 2018; Lu et al., 2019; Wang et al., 2020a,b). Our study indicated that S_{NC} was significantly lower at the summer maize harvest than the winter wheat harvest (Figs. 3, 5), and S_{NR} was slightly higher after the summer maize harvest than after the winter wheat harvest (Figs. 4, 6). Thus, the migration of nitrate-N from the topsoil into the deep soil mainly occurred during the summer maize growing season because it coincided with the highest rainfall (Fig. 1). The relationships between S_{NC} and S_{NR} at the winter wheat harvest and summer maize harvest differed significantly (Fig. 7). It exhibited an increasing linear trend at the winter wheat harvest, and a similar result was obtained by Zhang et al. (2019a,b). By contrast, the relationship between S_{NC} and S_{NR} exhibited an exponentially increasing trend at the summer maize harvest. Precipitation was scarce during the winter wheat growing season (from October to June in the following year), where it only accounted for 25 % of the annual precipitation (Fig. 1), and thus a relatively high amount of mineralized inorganic nitrogen accumulated in the 0–20 cm soil layer, and it readily accumulated in the 0–100 cm soil layer. Therefore, the fitted model showed that there was a highly significant increasing trend. The precipitation during the summer maize growing season (June to September) accounted for 65 % of the annual precipitation (Fig. 1), and the more abundant rain readily transported the nitrate-N that accumulated in 0–20 cm shallow soil layer into the deeper soil. We assume that the nitrate-N accumulated in the 0–20 cm soil layer was transported into the 0–100 cm soil layer by rainfall, and thus the nitrate-N that accumulated within the overall 0–100 cm layer was unchanged, whereas nitrate-N content decreased within the 0–20 cm layer. Therefore, the non-synchronous change in the nitrate-N content in the 0–20 cm soil layer and the accumulated nitrate-N in the 0–100 cm soil layer may explain the significant exponential relationship between them.

In addition, the observed and simulated S_{NR} values differed significantly under P0 compared with the model verification results (Fig. 8), where the actual values were higher than the values predicted at the winter wheat and summer maize harvests, possibly because of the lack of P in the soil due to the long-term absence of P fertilizer under P0. Previous studies have shown that P deficiency usually stimulates the root tips by inhibiting the elongation of the taproot and increasing the number of lateral roots, thereby increasing the P absorption capacity (Abel, 2017; Crombez et al., 2019). Therefore, crops mainly absorb N from the surface soil under this growth state, which results in a low nitrate-N content in the 0–20 cm soil layer. However, when the crops were deficient in P, they had a low capacity to absorb and use N fertilizer (Savini et al., 2016; Tang et al., 2008; Zhu et al., 2012), thereby resulting in the significantly greater accumulation of nitrate-N in the 0–100 cm layer compared with the P application treatments. Therefore, the underestimation by the model indicates that the value predicted without P fertilizer was a significant deviation, and it should be treated with caution.

The residual nitrate-N in the soil is readily lost through nitrate leaching when it exceeds the safe threshold (De Notaris et al., 2018; Huang et al., 2017a,b). Based on the present study, we recommend that the safe residue threshold for nitrate-N in the 0–100 cm soil layer at the winter wheat and summer maize harvests is 55 kg N ha^{-1} to achieve the goal of controlling residual nitrate-N in dryland areas (Fig. 9). Studies have shown that the average safe threshold is similar at the winter wheat and summer maize harvests (Liu et al., 2019). The soil nitrate-N threshold may vary due to differences in the precipitation, soil texture, crop varieties, and farming methods (Huang et al., 2017a,b), but this value is less than the soil nitrate-N buffer capacity (100 kg N ha^{-1}) in the winter wheat–summer maize cropping system in northern China (Liu et al., 2019). In addition, this level is close to the nitrate-N leaching threshold of 50 kg N ha^{-1} in the 0–100 cm soil layer proposed based on a worldwide meta-analysis (Zhou and Butterbach-Bahl, 2014), which demonstrates that the current residual nitrate-N threshold of 55 kg N ha^{-1} can achieve the aim of controlling soil nitrate-N residue in the winter wheat-summer maize double cropping system in dryland farming.

4.3. Nitrogen fertilizer recommendation method for nitrate residue control

Fertilizer recommendation methods based on soil testing require the collection and testing of soil samples to determine the soil nutrient or residual levels only a few days before fertilization (Huang et al., 2017a, b; Zhang et al., 2019a,b). Thus, making fertilizer application recommendations for implementation by extension workers and farmers in the winter wheat–summer maize double cropping system is difficult in practice. The N_{fer} can be calculated with the quantitative relationship among fertilizer N, soil N and crop uptake N in the crop root zone to obtain high target yield and minimize environmental risk (Ju and Christie, 2011; Huang et al., 2017a,b; Zhang et al., 2019a,b). In the present study, the soil was sampled when the previous crop was harvested and S_{NC} was used to predict S_{NR} to give a rapid estimate of the residual nitrate-N in the 0–100 cm soil layer before planting the following crop. Based on the differences in the levels of fertility after the long-term combined application of N and P fertilizer, we analyzed the relationships between the crop yield, N_R, residual nitrate-N, and fertilizer application in detail to optimize further and improve the N_{fer} method for the wheat–summer maize cropping system in dryland farming areas (Fig. 9).

At the winter wheat harvest, the 0–20 cm top soil layer was collected to test S_{NC}, which was used to predict S_{NR} using the established liner regression relationship, before substituting the target yield, N_R for summer maize, and predicted S_{NR} into the N_{fer} method to calculate the appropriate N fertilizer recommendation before sowing the summer maize. Similarly, the value of S_{NC} determined at the summer maize harvest can be used to predict S_{NR} using the established exponential regression relationship and the N application amount can be calculated as N_{fer} before sowing winter wheat. In terms of the recommendation for P fertilizer, we recommend applying P fertilizer at 107–119 kg ha^{-1} in both the winter wheat and summer maize seasons to significantly increased yields and to help the absorption of N fertilizer (Fig. 2). This recommended amount is equivalent to that recommended based on long-term positioning test results under the same production conditions (Dai et al., 2016).

Models for predicting certain soil properties using data from soil surveys are readily affected by factors such as the soil type, weather, crop type, and cropping system, it is not always possible to determine a very accurate fertilizer N rate and some uncertainty should be accepted when determining the fertilizer N rate (Oliver and Lark, 2005; Ju and Christie, 2011; Huang et al., 2017a,b). In the present study, the ANOVA results showed that the winter wheat and summer maize yields, N uptake, and residual nitrate-N differed highly significantly among years, so the recommended yield level and regression parameters between S_{NC} and S_{NR} may also fluctuate slightly among years. These differences could have been related to the precipitation and rainfall distribution during the crop growth periods in different years. Therefore, further studies of the variations in the crop yield and the regression relationships between S_{NC} and S_{NR} are still required in different experimental years. However, the results obtained in the present study also have some degree of universality. The ANOVA results showed that the differences in these indicators were mainly caused by the different amounts of N and P fertilizer, followed by the year, and the interaction effect. Therefore, in different agricultural production areas, it is important to use the same model building method to obtain reference values and to consider the local parameters to guide regional agricultural production.

5. Conclusions

The results obtained in this study showed that the target yield and N_R were generally relatively stable for winter wheat and summer maize when the other production conditions did not change significantly in a specific area. However, they were significantly affected by combined N and P fertilizer application, and optimizing the combined fertilizer application amounts significantly increased the winter wheat and summer maize yields by enhancing the absorption and utilization of N fertilizer and reducing nitrate-N residue at crop harvest. S_{NR} can be replaced with S_{NC} according to their linear relationship or exponential relationship after the previous crop harvest. Determining the target yield and N_R for the subsequent crop based on long-term in-situ observations can guide the recommended fertilizer application amounts for the following crop. The optimized fertilizer recommendation method based on S_{NC}, the target yield, and N_R is convenient for determining the appropriate amounts of N fertilizer for application in the winter wheat–summer maize double cropping system.

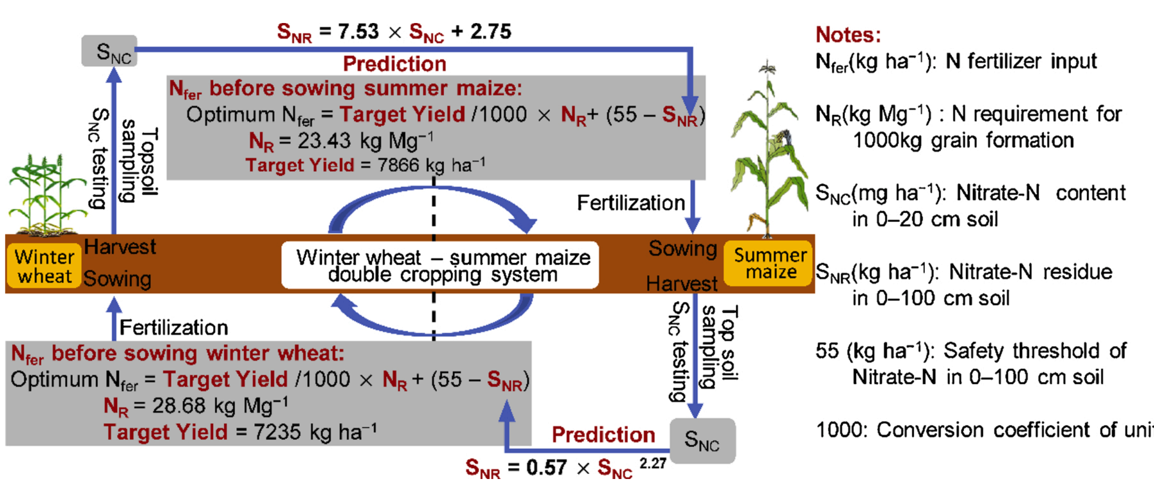


Fig. 9. Method proposed in this study for N fertilizer recommendation in the winter wheat–summer maize double cropping system.

CRediT authorship contribution statement

Zujiao Shi: Conceptualization, Investigation, Data curation, Writing - original draft, Writing - review & editing. **Donghua Liu:** Conceptualization, Writing - review & editing, Data curation, Investigation. **Miao Liu:** Data curation, Investigation. **Muhammad Bilal Hafeez:** Conceptualization, Language editing. **Pengfei Wen:** Data curation, Investigation. **Xiaoli Wang:** Conceptualization, Supervision, Investigation. **Rui Wang:** Conceptualization, Supervision, Investigation. **Xudong Zhang:** Conceptualization, Supervision, Investigation. **Jun Li:** Conceptualization, Funding acquisition, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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