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RESEARCH ARTICLE

Increasing soil organic matter and nitrogen use by optimizing summer maize straw return and nitrogen fertilizer rates minimize N_2O emissions in a wheat–maize system

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Highlights

- Straw return with N application increased yield by regulating soil quality and post-flowering N accumulation.
- Moderate reductions in the amount of straw or N applied did not reduce soil quality or crop yields.
- Straw and N fertilizers affect N_2O emissions by influencing the abundance of bacteria involved in aerobic ammonia oxidation and nitrate respiration.

Abstract

The effects of maize straw return and N fertilizer application on soil quality and crop yield have been extensively investigated. However, the effects of different amounts of maize straw returned to the field with different nitrogen application rates on the soil–crop system quality, abundance of functional N cycle microorganisms, N_2O emissions, and crop N nutrition status of crops have not been thoroughly explored. The objective of this study was to assess the effects of different summer maize straw return rates and N application rates on i) soil quality and crop productivity; ii) the community of N cycle functional microorganisms and N_2O emission; and iii) crop N status. The results indicated that crop yields increased by 7.62 to 12.69% at 210 kg ha^{-1} of N application for full straw return (SN) and half return (1/2SN) compared to the no-return treatment (CK). No significant difference was noted in the yields between the full straw return reduced by 15% (178.5 kg N ha^{-1}) of N fertilizer (S-15%N) and SN. The surface soil layer (0–20 cm) showed significantly higher levels of soil organic matter (SOM), the community of N-cycling functional microorganisms, crop N nutrition status and N uptake efficiency in SN, 1/2SN, and S-15%N as compared to other treatments. Compared to SN, S-15%N and 1/2SN reduced cumulative N_2O emission fluxes by 19.11 and 5.51%, respectively. Furthermore, the nitrogen nutrient index (NNI) values of 1/2SN and S-15%N were closer to the critical N requirement than SN. In summary, schemes for determining the optimal rates of straw return and N application (1/2SN and S-15%N) based on SOM, NNI, cumulative N_2O emission fluxes, and yield can be applied to the annual production of winter wheat and summer maize in China.

Keywords: maize straw return, nitrogen application, soil physicochemical properties, nitrogen use efficiency, N_2O emission, nitrogen cycle functional microorganisms

1. Introduction

The North China Plain (NCP) is one of the largest grain-producing regions in China, with a primary cropping pattern of winter wheat followed by summer maize. As the world's population increases, the demand for food is also increasing. Despite its long history of food security, this region has recently incurred high costs due to nitrogen consumption (Feng *et al.* 2020). To meet the growing demand for food, crop yields have increased, resulting in an annual production of 240 million tons of straw in the NCP, with nearly 43% of this total contributed by maize crops (Li and Wang 2020; Liu *et al.* 2022). Given this substantial resource of maize straw, finding efficient utilization methods has become a pressing issue. Currently, the uses of maize straw include various options

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such as direct field return, biomass energy generation, feed processing, industrial raw material production, and activated carbon preparation (Shi *et al.* 2022; Chang *et al.* 2023; Qian *et al*. 2024). To maximize the value derived from maize straw, it is essential to select appropriate utilization pathways based on local conditions while considering factors such as economic costs, environmental impacts, and technical feasibility.

Among the diversified methods of straw application, straw return to the field is widely recommended as an environmentally friendly management practice for sustainable agriculture to ensure continuing crop production (Dhaliwal *et al.* 2020; Tian *et al.* 2023). A recent study has indicated that incorporating straw into the field can significantly increase crop yields and nitrogen use efficiency, while also promoting synergistic carbon efficiency and economic benefits (Li *et al.* 2022; Guo *et al*. 2024). However, most studies on the impact of straw return on yield increases rely on applying chemical fertilizers. Researchers often overlook the potential effect of chemical fertilizers on enhancing the efficacy of returning straw to the field. In one study, Wang *et al.* (2019) showed that the incorporation of straw without chemical fertilizers led to a reduction in maize yield. This can be attributed to the high cellulose and lignin content in straw, resulting in a large C/N ratio (25–30:1), which leads to the significant consumption of available N during decomposition. This creates biological N competition that affects crop productivity (Song *et al.* 2024). Therefore, higher rates of straw incorporation result in greater consumption of soil available N, ultimately reducing its availability for crop productivity and impacting yield (Xie *et al.* 2022).

Regulating the soil nitrogen content is crucial for improving the utilization efficiency of returned straw. Nitrogen application increases microbial necrotic C within the soil organic carbon, promoting nutrient cycling and accelerating straw decomposition (Meng *et al.* 2024). Gao *et al.* (2023) demonstrated that when straw was returned to the field, applying N fertilizers resulted in higher yields and better nitrogen utilization than no fertilizer application. However, applying N fertilizers to straw returned to the field also carries the risk of increasing N_2O emissions (Zhang L *et al.* 2024). This may occur because the combination of straw and N fertilizer amplifies the soil carbon-to-nitrogen ratio, thus stimulating the mineralization and decomposition of SOM (Ma *et al.* 2021). Guo *et al.* (2024) demonstrated that the reciprocal effect of straw return and an appropriate dose of N application was significant, in that returning straw to the field simultaneously increased the contribution of N fertilizer to the yield and reduced its contribution to the N_2O emission. Therefore, optimizing the combined effects of straw and N fertilization on the soil–crop production system is crucial. In addition, this may help to alleviate the problems of low summer maize straw resource utilization and the excessive N application by farmers in China. Finding the appropriate dose of nitrogen to apply with different amounts of straw returned to the field is essential. This approach aims to reduce agricultural production costs and improve the efficiency of straw and N fertilizer utilization.

The specific objectives of this study were: (1) to quantify the effects of different maize straw return rates and N rates on the annual yield, N accumulation and N utilization characteristics of winter wheat-summer maize; (2) to clarify the effects of different straw return rates and N rates on the physical properties and nutrient effectiveness of soils; and (3) to optimize straw return and N rates by using N nutrient indices to evaluate the nutrient status of winter wheat-summer maize.

2. Materials and methods

2.1. Experimental site

A long-term field experiment on straw return has been conducted in the Maize Innovation Center of Shandong Agricultural University (117°12′E, 36°18′N), Shandong Province, China, since 2011 (Gao *et al.* 2020). The soil of this area is classified as brown soil according to the USDA soil classification (Zhang Y *et al*. 2024). This study was conducted from 2019 to 2021. This region is in a temperate zone characterized by a continental monsoon climate. Meteorological data from October 2019 to October 2021 were provided by the weather stations nearest to the experimental site (Meteorological Bureau of Daiyue District, Tai'an City, Shandong Province, China) (Fig. 1).

2.2. Experimental design

In the annual winter wheat and summer maize production system based on the complete return of wheat straw to the field, three maize straw return treatments were designed. (1) Harvesting after the physiological maturity of maize (approximately 5 October), where the entire summer maize straw produced in one season was mechanically shredded by the harvester and returned to the field using a rototiller (S). (2) After the physiological maturity of maize, half of the summer maize straw produced in one season was harvested and returned to the field by mechanical shredding (1/2S). To improve the accuracy of straw return, half of the straw was manually removed, and the remaining straw was then spread evenly over the entire trial area. (3) All summer maize straw was manually removed from the trial area (CK). The experimental plot size was 9 m×30 m, and each treatment had three replicates, using a randomized complete block design (Gao *et al.* 2020). In 2016, a split plot experiment was designed, where each plot area was 9 m×10 m with three replicates and the following treatments were tested. Three N rates were used in conjunction with the three different maize straw return doses: 210 kg ha^{-1} of N fertilizer (SN, 1/2SN, CK), 15% N fertilizer reduction (S-15%N, 1/2S-15%N, CK-15%N) and 30% N fertilizer reduction (S-30%N, 1/2S-30%N, CK-30%N). Wheat was planted in mid-October at a sowing rate of 133.5 kg ha^{-1}, while maize was planted in mid-June with a planting density of 67,500 plants ha^{-1}. The application rates of phosphorus (P_2O_5) and potassium (K_2O) for the wheat and maize seasons were 75 and 150 kg ha^{-1}, respectively, and they were applied once before sowing. N fertilizer was applied at the sowing and jointing stages of wheat in the ratio of 1:1. The amount of N fertilizer in the maize season was the same as in the wheat season, and it was applied at a ratio of 2:3 before sowing and at the 9th leaf growth stage (V9). Both crops were

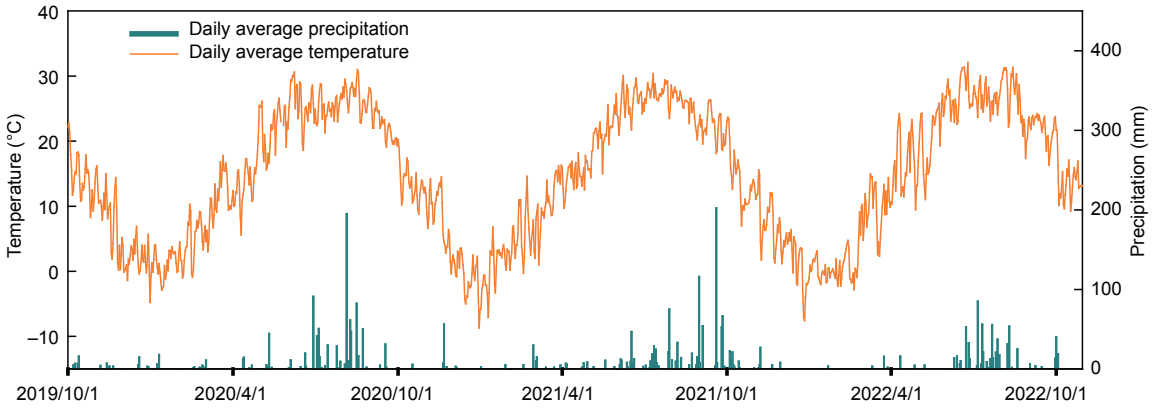


Fig. 1 Temperature and precipitation during the growing seasons of winter wheat and summer maize from 2019 to 2022.

tilled by shredding the straw and returning it to the field, and the materials were tilled once with a spar plow to a depth of 20 cm, followed by rotation and then sowing. The amount of straw returned to the field for each treatment of wheat and maize is detailed in Table 1 (2019–2021). Straw from wheat was uniformly spread to cover the ground surface using a crushing and throwing device, and the straw on the ground surface was well mixed with the soil through rotary tillage. Data for the base soil composition of the 0–40 cm tillage layer for each treatment before setting up the split zone trial (2016) are shown in Table 2 (Gao *et al.* 2020).

2.3. Sampling and measurements

N use characteristics (1) Sample collection and total N measurement. For sample collection, sets of 30 uniform plants were taken from each treatment at the jointing stage (WJ), flowering stage (WF), and harvest stage (WH) of wheat. Samples were oven dried at 105°C for 30 min, then dried again at 75°C to a constant weight before they were finally weighed.

For uniform sample collection in the maize crop, five plants with uniform growth were selected from each treatment at the sixth leaf stage (V6), tasseling stage (VT), and physiological maturity stage (R6). All plant samples were oven-dried at 105°C for 30 min and then dried at 70°C to a constant weight. The dry matter weight of each plant was recorded according to a method reported previously (Gao *et al.* 2022a).

Soil and plant samples were collected at the same growth stages. Five soil samples were taken from the 0–60 cm soil profiles in each treatment plot using a soil auger (3.5 cm diameter). Three depth increments of 0–20, 20–40, and 40–60 cm were used for each sample. Soil samples from the same layer were mixed together, air-dried, ground, and passed through a 0.25 mm sieve before determining total N content.

Plant and soil samples were dried, powdered, and then digested with H_2SO_4-H_2O_2. Total nitrogen in the plant samples was determined using an AA3 Auto Analyzer 3 Continuous-Flow Analysis instrument (Original manufacturer: SEAL Germany) (Gao *et al.* 2020).

(2) N utilization index. The N accumulation in aboveground plant parts (NAA) was calculated according to Zhao *et al.* (2024) by using the following equation:

NAA=Plant dry weight×Plant N content

Soil N content was calculated according to Gao *et al.* (2020) by using the following formula.

Soil N content=(Soil nitrate N content+Soil ammonium N content)×Soil bulk density×Soil thicknesses/10

The nitrogen nutrition index (NNI) was calculated according to Liu *et al.* (2023) by using the following formula.

NNI=Actual N uptake/Critical N uptake

where critical N uptake=$a_c \times W^{-b}$ (in which a_c is minimum amount of N needed to produce 1 ton of dry matter per hectare of land, with values of 5.3% for wheat and 3.4% for maize; W is actual amount of dry matter in tons; and b is the rate of nitrogen concentration decline, with values of 0.44 for wheat and 0.37 for maize).

Table 1 Straw return of winter wheat and summer maize from 2019 to 2021 (kg ha^{-1})

Treatment	Amount of maize straw returned in 2019	Amount of wheat straw returned in 2020	Amount of maize straw returned in 2020	Amount of wheat straw returned in 2021
Full straw return (SN)	10,133.6	9,306.3	10,539.5	10,063.0
S-15%N	9,286.2	9,347.4	10,666.4	9,955.9
S-30%N	9,242.1	6,079.2	8,963.6	9,647.2
1/2SN	4,609.0	9,412.8	5,241.4	10,264.7
1/2S-15%N	4,378.5	6,918.9	4,806.3	8,893.0
1/2S-30%N	4,242.8	5,228.4	4,329.1	8,063.5
CK	0	7,434.4	0	8,317.8
CK-15%N	0	6,569.6	0	6,950.9
CK-30%N	0	5,489.3	0	6,197.8

Table 2 Effects of different straw return amounts on the nutrient contents of the soil layer under 0–40 cm in 2016

Treatment	Bulk density of soil (g cm^{-3})	Total porosity (%)	Soil organic matter content (%)	Total N (g kg^{-1})	Total P (g kg^{-1})	Total K (g kg^{-1})
Full straw return SN)	1.52	47	1.58	1.28	4.5	4.9
1/2SN	1.54	44	1.47	1.26	4.3	4.9
CK	1.64	41	1.18	1.14	4.0	4.6

The N harvest index (NHI) was calculated according to Zhao *et al.* (2024) by using the following equation:

NHI=Grain N accumulation/NAA

The N uptake efficiency (UPE), N utilization efficiency (UTE) and N use efficiency (NUE) were calculated according to Moll *et al.* (1982) and Yin *et al.* (2018) by using the following formulas.

UPE=NAA/(Soil N content+Current N application)

UTE=Grain yield/NAA

NUE=Grain yield/(Soil N content+Current N application)

The pre-anthesis N translocation amount (PrNTA), pre-anthesis N translocation rate (PrNTR), contribution rate of pre-anthesis N translocation amount to grain (PrNTC), post-anthesis N accumulation amount (PoNAA), and contribution rate of post-anthesis N accumulation amount to grain (PoNAC) were calculated according to Li *et al.* (2023) by using the following formulas.

PrNTA=N accumulation amount of vegetative organs at anthesis–N accumulation amount of vegetative organs at maturity

PrNTR (%)=Pre-anthesis N translocation amount/N accumulation amount of vegetative organs at anthesis×100

PrNTC (%)=Pre-anthesis N translocation amount/N accumulation amount in the grain at maturity×100

PoNAA=N accumulation amount of the plant at maturity–N accumulation amount of the plant at anthesis

PoNAC (%)=Post-anthesis N accumulation amount/N accumulation amount in the grain at maturity×100

Grain yield and yield components The middle three rows were selected to measure yield-related attributes in corn, and 30 consecutive effective ears were randomly harvested. The number of grains per ear was recorded. The 1,000-grain weight was calculated after grain drying at 75°C, and the maize yield was calculated at the maturity stage and adjusted to a moisture content of 14% (Gao *et al.* 2022a).

For measuring yield-related attributes in wheat, like grains per spike, and the 1,000-kernel weight at maturity, three 1 m^2 plots (1 m×1 m) with uniform growth in each treatment plot were selected at random. For the grain number per spike, 30 individual spikes were randomly selected in each treatment, and each treatment was repeated three times at the maturity stage. Wheat yield was calculated with a 12% moisture water content according to Yin *et al.* (2018).

Soil physicochemical properties (1) Soil physical properties. Soil bulk density, soil gravimetric moisture, total porosity, and the soil three-phase ratio in the 0–20 cm soil layers were measured by the ring knife method (diameter 50.46 mm×height 50 mm, volume 100 cm^3) during maize harvesting on 29 September, 2020 and 11 October, 2021 (Gao *et al.* 2020). The calculation methods are as follows (Qi *et al.* 2021):

$$\rho=\frac{M3-M0}{V}$$

$$\theta_g=\frac{M1-M3}{M3-M0}\times100$$

$$P_t=(1-\frac{\rho}{P_d})\times100$$

$$R=\sqrt{0.4\times(X-50)^2+(Y-25)^2+(Z-25)^2}$$

$$X=100\times(1-P_t)$$

$$Y=100\times\theta_g\times\rho$$

$$Z=100\times(P_t-\theta_g)\times\rho$$

where ρ, soil bulk density (g cm^{-3}); M3, total weight of dry soil and the ring knife after drying (g); M0, weight of the ring knife (g); V, volume of the ring knife (cm^3); θ_g, soil gravimetric moisture (%); M1, total weight of fresh soil and the ring knife (g); P_t, total soil porosity (%); P_d, soil density, usually 2.65 g cm^{-3}; R, deviation value of the soil three-phase ratio; *X*, calculation formula of the soil solid value; *Y*, calculation formula of the soil sample liquid phase value; *Z*, calculation formula of the soil sample gas phase value; 0.4, weight of the soil solid phase; 0.6, weight of the soil gas sample.

(2) Soil chemical properties. 1) Soil pH. Soil samples were air-dried, pulverized, and mixed well at a water:soil ratio of 1:2.5. The pH was measured using a pH meter (Produced by Sartorius, Model PB-10). 2) Soil available nutrients and soil organic matter content (SOM).

SOM was determined by using the K_2CrO_7-H_2SO_4 oxidation method described by Walkley and Black (1934). Heat generated by rapidly mixing concentrated sulfuric acid and potassium dichromate was used to oxidize the organic matter. The reaction supernatant was then aspirated, and the colorimetric value was measured in a spectrophotometer at 590 nm. SOM was quantified using a standard curve made with glucose. Soil available nitrogen was determined according to Bao (2000). The hydrolysis of air-dried soil with NaOH solution (1 mol L^{-1}) and $FeSO_4$ reductant was performed in a diffusion tray. The ammonia released was absorbed by boric acid, and the ammonia in the boric acid solution was titrated with a standard acid to calculate the available nitrogen content of the soil.

Gas sampling and measurements A static chamber/gas chromatography method was used to measure soil N_2O emissions, as described by Wang *et al.* (2018). Each treatment included three static chambers placed between the corn and wheat rows. The length, width and height of the static chambers used in the maize season were 30, 30 and 40 cm, respectively, and the corresponding dimensions of the static chambers used in the wheat season were 30, 15 and 40 cm, respectively. A pedestal was placed under each static chamber, and the pedestal and static chamber were both sealed with water to ensure that the external environment did not cause any changes within the static chamber during sampling. Sample collections and measurements were made for one consecutive week after crop fertilization and were thereafter sampled weekly until the crop was harvested. N_2O collection for each treatment was conducted from 9:00 to 11:00 a.m. (Akhtar *et al.* 2020). After sealing the chamber for 0, 10, 20, and 30 min, 40 mL of gas was withdrawn from the chamber at each sealing time and placed into a sealed gas bag. Samples were analyzed using an Agilent GC7890 gas chromatograph. The emission flux (F) and cumulative emission flux (E) of N_2O were calculated as follows (Wang *et al.* 2018; Akhtar *et al.* 2020):

$$F=\rho\times(\frac{V}{A})\times(\frac{\Delta c}{\Delta t})\times(\frac{273}{T})$$

$$E=\sum_{i=1}^{n}(F_i+F_{i+1})/2\times(t_{i+1}-t_i)\times24$$

where F is the flux of N_2O (μg N_2O-N m^{-2} h^{-1}), ρ is the gas density of N_2O under a standardized state (mg cm^{-3}), V is the volume of the chamber (m^3), A is the chamber area (m^2), Δc/Δt is the rate of N_2O gas accumulation in the chamber (μg m^{-3} h^{-1}), and T is the absolute temperature (273 plus the air temperature in the chamber), E is the cumulative emission flux of N_2O (kg N_2O ha^{-1}), *n* is the total number of gas measurements, i is the sampling time, and (t_{i+1}–t_i) represents the number of days between two gas measurements.

Interpretation of soil bacterial functions Genomic DNA was extracted using CTAB, and 16S rRNA was amplified by PCR using primers 341F (5′-CCTAYGGGRBGCASCAG-3′) and 806R (5′-GGACTACNNGGGGTATCTAAT-3′) targeting the highly variable V3–V4 regions of bacteria and archaea. Sequencing libraries were generated using the TruSeq® DNA PCR-Free Sample Preparation Kit (Illumina, San Diego, CA, USA) according to the manufacturer's instructions, and index codes were added. Library quality was assessed with a Qubit 2.0 fluorometer (Thermo Fisher Scientific, Waltham, MA, USA). Finally, the libraries were sequenced on the Illumina NovaSeq 6000 platform to generate 250 bp paired-end reads. The QIIME tool import program was used to import raw data FASTQ files into a format operable by the QIIME2 system. Demultiplexed sequences for each sample were quality-filtered and trimmed, denoised, and merged.

2.4. Statistical analysis

Because there are many abbreviations in the experimental methods and analysis of the results, we have organized these abbreviations and placed them in Table 3 to help readers understand the results of this study more clearly. Analysis of variance (ANOVA) was performed for data analysis using IBM SPSS for Windows 22.0 (IBM Corp, Armonk, NY, USA). Microsoft Excel 2013 (Microsoft Corp, Redmond, WA, USA) was used to write the equations and calculate the experimental data. Duncan's multiple range test (DMRT) was used to separate significant differences among the treatment means at a 95% confidence interval. All graphs were prepared using Sigma Plot 14 software (San Jose, CA, USA). In addition, structural equation modeling (SEM) analysis was conducted using SPSS Amos 26. The effects of straw return and nitrogen application on soil, microorganisms, greenhouse gases, and crop growth were determined by combining the soil physicochemical properties (e.g., soil pH, SOM, available nitrogen, and bulk density), microbial diversity, N_2O emissions, and aboveground crop growth and development.

3. Results

3.1. Soil properties

Soil physical properties Our results show that straw return combined with nitrogen fertilization significantly influenced soil physical properties (Fig. 2). The physical properties in the SN and 1/2SN treatments were significantly higher than CK at 210 kg ha^{-1} N. The physical properties of soil from the S-15%N treatment were on par with SN at 178.5 kg ha^{-1} N (15% reduction in N fertilizer), but were significantly lower for 1/2S-15%N and CK-15%N. The physical properties of soil from S-30%N, 1/2S-30%N and CK-30%N were significantly lower compared to SN at 147 kg ha^{-1} N (30% reduction in N fertilizer). SN and 1/2SN showed significant reductions of 10.13 and 10.44% in soil bulk density, along with significant increases of 17.10 and 11.79% in soil total porosity, and significant increases of 18.60 and 16.33% in soil gravimetric moisture. There were significant reductions of 29.25 and 29.56% in R compared to CK. In S-15%N, the soil bulk density significantly decreased by 11.23%, soil total porosity significantly increased by 16.99% and soil gravimetric moisture significantly increased by 27.73% compared to CK-15%N.

Soil chemical properties (1) Soil pH. The application of straw return combined with N fertilizer significantly increased the soil pH in the 0–40 cm soil layer to a range of 6.59–6.75 (Fig. 3). At the maturity stage, with the same amount of straw returned to the field, a reduction in N application resulted in a significant increase in soil pH in the 0–20 cm soil layer, while the effect was not significant in the 20–60 cm layer. At the same N application rate, the soil pH in the 0–40 cm soil layer was significantly higher in the full and half-returned straw than in the non-returned treatment, but the effect was insignificant in the 40–60 cm layer. In the 0–40 cm soil layer, the pH values for SN and 1/2SN were significantly higher by 0.88 and 0.96%, respectively, compared to CK, while S-15%N was significantly higher by 0.69% compared to CK-15%N.

(2) SOM. N fertilization with summer maize straw significantly increased SOM in the 0–60 cm soil layer (Fig. 4). When the amount of straw return to the field was kept constant, a reduction in the nitrogen application rate resulted in a significant decrease in SOM in the 0–60 cm soil layer. Under a constant nitrogen application rate, SOM

Table 3 Abbreviations used in this study

Abbreviation	Description	Abbreviation	Description
C	Carbon	PoNAC	Contribution rate of post-anthesis N accumulation amount to grain
N	Nitrogen	R	Deviation value of the soil three-phase ratio
NCP	North China Plain	R6	Physiological maturity stage of maize
NNI	N nutrition index	SOM	Soil organic matter
NHI	N harvest index	UPE	N uptake efficiency
NUE	N use efficiency	UTE	N utilization efficiency
NAA	N accumulation in the plant aboveground	V6	Sixth leaf stage of maize
PrNTA	Pre-anthesis N translocation amount	VT	Tasseling stage of maize
PrNTR	Pre-anthesis N translocation rate	WJ	Jointing stage of wheat
PoNAA	Post-anthesis N accumulation amount	WF	Flowering stage of wheat
PrNTC	Contribution rate of pre-anthesis N translocation amount to grain	WH	Harvest stage of wheat

decreased significantly with a reduction in the straw return amount. The highest value of SOM in the 0–60 cm soil layer was observed in the SN treatment, followed by S-15%N and 1/2SN across all fertility periods of the crop. During the wheat maturity stage, the SOM values of SN and 1/2SN significantly increased by 33.09 and 20.40%, respectively, compared to CK. In addition, compared to CK-15% N, S-15% N significantly increased SOM by 50.51%.

(3) Soil available N content. The amount of maize straw returned to the field and N rate significantly affected the available N content in the soil (Fig. 5). At the crop maturity stage, soil available N was significantly highest in the SN treatment, followed by S-15%N and 1/2SN. During the wheat–maize harvest period, the soil available N contents

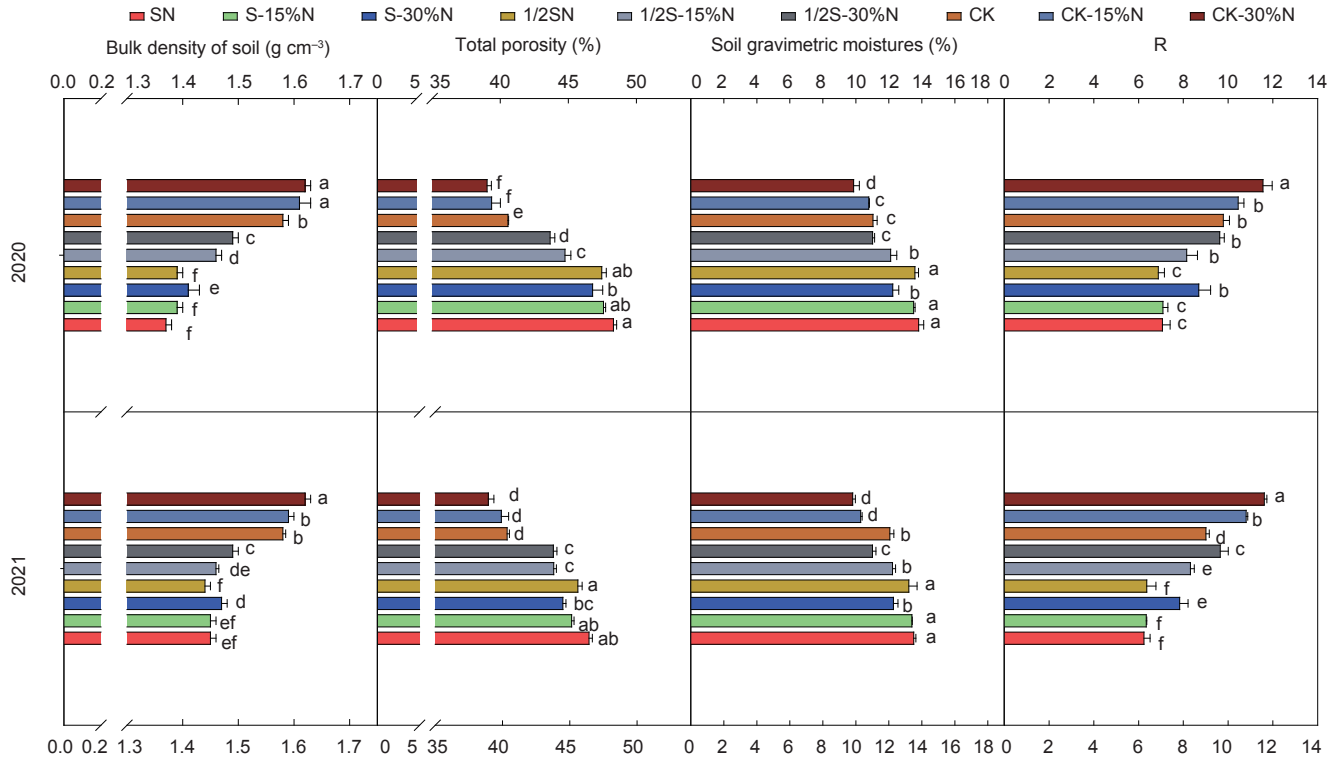


Fig. 2 Effects of the maize straw return amount and nitrogen rate on soil bulk density, total porosity, soil gravimetric moisture and the deviation value of the soil three-phase ratio in the 0–20 cm soil layer at maize maturity. SN, S-15%N, and S-30%N represent full straw return plus N application rates of 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively; 1/2SN, 1/2S-15%N, and 1/2S-30%N represent half-quantity straw return plus N application of 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively; CK, CK-15%N, and CK-30%N represent no straw return plus N application at 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively. Bars mean SE (n=5). Different letters indicate significant differences among treatments at the same stage (P<0.05).

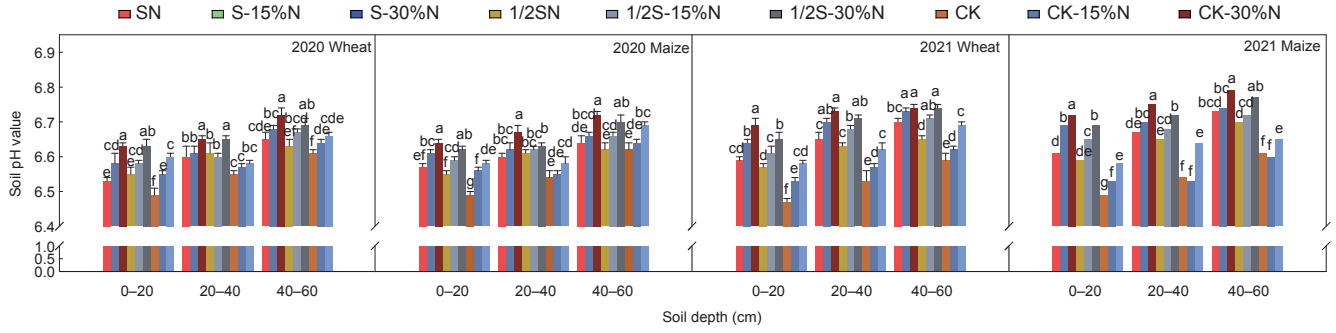


Fig. 3 Effects of the summer maize straw return amount and nitrogen application rate on soil pH values at the maturity stages of winter wheat and summer maize. SN, S-15%N, and S-30%N represent full straw return plus N application rates of 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively; 1/2SN, 1/2S-15%N, and 1/2S-30%N represent half-quantity straw return plus N application of 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively; CK, CK-15%N, and CK-30%N represent no straw return plus N application at 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively. Bars mean SE (n=5). Different letters indicate significant differences among treatments at the same stage (P<0.05).

in the 0–40 cm soil layer for the SN and 1/2SN treatments were increased significantly by 25.09 and 16.93%, and by 23.89 and 17.47%, respectively, compared to CK. The soil available N content for the S-15%N treatment significantly increased by 36.58 and 20.39%, and by 34.50 and 24.32% compared to CK-15%N and S-30%N, respectively.

3.2. Nitrogen accumulation and transport

Dry matter and N accumulation The amounts of maize straw returned and N applied significantly affected the aboveground dry matter and N accumulation in winter wheat–summer maize at different stages (Fig. 6). In the WJ stage, both dry matter and N accumulation increased significantly with a reduction in the straw return at the same N fertilizer application rate. However, the wheat trends observed during the WF and WH periods were the opposite of those in the WJ period. For example, in the WH stage of 2020, the aboveground dry matter and N accumulation for SN and 1/2SN increased by 21.1 and 25.54%, and by 20.41 and 27.44%, respectively, compared to the CK treatment. In addition, S-15%N showed significant increases of 25.73 and 46.47% compared to CK-15%N.

At the VT and R6 stages, under the same straw return amount, no significant differences were observed in the dry matter or N accumulation between the aboveground parts of S-15%N and SN. At a constant N application, with an increase in the straw return amount, the dry matter and N accumulation both increased significantly. However, the dry matter and N accumulation for 1/2SN did not significantly differ from SN. At the R6 stage in 2020, compared to CK, both the dry matter and N accumulation for the SN and 1/2SN treatments increased by 10.49 and 32.04%, and by 8.15, and 20.19%, respectively.

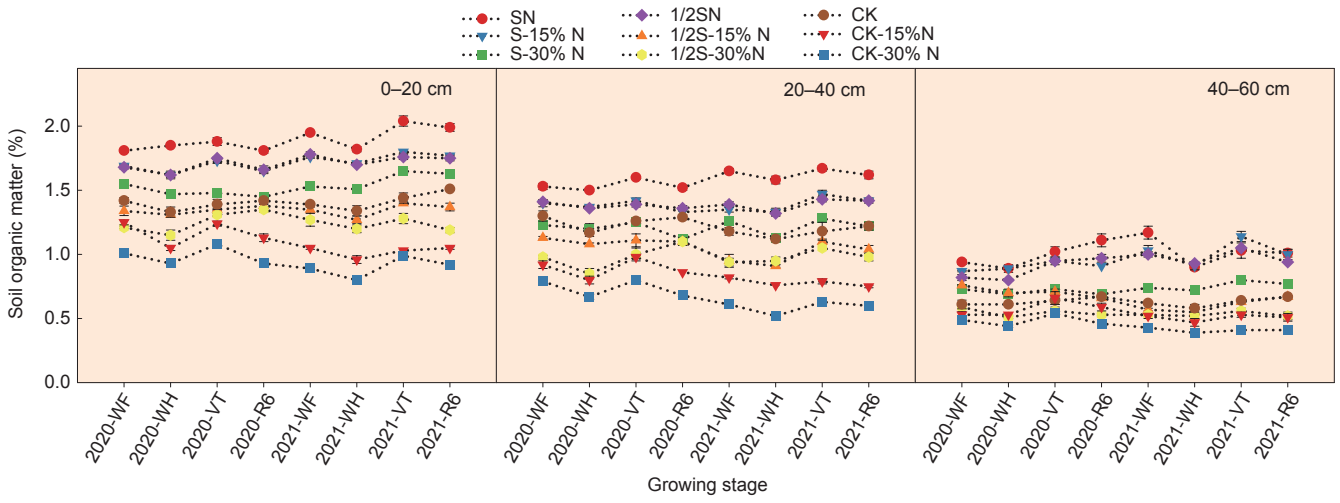


Fig. 4 Effects of the summer maize straw return amount and nitrogen rate on the soil organic matter contents at different growth stages of winter wheat and summer maize. WF, wheat flowering period; WH, wheat harvest period; VT, maize tasseling stage; R6, maize physical maturity stage. SN, S-15%N, and S-30%N represent full straw return plus N application rates of 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively; 1/2SN, 1/2S-15%N, and 1/2S-30%N represent half-quantity straw return plus N application of 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively; CK, CK-15%N, and CK-30%N represent no straw return plus N application at 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively. Bars mean SE (n=5).

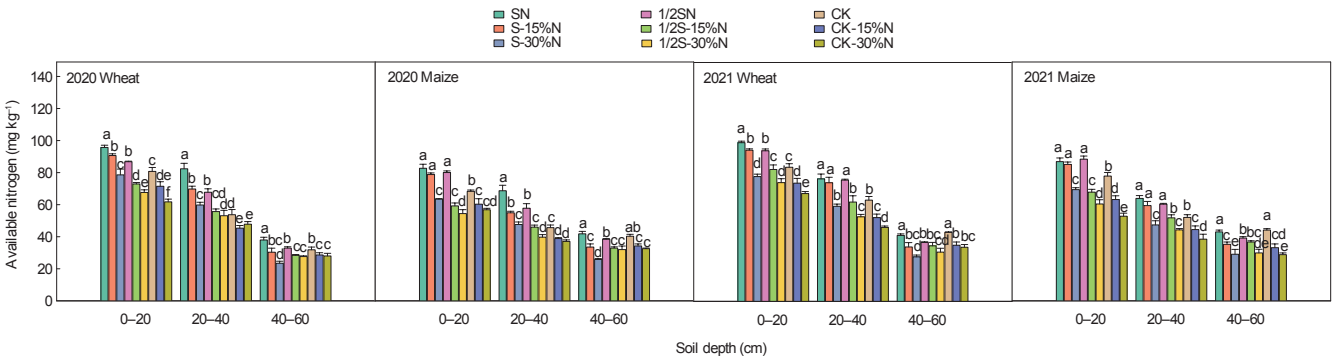


Fig. 5 Effects of the summer maize straw return amount and nitrogen rate on the contents of available nitrogen in soil at the maturity stages of winter wheat and summer maize in 2020 and 2021. SN, S-15%N, and S-30%N represent full straw return plus N application rates of 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively; 1/2SN, 1/2S-15%N, and 1/2S-30%N represent half-quantity straw return plus N application of 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively; CK, CK-15%N, and CK-30%N represent no straw return plus N application at 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively. Bars mean SE (n=5). Different letters indicate significant differences among treatments at the same stage (P<0.05).

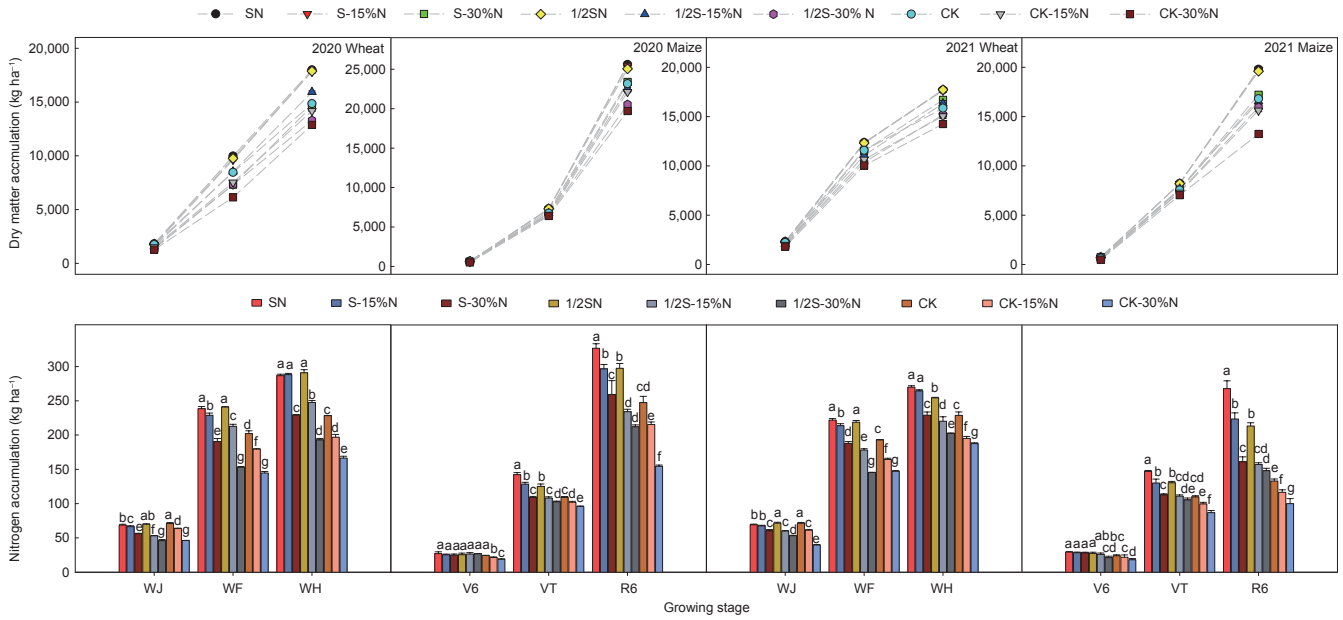


Fig. 6 Effects of the summer maize straw return amount and nitrogen rate on dry matter and nitrogen accumulation in winter wheat and summer maize in 2020 and 2021. SN, S-15%N, and S-30%N represent full straw return plus N application rates of 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively; 1/2SN, 1/2S-15%N, and 1/2S-30%N represent half-quantity straw return plus N application of 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively; CK, CK-15%N, and CK-30%N represent no straw return plus N application at 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively. WJ, wheat jointing stage; WF, wheat flowering period; WH, wheat harvest period; V6, maize sixth leaf stage; VT, maize tasseling stage; R6, maize physical maturity stage. Bars mean SE (n=5). Different letters indicate significant differences among treatments at the same stage (P<0.05).

Compared to CK-15%N, the S-15%N treatment values were significantly increased by 15.03 and 37.66%, respectively.

Annual N translocation Maize straw return and N application significantly affected winter wheat–summer maize annual N transport (Table 4). The combined application of straw and N fertilizer significantly increased the PoNAA and PoNAC of winter wheat–summer maize, while PrNTC significantly decreased. For example, during the wheat growing season, PrNTC decreased by 11.90%, while PoNAA and PoNAC increased by 83.33 and 52.53%, and by 90.45 and 62.32% in SN and 1/2SN, respectively, compared to CK. Compared to CK-15%N, the S-15%N treatment showed significantly reduced PrNTC by 10.03%, and significantly increased PoNAA and PoNAC by 239.45 and 136.90%.

Dynamics of nitrogen nutrition index Maize straw return with N fertilizer significantly affected the annual NNI of winter wheat-summer maize (Fig. 7). At the WJ stage, the NNI of each treatment was significantly less than "1", which indicated that the N nutritional status of wheat was in a deficit. In the WF and WH stages, the NNI values of all treatments increased significantly compared to the WJ stage. At the WH stage, the SN (NNI=1.116) value was greater than "1", while the values for S-15%N (NNI=0.954) and 1/2SN (NNI=0.944) were near "1". At the VT and R6 stages, the NNI of the six treatments were significantly lower than "1" except for SN, S-15%N and 1/2SN. At the wheat and maize maturity stage, the NNI values of S-15%N (NNI=1.010) and 1/2SN (NNI=1.006) were near "1", while that of SN (NNI=1.179) was greater than "1". This indicates that the plant N contents of the S-15%N and 1/2SN treatments were closer to the critical N requirement and nitrogen utilization was significantly increased in this period as compared to the SN treatment. In summary, the S-15%N and 1/2SN treatments had the best nitrogen nutrient status, while the SN treatment had a nitrogen surplus, and the remaining treatments had a nitrogen deficit status.

3.3. Temporal dynamics of N_2O emission in cropland

In the wheat–maize annual system, the N_2O emission fluxes ranged from 1.28–975.54 (Fig. 8-A) and 2.99–645.56 μg m^{-2} h^{-1} (Fig. 8-B), respectively. After fertilization, the N_2O emission fluxes increased. The emission flux was higher in the maize season than in the wheat season. This may be related to differences in temperature and soil water content (Figs. 1 and 8). The cumulative N_2O emission fluxes of SN and 1/2SN were significantly increased by 68.18 and 58.91%, respectively, in the wheat-maize annual system compared to CK. The cumulative N_2O emission flux was significantly increased by 61.83% for S-15%N compared to CK-15%N, while 1/2SN and S-15%N had significantly lower cumulative N_2O emission fluxes than SN (Fig. 9).

3.4. Prediction of microbial functions in the nitrogen cycle

The effect of straw with nitrogen fertilizer on the community of soil bacterial taxa in the wheat–maize annual production system is shown in Fig. 10. The samples contained seven bacterial groups related to soil nitrogen metabolism, as categorized by classifiable sequences. Bacteria involved in

Table 4 Effects of summer maize straw return amount and nitrogen rate on annual nitrogen retransfer in winter wheat and summer maize[1)]

Year	Crop	Treatment[2)]	PrNTA (kg ha^{-1})	PrNTR (%)	PrNTC (%)	PoNAA (kg ha^{-1})	PoNAC (%)
2020	Wheat	SN	148.8 a	62.4 de	75.6 cd	48.2 b	24.5 bc
		S-15%N	136.7 b	54.1 f	68.1 e	58.3 a	31.9 a
		S-30%N	128.8 c	67.7 bc	77.0 cd	38.7 c	23.1 bc
		1/2SN	142.2 ab	59.0 e	74.0 d	50.0 b	26.0 b
		1/2S-15%N	124.3 c	64.3 cd	79.6 bc	35.0 c	20.4 cd
		1/2S-30%N	110.0 d	67.9 bc	73.4 d	39.9 c	26.6 b
		CK	137.2 b	67.9 bc	84.0 ab	26.3 d	16.0 de
		CK-15%N	110.6 d	71.5 ab	86.5 a	17.2 e	13.5 e
		CK-30%N	108.0 d	74.7 a	83.3 ab	21.8 de	16.8 de
	Maize	SN	79.2 a	48.5 bc	33.3 d	158.8 a	66.8 a
		S-15%N	70.1 ab	44.9 cd	32.1 d	148.6 a	67.9 a
		S-30%N	59.7 c	43.0 d	33.1 d	123.3 b	67.0 a
		1/2SN	73.6 ab	46.2 bcd	32.3 d	154.1 a	67.7 a
		1/2S-15%N	67.4 bc	49.0 bc	41.2 c	96.6 c	58.8 b
		1/2S-30%N	80.1 a	56.3 a	53.5 b	69.8 d	46.5 c
		CK	73.9 ab	50.1 b	42.5 c	99.9 c	57.5 b
		CK-15%N	79.7 a	58.1 a	50.4 b	78.4 d	49.6 c
		CK-30%N	65.5 bc	56.0 a	63.6 a	37.6 e	36.4 d
2021	Wheat	SN	135.9 b	62.2 d	72.5 f	51.6 b	27.5 b
		S-15%N	135.3 b	62.5 d	73.8 de	48.1 b	26.3 bc
		S-30%N	122.0 d	64.9 cd	74.9 de	41.0 c	25.1 bc
		1/2SN	151.7 a	63.4 d	81.0 ab	35.6 d	19.0 ef
		1/2S-15%N	116.2 e	65.3 cd	74.0 e	42.0 c	26.5 b
		1/2S-30%N	108.0 f	72.3 a	64.7 g	57.2 a	35.3 a
		CK	129.1 c	66.9 bc	82.1 a	28.1 e	17.9 f
		CK-15%N	109.1 f	66.4 bc	78.1 bc	30.7 de	21.9 de
		CK-30%N	102.2 g	69.5 ab	76.8 cd	30.8 de	23.2 cd
	Maize	SN	77.3 ab	57.1 c	54.0 c	65.4 a	46.0 a
		S-15%N	82.8 a	63.5 b	55.4 c	66.5 a	44.6 a
		S-30%N	76.7 ab	65.6 b	63.7 bc	44.0 b	36.3 c
		1/2SN	84.3 a	66.5 ab	58.0 bc	61.5 a	42.0 ab
		1/2S-15%N	74.6 ab	67.3 ab	79.5 ab	46.2 b	38.1 bc
		1/2S-30%N	75.0 ab	71.2 a	94.0 a	42.7 b	36.3 c
		CK	70.2 bc	64.0 b	80.1 ab	23.2 c	24.8 d
		CK-15%N	63.7 cd	64.0 b	73.1 abc	17.0 c	21.0 de
		CK-30%N	56.2 d	64.7 b	73.5 abc	13.2 c	19.1 e

[1)] PrNTA, pre-anthesis nitrogen translocation amount; PrNTR, pre-anthesis nitrogen translocation rate; PrNTC, contribution rate of pre-anthesis nitrogen translocation amount to grain; PoNAA, post-anthesis nitrogen accumulation amount; PoNAC, contribution rate of post-anthesis nitrogen accumulated to grain nitrogen.

[2)] SN, S-15%N, and S-30%N represent full straw return plus N application rates of 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively; 1/2SN, 1/2S-15%N, and 1/2S-30%N represent half-quantity straw return plus N application of 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively; CK, CK-15%N, and CK-30%N represent no straw return plus N application at 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively.

Different letters indicate significant differences among treatments at the same stage (P<0.05).

chemoheterotrophy and aerobic_chemoheterotrophy were the most abundant. With the same N application conditions, the absolute communities of chemoheterotrophy and aerobic_chemoheterotrophy bacteria tended to decrease, and the communities of bacteria involved in aerobic_ammonia_oxidation, nitrate_reduction and cellulolysis significantly increased in the straw-return treatment compared with the non-return treatment. In particular, the communities of bacteria involved in aerobic_ammonia_oxidation and nitrate_respiration were significantly lower in the S-15%N treatment compared to SN and 1/2SN during the 2022 maize season.

3.5. Grain yield and yield components

Returning maize straw to the field and applying N fertilizer significantly affected the annual yield of winter wheat–summer maize and its components (Table 5). The yields of SN, S-15%N, and 1/2SN were not significantly different from each other, but they were significantly higher than those of the other treatments. Under the same N rate, the wheat and maize yields increased with the straw return amount. When the amount of straw was the same, the wheat and maize yields decreased as the N application rate decreased. Annual winter wheat–summer maize yields significantly increased by 10.21 and 10.13% for SN and 1/2SN as compared to CK; and increased by 14.27% for S-15%N compared to CK-15%N. For example, during the maize season, the grains per ear and 1,000-grain weight significantly increased by 4.78 and 4.67%, and by 3.96 and 3.71% in the SN and 1/2SN treatments,

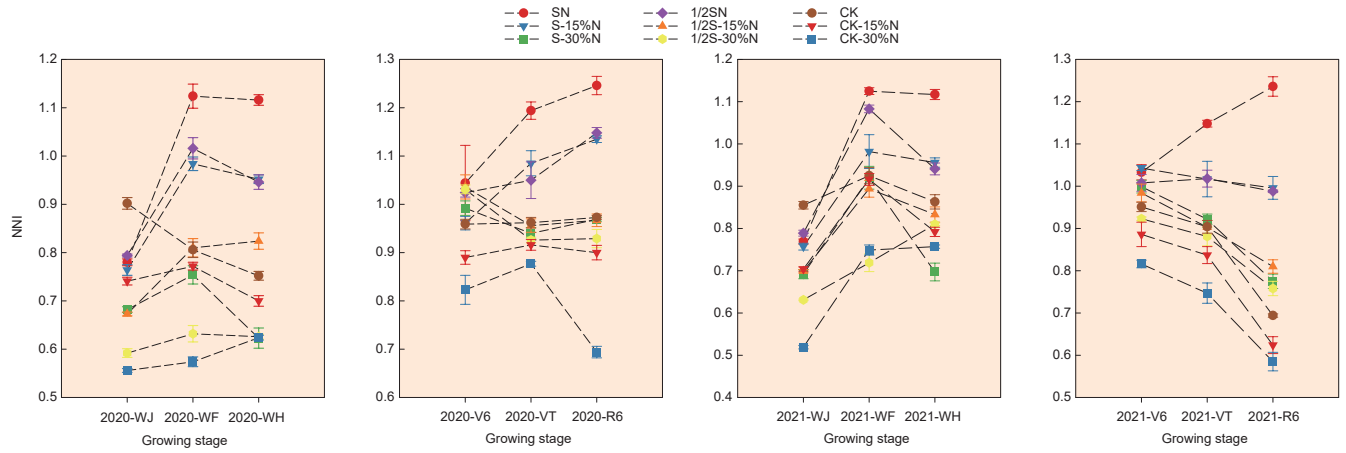


Fig. 7 Effects of the summer maize straw return amount and nitrogen rate on the nitrogen nutrition index (NNI), which indicates the nitrogen nutrition status. SN, S-15%N, and S-30%N represent full straw return plus N application rates of 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively; 1/2SN, 1/2S-15%N, and 1/2S-30%N represent half-quantity straw return plus N application of 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively; CK, CK-15%N, and CK-30%N represent no straw return plus N application at 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively. WJ, wheat jointing stage; WF, wheat flowering period; WH, wheat harvest period; V6, maize sixth leaf stage; VT, maize tasseling stage; R6, maize physical maturity stage. Bars mean SE (n=5).

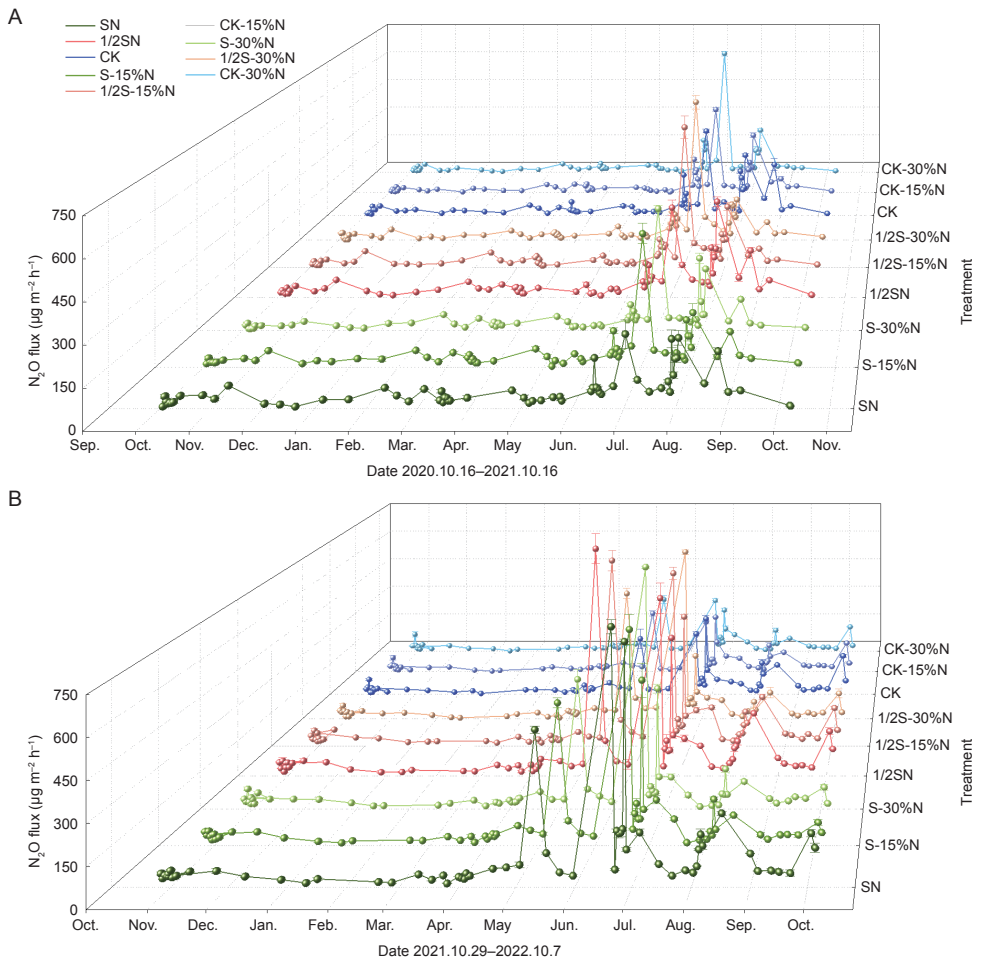


Fig. 8 Effects of straw return and nitrogen application on N_2O emissions in 2020 to 2022. SN, S-15%N, and S-30%N represent full straw return plus N application rates of 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively; 1/2SN, 1/2S-15%N, and 1/2S-30%N represent half-quantity straw return plus N application of 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively; CK, CK-15%N, and CK-30%N represent no straw return plus N application at 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively. CK, no-return treatment.

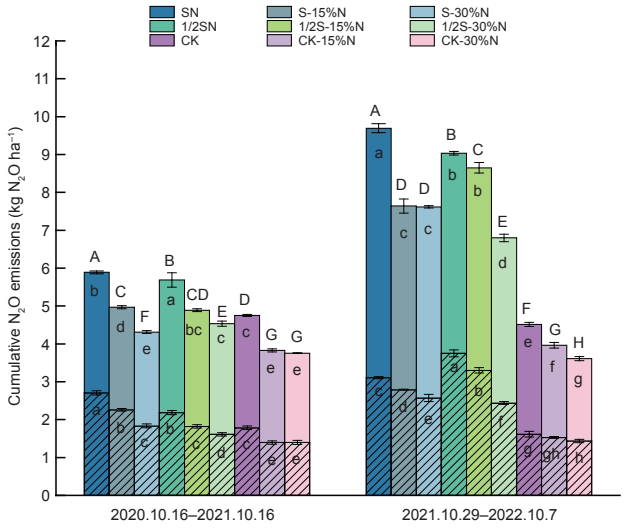


Fig. 9 Effects of straw return and nitrogen application on the cumulative emission fluxes of N_2O. SN, S-15%N, and S-30%N represent full straw return plus N application rates of 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively; 1/2SN, 1/2S-15%N, and 1/2S-30%N represent half-quantity straw return plus N application of 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively; CK, CK-15%N, and CK-30%N represent no straw return plus N application at 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively. The shaded portion at the bottom of the bar chart represents the cumulative nitrous oxide emission flux during the wheat season, while the unshaded portion at the top represents the cumulative nitrous oxide emission flux during the maize season. Bars mean SE (n=6). Different capital letters indicate significant differences (P<0.05) in annual cumulative nitrous oxide emission fluxes among treatment groups within the same stage; different lowercase letters indicate significant differences (P<0.05) in seasonal cumulative nitrous oxide emission fluxes among treatment roups within the same stage .

respectively, compared to CK. Grains per ear significantly increased by 7.73% in S-15%N compared to CK-15%N.

3.6. Annual N utilization of winter wheat and summer maize

The N use efficiency of winter wheat-summer maize was significantly affected by the amounts of maize straw returned and N application (Table 6). At the same amount of straw return to the field, the annual UTE and NUE of winter wheat–summer maize increased significantly with a reduction in nitrogen application. Under the same N rate, the UPE and NUE of straw-returning treatments were significantly higher than that of the no straw-returning treatment, while UTE was significantly lower. For example, in the 2020 wheat season, the SN and 1/2SN treatments had significantly increased UPE and NUE by 32.91 and 12.75%, and by 39.69 and 12.91%, while UTE significantly declined by 15.09 and 18.96% compared to CK. In addition, S-15%N showed significantly increased UPE and NUE by 37.66 and 10.12%, respectively, compared to CK-15%N, and UTE significantly decreased by 20.00%.

3.7. Relationships between soil properties, soil microbial functional flora, crop yields, crop nitrogen accumulation and cumulative N_2O emissions

Improvements in soil physicochemical properties have a positive effect on increasing crop yield. As shown in Fig. 11, soil physical properties were significantly and positively correlated with SOM, soil available N content, and nitrogen-cycling microbial functional flora. This suggests that straw return with N fertilization improves soil physical properties, thereby increasing SOM and the community of nitrogen-cycling microbial functional flora. Straw return with N fertilization increased the microbial community while also increasing

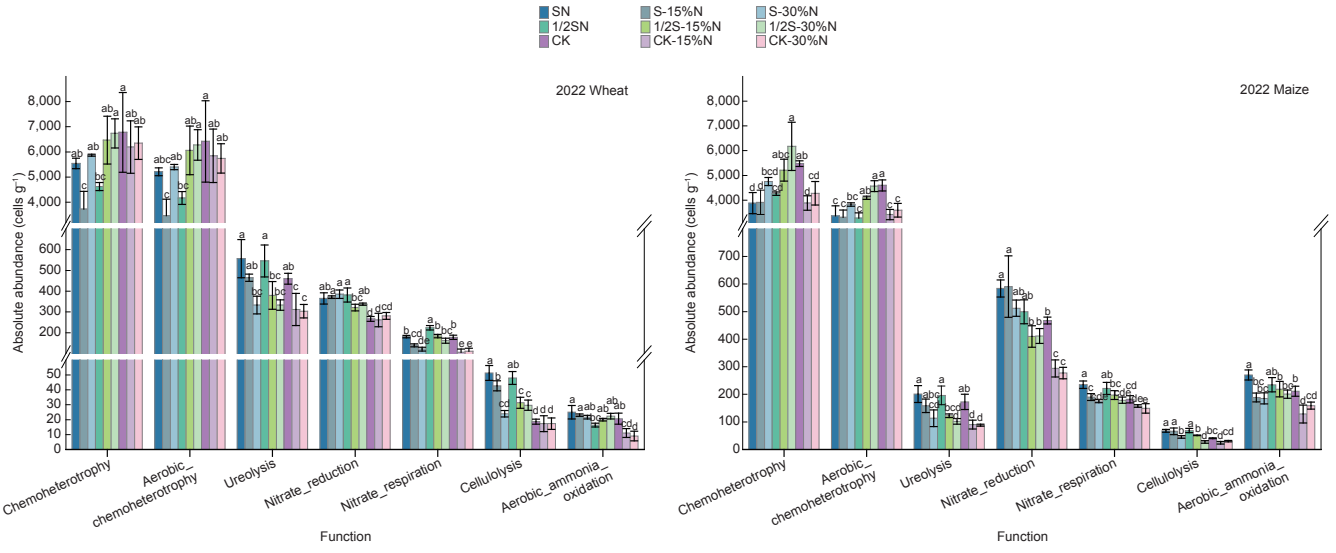


Fig. 10 Effects of straw return and nitrogen application on the absolute abundance of microorganisms related to soil nitrogen metabolism functions. SN, S-15%N, and S-30%N represent full straw return plus N application rates of 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively; 1/2SN, 1/2S-15%N, and 1/2S-30%N represent half-quantity straw return plus N application of 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively; CK, CK-15%N, and CK-30%N represent no straw return plus N application at 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively. Bars mean SE (n=5). Different letters indicate significant differences among treatments at the same stage (P<0.05).

Table 5 Effects of straw return amount and nitrogen rate on winter wheat–summer maize annual yield and its components

Year	Treatment[1)]	Winter wheat				Summer maize			
		Spike no. ($\times10^6$ ha^{-1})	Grains per spike	1,000-kernel weight (g)	Grain yield (kg ha^{-1})	Harvested ears (ear ha^{-1})	Grains per ear	1,000-grain weight (g)	Grain yield (kg ha^{-1})
2020	SN	5.44 a	48.1 b	38.7 a	10,129.0 a	62,555.6 ab	570.9 ab	375.4 a	13,404.5 a
	S-15%N	5.31 ab	49.4 a	37.8 b	9,909.6 ab	62,000.0 b	574.9 a	377.2 a	13,444.2 a
	S-30%N	4.87 d	48.5 ab	38.2 abc	9,022.7 cde	61,722.2 b	572.2 ab	365.2 d	12,899.8 bc
	1/2SN	5.42 a	48.8 ab	38.1 ab	10,092.0 a	62,388.9 b	573.9 a	374.3 a	13,400.5 a
	1/2S-15%N	5.13 c	48.6 ab	38.2 ab	9,519.3 b	62,222.2 b	566.0 bc	373.5 ab	13,153.4 b
	1/2S-30%N	4.99 cd	48.3 ab	38.3 ab	9,231.0 cd	61,777.8 b	560.2 c	369.2 c	12,777.5 c
	CK	5.20 b	48.5 ab	36.2 c	9,146.6 c	63,305.6 a	548.7 d	370.3 bc	12,891.9 bc
	CK-15%N	4.89 d	46.9 c	37.0 c	8,494.8 d	62,222.2 b	543.0 de	374.3 ab	12,644.5 c
	CK-30%N	4.54 e	48.4 ab	37.3 cd	8,196.2 f	62,111.1 b	540.0 e	368.3 cd	12,353.6 d
2021	SN	3.84 abc	57.9 b	40.4 d	8,990.4 a	63,364.8 bcd	584.1 a	299.7 a	11,089.7 a
	S-15%N	3.80 bcd	57.4 b	41.0 bc	8,935.8 a	63,263.9 cd	583.4 a	299.0 a	11,032.8 a
	S-30%N	3.80 bcd	53.0 c	40.7 cd	8,188.9 b	62,959.7 de	566.7 b	294.6 a	10,511.1 b
	1/2SN	3.89 a	58.6 a	39.4 e	8,996.6 a	63,888.9 ab	580.4 a	299.1 a	11,092.4 a
	1/2S-15%N	3.86 ab	51.0 d	40.4 b	7,947.3 b	62,655.4 e	544.7 d	288.0 b	9,828.7 d
	1/2S-30%N	3.77 cd	50.9 d	41.1 ab	7,884.1 c	63,816.1 abc	532.4 e	276.1 cd	9,381.7 e
	CK	3.80 bcd	52.5 c	39.3 e	7,829.4 c	64,014.6 a	553.5 c	281.3 c	9,967.3 d
	CK-15%N	3.76 d	50.7 d	40.5 cd	7,721.0 d	63,683.9 abc	532.5 e	274.9 d	9,322.0 e
	CK-30%N	3.63 e	47.9 e	41.4 a	7,203.5 e	63,442.5 bcd	513.9 f	266.7 e	8,695.0 f

[1)] SN, S-15%N, and S-30%N represent full straw return plus N application rates of 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively; 1/2SN, 1/2S-15%N, and 1/2S-30%N represent half-quantity straw return plus N application of 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively; CK, CK-15%N, and CK-30%N represent no straw return plus N application at 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively. CK, no-return treatment.

Different lowercase letters in a column indicate significant differences among treatments (P<0.05).

the risk of N_2O emissions. In particular, the numbers of bacteria involved in the aerobic_ammonia_oxidation and nitrate_respiration processes were significantly and positively correlated with cumulative emissions of N_2O from the soil. The soil available N content was significantly and positively correlated with crop N accumulation, PoNAA, and PoNAC, which indicated that straw return to the field increased the crop aboveground N accumulation, especially the post-flowering N accumulation and translocation, by increasing the soil available N content. PoNAA and PoNAC were positively correlated with yield and NNI, while PrNTC was significantly negatively correlated with yield and NNI. This further suggests that the yield-increasing effect of straw return is mainly achieved by increasing nitrogen accumulation after crop flowering and stabilizing nitrogen nutritional status in the late reproductive stage of the crop, which in turn leads to increased yields. However, straw return is detrimental to pre-flowering nitrogen accumulation and pre-flowering nitrogen transfer to the seed.

In addition, a pathway analysis was conducted to understand the relationships between soil physicochemical properties, soil microbial functional flora, crop yield, crop nitrogen accumulation and utilization, and cumulative N_2O emissions (Fig. 12). The results indicate that soil physical properties directly affect the content of soil organic matter, which directly reflects the community of microorganisms associated with the soil nitrogen cycle. This study also confirmed that the soil microbial community affects aboveground crop nutrient accumulation and cumulative soil N_2O emission fluxes. Dry matter accumulation and post-flowering nitrogen accumulation directly affect crop yield. Yield and cumulative soil N_2O emission fluxes simultaneously affected crop nitrogen utilization, where the effect of cumulative N_2O emission fluxes was negative. In summary, straw return with N fertilization increased the crop above-ground N uptake, especially post-flowering N uptake, and consequently increased crop yields by improving soil physicochemical properties and increasing the community of nitrogen-cycling microflora, but there was also a risk of increasing the cumulative N_2O emission fluxes.

4. Discussion

4.1. Summer maize straw retention coupled with N fertilizer improves soil physicochemical properties and increases crop yield

Straw return to the field can effectively reduce soil bulk density and improve soil water, fertilizer, air, and heat, thus providing a better soil physical environment for crop productivity (Gao *et al.* 2020; Cui *et al.* 2021; Wang *et al.* 2024). However, studies on different maize straw return rates and N application rates are relatively rare. This study found that the physical properties, SOM, and available N content of the topsoil (0–20 cm) were significantly affected by straw return and N application (Fig. 11). As a low-density returned material, the organic matter released by straw decomposition can be closely complexed with the minerals in the soil, resulting in the improvement of soil physical properties, thus increasing the SOM and available nutrient contents, and favoring the accumulation and transfer of N in the winter wheat-summer maize (Cui *et al.* 2021; Yuan *et al.* 2022; Zhang X T *et al.* 2023; Meng *et al.* 2024). At the wheat and maize maturity stage, the dry matter accumulation and yields of the SN, S-15%N, and 1/2SN treatments were significantly higher than the other treatments. Correlation analysis showed that this might be related to the higher soil available N content with N fertilization with straw. An adequate nutrient supply is favorable for maintaining higher PoNAA in crops,

Table 6 Effects of summer maize straw return amount and nitrogen rate on annual nitrogen utilization in winter wheat and summer maize[1)]

Year	Crop	Treatment[2)]	NHI	UPE (kg kg^{-1})	UTE (kg kg^{-1})	NUE (kg kg^{-1})
2020	Wheat	SN	0.66 e	78.6 d	35.6 f	27.9 f
		S-15%N	0.70 d	90.0 a	36.1 f	32.5 c
		S-30%N	0.73 c	87.1 b	39.4 e	34.3 b
		1/2SN	0.65 e	82.5 c	33.9 g	28.0 f
		1/2S-15%N	0.76 b	75.1 de	42.1 d	31.6 d
		1/2S-30%N	0.88 a	71.8 e	47.9 b	34.4 b
		CK	0.65 e	59.2 h	41.9 d	24.8 g
		CK-15%N	0.66 e	65.4 g	45.2 c	29.5 e
		CK-30%N	0.67 de	67.5 g	51.0 a	34.8 a
	Maize	SN	0.74 a	75.9 cd	41.7 e	31.6 g
		S-15%N	0.72 bc	97.1 a	44.2 e	42.9 c
		S-30%N	0.70 cd	95.4 ab	49.4 d	47.0 a
		1/2SN	0.73 ab	90.7 b	42.8 e	38.8 e
		1/2S-15%N	0.70 cd	77.1 cd	56.2 c	43.3 c
		1/2S-30%N	0.71 cd	79.4 c	60.3 b	47.9 a
		CK	0.70 cd	72.1 de	52.1 d	37.6 f
		CK-15%N	0.69 d	70.1 e	58.7 bc	41.2 d
		CK-30%N	0.67 e	56.5 f	80.0 a	45.2 b
2021	Wheat	SN	0.67 e	70.5 d	37.6 f	26.5 g
		S-15%N	0.72 bc	81.9 b	38.3 f	31.4 d
		S-30%N	0.71 c	84.2 a	40.7 e	34.3 b
		1/2SN	0.71 c	70.7 d	40.1 e	28.4 f
		1/2S-15%N	0.74 b	68.4 e	42.0 d	30.7 e
		1/2S-30%N	0.80 a	78.7 c	44.3 c	34.8 a
		CK	0.69 d	61.5 h	39.9 e	24.6 h
		CK-15%N	0.72 bc	64.5 g	47.1 b	30.4 e
		CK-30%N	0.72 bc	66.8 f	49.2 a	32.8 c
	Maize	SN	0.71 c	56.0 b	55.5 f	31.0 f
		S-15%N	0.76 ab	65.8 a	56.3 f	36.9 b
		S-30%N	0.75 b	61.9 a	65.5 d	40.4 a
		1/2SN	0.77 ab	52.7 b	59.0 ef	31.1 f
		1/2S-15%N	0.77 ab	53.2 b	62.7 de	33.3 d
		1/2S-30%N	0.79 a	55.2 b	63.4 de	35.0 c
		CK	0.70 c	37.8 c	75.0 c	28.3 g
		CK-15%N	0.69 c	40.1 c	80.1 b	32.1 e
		CK-30%N	0.69 c	40.5 c	87.0 a	35.2 c

[1)] NHI, nitrogen nutrition index; UPE, nitrogen uptake efficiency; UTE, nitrogen utilization efficiency; NUE, nitrogen use efficiency.

[2)] SN, S-15%N, and S-30%N represent full straw return plus N application rates of 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively; 1/2SN, 1/2S-15%N, and 1/2S-30%N represent half-quantity straw return plus N application of 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively; CK, CK-15%N, and CK-30%N represent no straw return plus N application at 210, 178.5 (15% N reduction), and 147 kg ha^{-1} (30% N reduction), respectively. CK, no-return treatment.

Values followed by different lowercase letters in a column indicate significant differences among treatments (P<0.05).

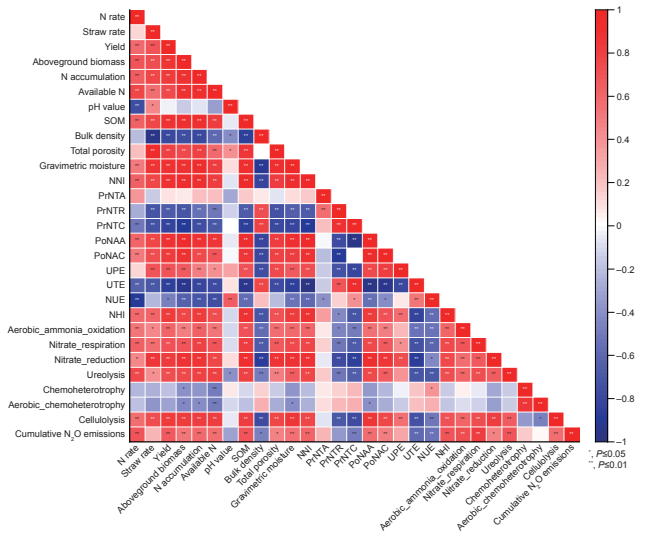


Fig. 11 Calculated Pearson correlation coefficients (*r*) for straw rate, N rate and other measured parameters. SOM, soil organic matter content; NNI, nitrogen nutrition index; PrNTA, pre-anthesis nitrogen translocation amount; PrNTR, pre-anthesis nitrogen translocation rate; PrNTC, contribution rate of pre-anthesis nitrogen translocation amount to grain; PoNAA, post-anthesis nitrogen accumulation amount; PoNAC, contribution rate of post-anthesis N accumulation amount to grain; UPE, nitrogen uptake efficiency; UTE, nitrogen utilization efficiency; NUE, nitrogen use efficiency; NHI, nitrogen harvest index.

which in turn increases the PoNAC and yield of crops (Fig. 11) (Yan *et al.* 2022; Liu *et al.* 2023).

The physical properties and crop yields of SN and 1/2SN were not significantly different and significantly higher than those of CK when the N fertilizer rate was 210 kg ha^{-1}. In contrast, the straw-return treatments were significantly lower than SN when the N fertilizer rate was reduced by 30%. This suggests that the amount of N fertilizer applied is an important factor limiting the improvement in soil physical properties and crop yield increase by straw return (Gao *et al.* 2023). This occurs because the maize straw C:N ratio is significantly higher than the soil C:N ratio, so N fertilizer application directly improves the soil C:N ratio, which in turn affects the rate of straw decomposition (Li *et al.* 2024). When the N application rate was reduced by 15%, the physical properties and yield of S-15%N were not significantly different from those of SN, while they were significantly reduced in the 1/2S-15%N treatment, which indicates that the physical properties of soil and the crop growth are not only affected by the nitrogen application rate, but also by the amount of straw returned to the field (Lin *et al.* 2025). The correlation analysis results are also consistent with other studies (Ventrella *et al.* 2016). Notably, the whole straw treatment did not show an exponential increase in SOM compared to the long-term, half-volume straw return. This may reflect the vulnerability of decadal SOM to the increase in the amount of exogenous C, which weakens the soil C sink, whereas reducing the frequency of carbon input suppresses the SOM priming (Zhou *et al.* 2022).

4.2. Optimizing straw return and N fertilizer application can improve nitrogen utilization and reduce soil N_2O emissions

Straw return with N fertilization is an important measure for ensuring soil quality and sustainable use. As the amount of straw returned to the field and the amount of N applied increased, the soil properties improved significantly, but this combination also increased N_2O emissions which reduced the NHI, UTE and NUE in the winter wheat-summer maize system (Wang *et al.* 2021; Chen *et al.* 2023). In this study, N_2O emissions were significantly higher in the maize season

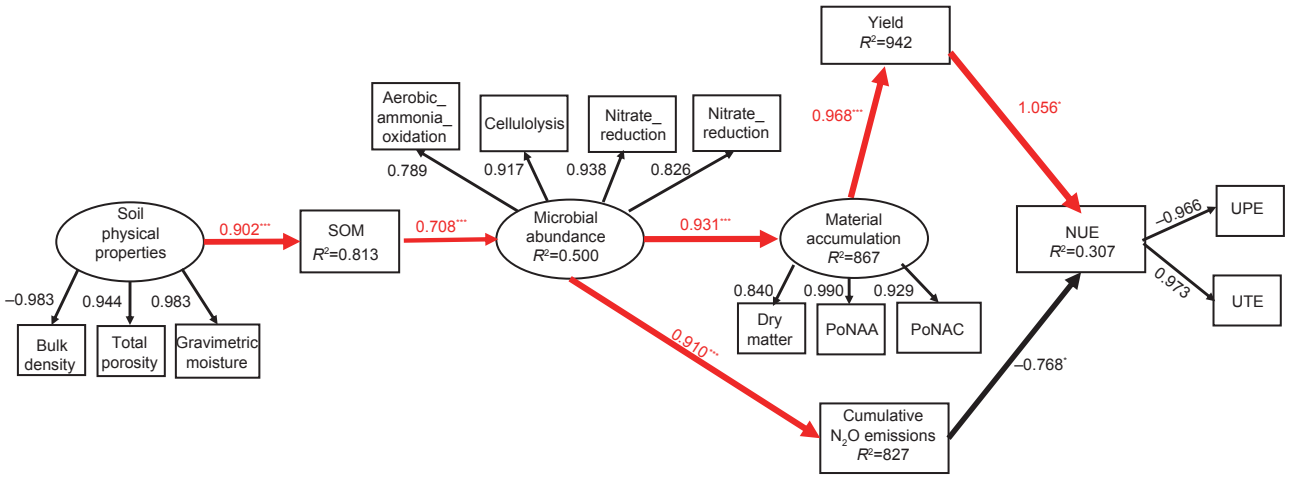


Fig. 12 Structural equation simulation of the effects of improved soil properties on yield, cumulative nitrous oxide emissions, and crop nitrogen use in a wheat–maize cropping system. SOM, soil organic matter; PoNAA, post-anthesis N accumulation amount; PoNAC, contribution rate of post-anthesis N accumulation amount to grain; NUE, N use efficiency; UPE, N uptake efficiency; UTE, N utilization efficiency. Boxes and ellipses indicate the explicit and latent variables included in the model, respectively, and the numbers adjacent to the arrows are standardized path coefficients and factor loading coefficients. The proportion of variance explained (R^2) appears with each dependent variable in the model. Red arrows for path coefficients indicate positive pathways and black arrows indicate negative pathways. The width of each arrow indicates the strength of the standardized path coefficient. Asterisks next to path coefficients indicate *P*-values. *, $P<0.05$; ***, $P<0.001$.

than the wheat season, mainly due to maize straw return and meteorological factors. Since the NCP region has a temperate monsoon climate (Hao *et al.* 2024), the high temperatures and rainfall during the maize season are more favorable for soil microbial activity, especially the nitrate_reduction and aerobic_ammonia_oxidation flora involved in nitrification and denitrification processes, as compared to the wheat season (Fig. 10). Nitrogen fertilizer application provides sufficient energy for microbial activity, and straw containing readily decomposable organic carbon improves the effectiveness of alkaline N decomposition in the soil by increasing the activity of soil microorganisms, as well as increasing N_2O emissions (Xu *et al.* 2016). The results of this study showed that the amount of maize straw returned to the field and the amount of nitrogen applied affected the SOM content, so the unstable organic substrate drove the increase in the community of microorganisms related to soil nitrogen metabolism, which in turn led to the higher emission of N_2O (Fig. 11) (Shakoor *et al.* 2020). Therefore, the straw-return treatment increased the cumulative N_2O emission flux as compared to the no-straw-return treatment. In addition, UPE and NUE were significantly higher in the straw-return treatment than in the no-straw-return treatment, while UTE was significantly lower. This occurred because at the same N application rate, the straw returned to the field increased the soil effective N content (Fig. 5), which increased the aboveground N accumulation of winter wheat-summer maize and improved the yield (Fig. 6; Table 5). However, the reduction in UTE indicated that straw return reduced the conversion capacity of nitrogen from the aboveground nutrient organs to seeds (Table 4) (Gao *et al.* 2022b). Note that while straw return with N fertilizer increases GHG emissions, it also enhances SOM storage, which may offset the GHG emissions to some extent (Zhang *et al.* 2021). SOM sequestration has been recognized as a win-win measure to reduce GHG emissions, ensure food security and improve agricultural sustainability.

Optimizing the amount of straw returned to the field and the amount of N applied according to the actual nutrient status of the crop is very important for improving crop yield and N utilization (Liu *et al.* 2023; Yang *et al.* 2024). The correlation analysis indicated that the amount of straw returned to the field and the amount of N applied were significantly and positively correlated with the NNI. The NNI of SN was greater than "1" in winter wheat after flowering and throughout the reproductive period of summer maize, indicating that the crop had an N surplus. This may have been due to the higher level of N supply from the full amount of straw returned to the field based on 210 kg ha^{-1} of N application, resulting in a lower NUE and higher N_2O emissions (Yin *et al.* 2018; Li *et al.* 2021). The NNI of S-15%N and 1/2SN were near "1", indicating that crop N nutrition status was the best, so the soil N supply could meet crop growth needs, and a crop N accumulation surplus would not occur (Liu *et al.* 2023). In addition, the S-15%N and 1/2SN treatments reduced the cumulative N_2O emission fluxes by 19.11 and 5.51%, respectively, compared to the SN treatment by reducing the amount of either N fertilizer or straw returned to the field. The N_2O emissions were significantly lower in the S-15%N treatment compared to SN, which was mainly due to the reduced application of nitrogen fertilizer and lower nitrogen fertilizer losses through NH_3 volatilization, NO_3 leaching, and N_2O emissions (Zhang *et al.* 2019; Yao *et al.* 2021). The cumulative N_2O emission flux was significantly reduced in the 1/2SN treatment compared to the SN treatment. This may be attributed to the significant reduction in the soil alkaline dissolved nitrogen content, which is a key factor in reducing N_2O emissions (Fig. 5) (Zhang *et al.* 2023). These two treatments (S-15%N and 1/2SN) stabilized crop yields and increased soil SOM storage while further offsetting N_2O

emissions to some extent. Therefore, from the perspective of ecosystem sustainability and greater nitrogen use efficiency, S-15%N and 1/2SN can be good decision options for promoting cleaner production in the wheat-maize systems.

However, in this study, the main focus was investigating the abundance of bacterial taxa during the soil maturation period rather than describing their dynamics during the reproductive period of the crop, which prevented us from obtaining a full picture of the patterns of variability in soil bacterial taxa. Therefore, future studies should fully consider the variability of soil microbial communities in the time dimension. In addition to this limitation, we only analyzed the total SOM and did not investigate the contents of different types of organic matter. The effects of straw return and nitrogen application on the contents of different types of organic matter at different times still need to be further explored.

5. Conclusion

The results of an experiment in four consecutive seasons showed that optimizing summer maize straw return and N fertilizer significantly improved soil quality, increased the community of soil nitrogen metabolizing functional microorganisms, increased the aboveground nutrient accumulation and translocation in winter wheat–summer maize, and further improved yield and N utilization. However, straw return with N fertilizer also increased N_2O emissions. The SN, S-15%N and 1/2SN treatments increased aboveground dry matter quality and yield. However, S-15%N and 1/2SN reduced N_2O emissions and improved crop N uptake efficiencies under appropriate N nutrient conditions (indicated by NNI close to "1"). Therefore, either of the 1/2SN or S-15%N treatments are recommended as management practices to optimize straw return in winter wheat–summer maize systems. This is important for improving soil physicochemical properties, reducing greenhouse gas emissions, and increasing the utilization of straw and N fertilizer in summer maize.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that they did not use AI in the preparation and writing of this manuscript.

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