Straw return enhanced soil carbon and nitrogen fractions and nitrogen use efficiency in a maize-rice rotation system

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Abstract

Considering straw resource utilization and air pollution prevention, straw return has been commonly practiced in China. However, the practicability of plenty straw return in an emerging maize-rice rotation and their effects on soil C and N pools have not been extensively investigated. This study was to examine effects of straw return on soil nutrients, soil functional C and N fractions, then to figure out their relationships with yield and N use efficiency. Two treatments of straw return (S2Nck) and without straw return (S0Nck) were compared in 3-year field experiment, and subplots without N application were added in their respective plots in the third year. The results showed that, relative to the control (S0Nck), straw return significantly increased soil mineralized nitrogen (Nmin), available P, and exchange K content by 11.7%, 41.1%, and 17.4% averaged across 3-year experiment, respectively. Straw return substantially increased soil dissolved organic C (DOC), microbial biomass C (MBC), and microbial biomass N (MBN) content by 73.0%, 25.2%, and 36.8%, respectively. Furthermore, straw return markedly increased C and N retention in particulate organic matter in microaggregates (iPOM) and mineral associated organic matter within microaggregates (intra-SC), but significantly reduced in free mineral associated organic matter (free-SC) fraction. The structural equation modeling analysis showed that yield and the partial factor productivity of N (PFPN) were positively correlated with labile and slow soil C and N fractions. Consequently, straw incorporation significantly increased grain yields of maize by 14.7% and rice by 15.1%. The annual potential reduction proportion in fertilizer-N induced by straw return (PRP) was estimated to 25.7% in the third year. This study suggests that incorporation of straws is an effective way to enhance soil nutrients and regulate soil C and N pools to improve crops production and has the potential to reduce N fertilizer application under maize-rice rotation in subtropical regions.

Introduction

Crop straw, a by-product of agriculture, is rapidly increasing with crop production (Yin et al. 2018). China is reported to produce about 1.04 billion tons of crop straw annually, accounting for nearly 30% of the global (Li et al. 2017). Purposely to prevent air pollution by straw burning and to reuse its nutrients, incorporation of crop straw to the soil as fertilizer has become the most widely adopted method in China (Li et al. 2018). Studies have showed that return of crop straw to the field is an effective and economically sound management practice to address cropland productivity degradation under the practices of intensified conventional tillage and high nitrogen input for food production (Majumder et al. 2008; Liu et al. 2010; Xia et al. 2018; Huang et al. 2019). Straw return can increase crop yield by supplying mineral elements, improving soil physicochemical properties and regulating soil microbial activity (Majumder et al. 2008; Turmel et al. 2015; Zhang et al. 2017; Guo et al. 2017). However, these effects vary depending on conditions like straw quality, soil properties, climate conditions, straw returning method and cropping types (Gentile et al. 2009; Soon and Lupwayi 2012; Tian et al. 2019). Apparently, straw returning is a comprehensive practice to intervene in the soil ecological processes of farmland, particularly the soil C and N cycle. How straw incorporation influences soil C and N fractions, and then affects crop yield and N fertilizer utilization efficiency remains to be further addressed, especially under the double cropping with large amounts of straws.

Carbon sequestration by soils is widely concerned for its helps in mitigating climate change and improving soil fertility (Wiesmeier et al. 2014). Straw incorporation was extensively reported an important practice to increase and maintain soil organic carbon (SOC) (Liu et al. 2014; Huang et al. 2019). Besides as an important source of SOC in farmland, incorporation of crop straw into the field can compound the soil particles and promote the formation of soil aggregates (Zhao et al. 2018), thus may change SOC distribution in different functional fractions (Huang et al. 2018; Zhao et al. 2018). Some studies reported that the incorporated straw had profound influence on active SOC fractions, such as dissolved organic carbon (DOC), microbial biomass carbon (MBC) and free particulate organic matter (fPOM) fraction (Jagadamma and Lal 2010), and these active SOC fractions could be increased by 27.4−56.6% according to a meta-analysis (Liu et al. 2014). Other reports showed that straw return even enhanced slow and passive SOC fractions (such as intra-aggregate particulate organic matter, iPOM, mineral-associated matter, mSOM) (Huang et al. 2018; Zhao et al. 2018), indicating that straw input is conducive to sequestration and stability of SOC (Six and Paustian 2014). However, more studies are needed to fully clarify the complicated influence of straw return on SOC pools due to the process is regulated by various factors (Zhao et al. 2018) and to support SOC stability assessment under different cropping systems in different regions.

Considering the tightly coupled biogeochemical cycles of C and N in soil (Luo et al. 2006), N dynamics are also strongly influenced by straw return, depending mainly on soil properties, climatic conditions and straw quality (e.g. C:N ratio) (Chen et al. 2013). Straw return can promote soil microorganism activities and N fixation by altering soil structure, moisture, soil total C and C/N ratio (Zhang et al. 2014; Li et al. 2019). Recent studies showed that straw return could release additional N into the soil, increase N retention, reduce N leaching and improve N storage in the soil (Yang et al. 2015; Huang et al. 2021). Straw return was also reported an improvement in soil particulate N, available N content and total N content by 80%, 27.5% and 10.8% respectively (Zhang et al. 2016; Cui et al. 2022), which indicates higher N retention capability induced by straw return. Likewise, Desrochers et al. (2020) demonstrated that straw return can increase the soil particulate C and N content, which may be the key to improving the long-term sustainability of intensive farming. Even though, a meta-analysis showed that straw return increased net reactive N losses due to enhancement on denitrification and a greater stimulation of NH_3 emissions (Xia et al. 2018). It could be deduced that changes in soil N fractions under straw return have close relations to soil N retention potential and N use efficiency, however, few studies have tackled such knowledge gap leading to weak support for rational N fertilizer application under a specific cropping system.

Maize (*Zea mays L.*)-rice (*Oryza sativa L.*) cropping system has been developing in tropical and subtropical Asia (Sun et al. 2019). Under this double-crop rotation, large amounts of straw are produced due to higher productivity of maize and rice, which is a challenge of straw return for farmers. Furthermore, how straw incorporation of double crops affect soil C and N retention capacity and N use efficiency have rarely been tested under maize -rice rotation. Therefore, our objective was to clarify the effects of double-season straw return on soil C and N fractions and their causal effect on fertilizer N use efficiency for supporting the straw and nitrogen fertilizer management under maize-rice rotation.

Materials and Methods

Experimental site

The study was conducted in a paddy field from 2017 to 2019 in the town of Qujialing (30°50'N, 112°50'E), Hubei province, China. The study area belongs to a subtropical region, with an annual average daily temperature of 16.2°C and precipitation of 1140 mm over the last 30 years. The air temperature and precipitation during the experimental period were shown in Fig. S1. The average temperature was 22.4°C, 23.5°C and 21.9 °C across maize growing season, while was 23.4°C, 24.5°C and 25.0°C across rice growing season in 2017, 2018 and 2019, respectively. The accumulated precipitation was 454.3 mm, 571.9 mm and 636.4 mm across maize growing season, and was 339.7 mm, 98.4 mm and 81.4 mm across rice growing season in 2017, 2018 and 2019, respectively. The basic soil at 0–20 cm depth featured in pH 7.03, bulk density 1.27 g cm^{-3}, organic carbon 14.07 g kg^{-1}, total N 1.49 g kg^{-1}, total P 0.53 g kg^{-1}, total K 9.02 g kg^{-1}, available P 13.50 mg kg^{-1}, exchangeable K 201 mg kg^{-1}, soil NH_4^+ content 4.04 mg kg^{-1}, and soil NO_3^- content 4.95 mg kg^{-1}.

Experimental design and agronomic management

The field experiment was initiated in early November 2016 and ended in early November 2016. After the late rice harvest in 2016, the field was separated into 6 plots to implement maize -rice rotation in two treatments with three replications, including S0Nck (without straw return) and S2Nck (straw return from maize and late rice). The plot area was 133 m² surrounded by a 0.5 m wide ridge and a 0.5 m wide ditch. The maize -rice rotation went through 3 period in an annual cycle, including the fallow period (from early November to late March next year), maize grow season (from late March to late July) and late rice season (from late July to early November) as shown in Fig. S1. In the straw return plots (S2Nck), all of the the maize and rice straw were chopped into 5–10 cm pieces after harvesting and then were incorporated by rotary tillage into the 0–20 cm soil. Meanwhile, all leftover straws were manually cleared from the S0Nck plots. To test the fertilizer N use efficiency after a 2-year cycle of straw return, each plot of the treatment was separated into two subplots in 2019, one of them continued the previous treatment (S0Nck or S2Nck), and the other was used for the added treatment without N fertilizer application (S0N0 or S2N0). The amount of the returned maize and rice straw of each year were shown in Table S1. The biomass of the returned maize straw was assessed to 8.85 t ha^{-1}-9.19 t ha^{-1}, and the biomass of the returned rice straw was in range of 5.89 t ha^{-1}-7.09 t ha^{-1}.

Except for straw returning, other agronomic management practices in the plots followed local farmer's practices on maize-rice rotation. After land preparation using a small rotary tiller, spring maize of a local cultivar, Fengken139, was sown in late March each year at plant spacing of 22 cm and row spacing of 60 cm, followed immediately by spraying with herbicides to prevent weeds. Fertilizers of urea (46.0% N), calcium super phosphate (12.0% P_2O_5), and potassium chloride (60.0% K_2O) were used for both crops. According to the local practice, the fertilizer application rate for maize was 300, 90, and 135 kg ha^{-1} of N, P_2O_5, and K_2O, respectively. All of P was applied as basal fertilizer when field preparation before maize sowing. N fertilizer allocation is 40% for basal application, 20% at the 6-leaf stage and the remaining 40% at the 12-leaf stage. Half of the K was applied as a basal fertilizer for maize and the other half at the 12-leaf stage. The spring maize was harvested in late July, and then a base fertilizer was applied after soaking the plot land for 2–3 days. The late rice of a local cultivar, Tianliangyou953, was sown in late June for seedling culture and then was manually transplanted to the soaked plots after the land preparation by a small rotary tiller. The fertilizer application rate for late rice was 150 kg N ha^{-1}, 75 kg P_2O_5 ha^{-1} and 80 kg K_2O ha^{-1}, respectively. The 40%, 20% and 40% N fertilizer were applied at the seedling, tillering and booting stages of rice. The 50% of the K fertilizer was used as basal fertilizer and 50% at booting stage. 100% of the P was applied as basal fertilizer after the plot land preparation. No irrigation was practiced during the spring maize seasons. An alternating wet and dry irrigation was conducted during the rice growing stage. The late rice was harvested in early November each year, then the plot was plowed and left fallow in winter.

Plant biomass and grain yield measurements

At the full mature stage, five uniform maize plants or ten uniform rice plants were sampled at diagonal five points in each plot. The plant samples were oven-dried at 85°C to a constant weight to determine the dry matter weight. At the spring maize maturity, three diagonal sample sites were selected in each plot and the ears of 30 adjacent maize plants were collected from each site to determine grain yield. Three 3 m^2 subplots of each plot were harvested to determine the grain yield of late rice. The final yield was determined by adjusting air-dried maize and rice grain samples to 14% moisture content.

Soil sampling and measurements

Available soil nutrients

Soil samples (0–20 cm depth) were collected at five diagonal sites in each plot at rice harvest in each year. Some of the fresh soil samples were used to measure the inorganic soil N. The remaining soil samples were air dried for other measurements. Soil NH_4^+–N and NO_3^-–N were extracted with KCl (2 M) and then measured by colorimetry using flow injection analysis (Bran Luebbe, Germany). The mineralized nitrogen content (Nmin) was the sum of NH_4^+–N and NO_3^-–N content. Soil exchangeable K was extracted using 1 mol L^{-1} ammonium acetate, and measured with flame photometry (FP640, INASA Instrument, China). Soil available P was extracted using 0.5 M $NaHCO_3$ with pH 8.5, and measured using the molybdenum blue method.

Active soil organic C and N fractions: Soil at 0–20 cm depth was sampled at maize silking, rice heading in 2019 for measurements of dissolved organic C (DOC), dissolved organic N (DON), microbial biomass C (MBC) and microbial biomass N (MBN). Soil MBC and MBN content were analyzed with the CH_3Cl_3 fumigation-K_2SO_4 extraction method (Qiu et al. 2018). Briefly, fumigated (with ethanol-free chloroform in the dark for 24 h) and nonfumigated soil samples were extracted with 2 M K_2SO_4 for 1 h (soil/extractant ratio = 1:4). Then K_2SO_4 extracts were filtered through 0.45 μm filter membrane. The filtrates were measured by a TOC/TN analyzer (Shimadzu TOC-Vcsh, Japan). Then, the C and N concentration in the unfumigated soil samples filtrates were DOC and total dissolved N (TDN). The DON content was calculated by difference of TDN and inorganic N (sum of NO_3^-–N and NH_4^+-N). The MBC and MBN content were calculated by using the difference between the C and N content of the fumigated and unfumigated soil samples with a conversion factor (K_{EC}) of 0.45.

Isolation and measurements of soil particulate C and N fractions

Firstly, different soil aggregates were separated by using the wet-sieving method according to Yan et al. (2012). 50 g of the air-dried soil sampling at rice harvest in 2019 were immersed with deionized water for 5 min, then passed through the 250 μm sieve down to the 53 μm sieve. The separated soil particles, including large macroaggregates (> 250 μm, LM), microaggregates (250 – 53 μm, Mi), and free silt and clay (< 53 μm, free-SC), were dried to constant weight to weighing at 60 °C. Then, different particulate organic matter (POM) was further segregated from the different aggregates using a modified method of Six et al. (1998), Six et al. (2000), and Yu et al. (2012). The dried LM and Mi samples obtained above were shifted into 500 ml centrifuge bottles and immersed into 150 ml of 1.85 g cm^{-3} ZnBr solution. The bottles were shaken for 20 min, then centrifuged for 30 min at 2500 r/min. The precipitate from LM and Mi aggregates was rinsed out of the centrifuge tube and shaken for 18 h with 0.5% sodium hexametaphosphate solution. The samples were then thoroughly rinsed on a 53 μm sieve. The soil particulates above 53 μm sieve were the intra-microaggregate POM (iPOM, 250 – 53 μm), and the passing through particulates were the silt + clay sized fraction within microaggregates (intra-SC, < 53 μm). All fractions were dried at 60°C and weighed. The C and N content of each fraction was determined using the CHNOS elemental analyzer (Vario MAX, Elementar, Germany). The iPOM, and SC (intra and free-SC) fractions originating from the different aggregate size classes are considered to have different functional features in the SOM pool (Six et al. 1998). The iPOM represents the slow SOM pool, while, the intra-SC and free-SC were considered as the passive SOM.

Determination of straw degradation rate

After the maize and rice harvest in 2018, 80 g of straw pieces (crushed into small pieces smaller than 5 cm) were put into a 300 nylon mesh bag in the size of 20 cm×15 cm, which was buried 10–15 cm into the soil in the S2Nck plots. Samples were taken out on 30d, 63d, and 85d after burying for maize straw and on 35d, 60d, and 120d after burying for rice straw with three replicates. The samples were thoroughly rinsed and then dried at 80°C. The residues in the bag were completely taken out and weighed. The C and N content of one portion of the residues was determined using an elemental analyzer (Vario MAX, Elementar, Germany). Meanwhile, the residual was digested using the H_2SO_4–H_2O_2 method. Then, P concentration in the residual was measured using flow injection analysis (Bran Luebbe, Germany), and K concentration was determined with a flame photometer (FP640, INASA Instrument, China). Finally, C, N, P, and K release rates from straw were calculated according to changes in weight and nutrient concentration in the residues over the period of two adjacent sampling events.

Calculation of fertilizer N use efficiency and replacement proportion by straw N

The agronomic N efficiency (AE) and Partial factor productivity of N (PFPN) were calculated as follows:

$$\mathrm{AE}\left(\mathrm{kgkg^{-1}}\right)=\frac{(\mathrm{grainyieldinNapplicationarea}-\mathrm{grainyieldinnonnitrogenapplicationarea})}{\mathrm{Napplicationrate}}$$

(1)

$$\mathrm{PFPN}\left(\mathrm{kgkg^{-1}}\right)=\frac{\mathrm{grainyieldinNapplicationarea}}{\mathrm{Napplicationrate}}$$

2

In order to evaluate the enhancement effect on the N use efficiency by straw return, we proposed an index of the potential reduction proportion in fertilizer-N induced by straw return (PRP), which was calculated as the following:

$$\mathrm{Yieldincreasebyfertilizerapplication}\left(\mathrm{Yield\text{-}F,kgha^{-1}}\right)=\mathrm{maizeorriceyieldintheS0Ncktreatment}\text{–}\mathrm{maizeorriceyieldintheS0N0treatment}$$

(3)

$$\mathrm{Yieldincreasebystrawreturn}\left(\mathrm{Yield\text{-}F,kgha^{-1}}\right)=\mathrm{maizeorriceyieldintheS2N0treatment}\text{–}\mathrm{maizeorriceyieldintheS0N0treatment}$$

$$\text{Yield increase by straw return (Yield-F, kg ha}^{-1}\text{)} = \text{maize or rice yield in the S2N0 treatment} - \text{maize or rice yield in the S0N0 treatment}$$

(4)

$$PRP\ (\%) = Yield\text{-}S / Yield\text{-}F \quad (5)$$

Statistical analyses

Analysis of variance (ANOVA) was performed using randomized complete block or split-plot model by the Statistix 8.0 statistical package. The least significant difference (LSD) was computed to evaluate the differences between treatments at $p < 0.05$. Structural equation modeling (SEM) was performed with AMOS 7.0 software to reveal the relationships and interactions among soil C pool, N pool, yield, and PFPN. The general fit of the model was validated by indices including probability level (P), chi-square ($\chi 2$), comparative fit index (CFI), goodness-of-fit (GFI), and root square mean error of approximation (RSMEA).

Results

Biomass and grain yield

Straw return significantly promoted the dry matter accumulation at maturity and grain yield from 2017 to 2019 (Table 1). Compared to the no straw return treatment (S0Nck), the treatment with double crops straw return (S2Nck) significantly increased the dry matter of maize by 5.6%-17.0%, rice by 7.1%-14.2%, and annual dry matter by 9.4%-12.2% over the three years. Similarly, maize yield was greatly improved by 11.3%-17.7%, rice yield by 6.3%-20.6%, and annual yield by 8.8%-18.0% under S2Nck treatment. In 2019, both dry matters at maturity and yield in the S2N0 were also significantly higher than that of the S0N0 treatment, which proved that the basic productivity of soil N was enhanced after a 3-year straw return.

Table 1
Biomass and grain yield of crops under maize-rice rotation with different straw treatments treatment from 2017 to 2019

Year	Treatments	Dry matter at maturity ($t \cdot ha^{-1}$)			Grain yield($t \cdot ha^{-1}$)		
		Maize	Rice	Annual	Maize	Rice	Annual
2017	S2Nck	15.23 ± 0.07 a	14.20 ± 0.01 a	29.43 ± 0.06 a	7.41 ± 0.20 a	8.51 ± 0.04 a	15.92 ± 0.19 a
	S0Nck	14.04 ± 0.17 b	12.91 ± 0.44 b	26.95 ± 0.61 b	6.44 ± 0.06 b	7.05 ± 0.03 b	13.49 ± 0.06 b
2018	S2Nck	17.49 ± 0.22 a	15.06 ± 0.20 a	32.54 ± 0.41 a	9.65 ± 0.44 a	9.27 ± 0.22 a	18.92 ± 0.48 a
	S0Nck	14.95 ± 0.20 b	14.06 ± 0.28 b	29.01 ± 0.12 b	8.67 ± 0.13 b	8.72 ± 0.32 b	17.39 ± 0.40 b
2019	S2Nck	16.42 ± 0.36 a	13.70 ± 0.03 a	30.11 ± 0.06 a	8.58 ± 0.10 a	8.28 ± 0.16 a	16.86 ± 0.15 a
	S0Nck	15.54 ± 0.28 b	11.99 ± 0.62 b	27.52 ± 0.62 b	7.29 ± 0.17 b	7.00 ± 0.21 b	14.29 ± 0.20 b
	S2N0	9.25 ± 1.64 c	9.21 ± 0.62 c	18.46 ± 1.07 c	3.53 ± 0.20 c	6.38 ± 0.31 c	9.91 ± 0.23 c
	S0N0	7.01 ± 0.30 d	7.40 ± 0.45 d	14.40 ± 0.60 d	2.87 ± 0.31 d	5.38 ± 0.13 d	8.24 ± 0.19 d

Values are mean ± standard errors. Different letters in a column within the same year indicate significant differences at $p < 0.05$

Soil available N, P and exchangeable K

Significant effects on soil Nmin and available P were noted by the year, straw return treatment and also their interactions (Table 2). Straw return significantly increased soil Nmin content at rice harvest in 2018 and 2019, except for 2017. Compared with S0Nck treatment, S2Nck treatment had 10.01% and 18.78% higher in Nmin content in 2018 and 2019, respectively. An obvious increase in soil available P was also observed in S2Nck treatment, furthermore, it gradually increased with the years and had the increment of 41.04% averaged across the 3-year with the contrast to the S0Nck treatment. The straw incorporation significantly enhanced soil exchangeable K content in each year, but it showed no interaction with the application year (Table 2). Compared with S0Nck treatment, S2Nck treatment increased exchangeable K content by 17.41% averaged across the 3-year. Moreover, a declining trend in soil exchangeable K content was observed in S0Nck treatment, but did not occur in S2Nck treatment.

Table 2
Changes in Nmin, available P, and exchangeable K content in the 0–20 cm soil layer at rice harvest under different straw return treatments from 2017 to 2019

Year	Treatments	Nmin (mg kg^{-1})	Available P (mg kg^{-1})	Exchangeable K (mg kg^{-1})
2017	S2Nck	11.73 ± 0.10 de	19.83 ± 0.50 b	203.75 ± 2.78 a
	S0Nck	11.04 ± 0.12 e	14.38 ± 0.07 c	177.21 ± 0.76 c
2018	S2Nck	14.20 ± 0.44 c	20.31 ± 0.24 b	191.24 ± 1.65 b
	S0Nck	12.91 ± 0.28 d	14.54 ± 0.07 c	167.55 ± 3.21d
2019	S2Nck	24.98 ± 1.56 a	21.58 ± 0.23 a	198.00 ± 8.84 ab
	S0Nck	21.03 ± 0.55 b	14.82 ± 0.30 c	160.82 ± 2.08 d
Source of variation				
Year(Y)		**	*	*
Straw return treatment (S)		**	**	**
Y × S		**	*	ns

Values are mean ± standard errors. Different letters in a column indicate significant differences among different treatments at $p < 0.05$. * and ** refer to significance at $p < 0.05$ and $p < 0.01$, respectively. ns, not significant at $p < 0.05$

Active soil organic carbon and nitrogen fractions

The active soil organic C and N fractions at 0–20 cm depth were markedly enhanced by straw returning in the third year-cycle (Table 3). At maize silking and rice heading, the straw return treatments had significantly higher soil DOC and MBC than the treatments without straw return, with an increase of 73.0% and 25.2%, respectively, averaged over the two crop seasons. N application had significantly increased soil MBC at maize silking and DOC at rice heading, however, its effects on MBC and DOC were far lower than the straw return. The straw return also had greater effect on soil MBN than N application treatment, which had an increase of 36.8% averaged two sampling events. Conversely, N application had larger effects on soil DON than the straw return in both crop seasons, with an average increase of 157.0%. The straw return treatment only showed significant enhancement on DON at rice heading. Overall, the dissolved organic C and N were more susceptible to the straw return than the microbial biomass C and N.

Table 3
Active soil C and N fractions at 0–20 cm depth at maize silking and rice heading in 2019

Treatments	DOC ($mg\ kg^{-1}$)	MBC ($mg\ kg^{-1}$)	DON ($mg\ kg^{-1}$)	MBN ($mg\ kg^{-1}$)
At maize silking				
S2Nck	34.13 ± 2.60 ab	330.18 ± 24.33 a	18.61 ± 1.37 a	19.12 ± 2.35 a
S0Nck	29.69 ± 0.48 b	251.61 ± 2.51 bc	14.13 ± 1.20 a	13.25 ± 1.15 bc
S2N0	37.74 ± 3.99 a	274.54 ± 10.04 b	8.77 ± 1.67 b	14.54 ± 1.01 b
S0N0	22.83 ± 4.12 c	220.60 ± 18.97 c	5.61 ± 0.82 b	10.79 ± 2.26 c
Straw return (S)	**	**	ns	**
N application (N)	ns	*	**	**
S×N	*	ns	ns	ns
Increase by straw (%)	40.13	27.84	44.01	39.48
Increase by N application (%)	10.23	17.16	132.04	27.17
At rice heading				
S2Nck	51.23 ± 2.25 a	348.24 ± 37.84 a	27.93 ± 1.07 a	20.06 ± 1.45 a
S0Nck	27.22 ± 3.01 c	297.22 ± 11.19 ab	13.31 ± 0.90 b	15.62 ± 0.78 c
S2N0	38.77 ± 2.23 b	332.97 ± 12.88 a	11.16 ± 0.97 b	17.63 ± 1.11 b
S0N0	17.33 ± 4.40 d	259.93 ± 40.48 b	4.24 ± 0.81 c	12.63 ± 1.87 d
Straw return (S)	**	*	**	**
N application (N)	**	ns	**	**
S×N	ns	ns	**	ns
Increase by straw(%)	105.95	22.63	136.36	34.02
Increase N application(%)	44.60	9.47	181.87	18.80

Values are mean ± standard errors. Different letters in a column indicate significant differences among different treatments at $p < 0.05$. * and ** refer to significance at $p < 0.05$ and $p < 0.01$, respectively. ns, not significant at $p < 0.05$

Particulate soil carbon and nitrogen fractions

Significant improvement in soil particulate C and N fractions at 0–20 cm depth was observed at 2019 rice harvest under straw return treatments (Table 4). Compared to the control (S0Nck), S2Nck treatment significantly increased the mass proportion of iPOM and intra-SC in bulk soil, but significantly decreased mass proportion of free-SC fraction. Straw return obviously increased C content in intra-SC fractions by 21.2%, but greatly reduced it in iPOM and free-SC fraction by 9.5% and 23.9%, respectively. Discrepantly, N contents in particulate fractions under straw return were obviously decreased in iPOM fraction by 14.3%, while were markedly promoted in intra-SC and free-SC fraction by 16.9% and 15.3%, respectively. Comprehensively due to changes in mass proportion and C content, the C retention of S2Nck was greatly improved by 16.6% in iPOM and by 92.8% in intra-SC, but obviously decreased by 53.3% in free-SC fraction. For N retention, S2Nck resulted in notable enhancement of 84.2% in intra-SC and obvious reduction of 29.7% in free-SC.

Table 4
Particulate soil C and N fractions at 0–20 cm depth at rice harvest in 2019

Items	Treatments	iPOM	intra-SC	free-SC
Proportion in bulk soil (%)	S2Nck	86.58 ± 2.12 a	5.17 ± 0.65 a	7.65 ± 1.22 b
	S0Nck	66.88 ± 2.11 b	3.23 ± 0.72 b	12.49 ± 1.61 a
C content	S2Nck	10.91 ± 0.80 b	11.05 ± 0.85 a	10.60 ± 0.57 b
(g kg^{-1} fraction)	S0Nck	12.05 ± 0.44 a	9.11 ± 0.31 b	13.94 ± 0.75 a
N content	S2Nck	1.18 ± 0.05 b	1.28 ± 0.10 a	1.82 ± 0.03 a
(g kg^{-1} fraction)	S0Nck	1.37 ± 0.03 a	1.09 ± 0.04 b	1.58 ± 0.12 b
C retention	S2Nck	24263 ± 1798 a	1460 ± 85 a	2096 ± 445 b
(kg ha^{-1})	S0Nck	20811 ± 591 b	757 ± 150 b	4491 ± 530 a
N retention	S2Nck	2618 ± 156 a	169 ± 9 a	358 ± 54 b
(kg ha^{-1})	S0Nck	2370 ± 71 b	92 ± 24 b	509 ± 50 a

Values are mean ± standard errors. Different letters in a column indicate significant differences at $p < 0.05$

Fertilizer N use efficiency and replacement proportion by straw N

The fertilizer N use efficiency was significantly improved by straw return under maize-rice rotation in 2019 (Fig. 1). S2Nck had significant increases in AE in maize and resulted in higher annual AE by 14.3% compared to S0Nck (Fig. 1a). Meanwhile, PFPN of S2Nck was significantly promoted both in maize and late rice, and was annually increased by 15.2%. An assessment of the potential reduction proportion in fertilizer-N induced by straw return (PRP) is shown in Fig. 2. The PRP was significantly higher in the rice season than in the maize season. The annual PRP was 25.7% in 2019. This result indicates that it is possible to cut down fertilizer-N with straw return by more reduction for late rice and relatively less for spring maize under the context of the local practice.

Correlations among soil C pool, N pool, yield, and PFPN

Structural equation modeling analysis was performed to evaluate the correlations among soil C pool, N pool, yield, and PFPN (Fig. 3). The analysis showed that yield and PFPN were mainly positively correlated with soil labile C and N pool (DOC, DON, MBN and MBC), slow C and N pool (iPOM-C and iPOM-N). Straw return showed significant positive effects on the soil C and N pools, especially greater in labile pools. Although straw return significantly and positively promoted passive C and N pools (SC-C and SC-N), the passive C and N pools did not significantly affect yield and PFPN over the 3-year experimental cycle. Straw return may indirectly affect yield and PFPN by directly enhancing the labile and slow soil C and N pools in short-term period.

Discussion

Effect of straw return on soil available nutrients and grain yield

Straw returning greatly enhanced crop biomass and grain yields (Table 1) in our study, which is consistent with the findings of Chen et al. (2020). The average increase in yield over 3-year was 14.7% for maize and 15.1% for rice under straw return, which was higher than the average of 12.3% and 13.4% shown in the meta-analysis (Liu et al. 2014; Han et al. 2018). The general increase in yield was due to the boosting effect of straw return on maize and rice growth, and thus gained higher dry matter accumulation (Liu et al. 2017). Increased dry matter accumulation makes an overall contribution to the source-sink relationship in crop growth, which in turn ultimately benefits grain yield. However, some studies founded that straw return did not significantly increase yields (Mehmood et al. 2020), but can increase the yield stability (Zhang et al. 2021). Possible reasons for this are that the positive impact of straw return on yield can be influenced by environmental conditions and management practices, which are closely related to the straw decomposition status.

One of the major reasons for improvement on crop yield under straw return is the promotion in nutrient availability in the soil during the straw degradation (Yadvinder et al. 2010; Turmel et al. 2015; Guo et al. 2017). Our study observed significant increase in soil Nmin, available P and exchangeable K under straw return treatment during the three experimental years (Table 2). These results are according with most of the previous reports as shown in a review paper by Huang et al. (2021). Moreover, soil available N, P and K have significantly positive relationships with the crop yield (Huang et al. 2021). Notably, in comparison with the no straw return control, straw incorporation in our study had higher improvement effects on soil available N, P and K than those reported in previous studies in China (Huang et al. 2021). The variation in such effects might be related to environmental conditions, cropping system and management practice. Above all, higher air temperature and higher rainfall at our subtropic experimental site (Fig. S1) provided preconditions for fast degradation of maize and late rice straw (Tables 5, 6), as the similar previous finding (Huang et al. 2013). In current study, the rapid release of more than half of C, N, P and almost all of K from straw within 4-months favored nutrients supply for crop growth (Tables 5, 6). Moreover, the convenient soil conditions (higher soil temperature and moisture) during late rice growth period facilitated rapid degradation of maize straw than that of the late rice straw (Tables 5, 6). Our study also found that the release rates of maize straw C and N were obviously higher than those from straw oilseed rape and wheat straw which were observed during the similar period by Wang et al. (2022). This might be relevant to the lower C/N of maize rice which favors to soil micro-organisms activities. In addition, the late rice straw had been left to degrade within more than 4-month fallow period and had little impact on maize sowing and germination. The transplanting of late rice after maize straw return escaped the adverse effect on seed gemination as practical problems found in other cropping systems with straw return, such as rapeseed-rice rotation, wheat-rice rotation or wheat-maize cropping. These favorable conditions, to a certain extent, guaranteed reinforcing effect on yield induced by the enhancement of soil available nutrients under straw return.

Table 5
Elements retention in the maize straws and their released proportion in the buried bag during the late rice growing period in 2018

Elements in maize straws	**Total amount in the returned maize straws**	**Proportion of released element after burying (%)**		
	(kg ha^{-1})	**30 d**	**63 d**	**85 d**
C	4088.73 ± 245.04 a	41.85 ± 0.78 d	51.54 ± 0.87 d	60.48 ± 4.59 c
N	82.44 ± 6.44 c	61.11 ± 2.48 b	71.85 ± 0.91 b	79.85 ± 2.40 b
P	33.10 ± 1.36 d	52.59 ± 1.63 c	66.44 ± 0.60 c	78.84 ± 0.71 b
K	106.49 ± 8.93 b	74.23 ± 0.66 a	91.30 ± 0.88 a	95.27 ± 0.42 a

Values are mean ± standard errors. Different letters in a column indicate significant differences among different elements at $p < 0.05$

Table 6
Elements retention in the late rice straws and their released proportion in the buried bag during the fallow period between 2018 and 2019

Elements in rice straws	**Total amount in the returned rice straws**	**Proportion of released element after burying (%)**		
	(kg ha^{-1})	**35 d**	**60 d**	**120 d**
C	3115.01 ± 32.02 a	27.14 ± 1.62 b	38.86 ± 2.08 b	51.95 ± 2.91 b
N	58.33 ± 0.83 c	28.40 ± 1.33 b	34.81 ± 4.85 b	46.90 ± 1.23 c
P	27.54 ± 0.33 d	23.38 ± 0.96 c	33.14 ± 3.28 b	53.96 ± 2.79 b
K	81.79 ± 2.66 b	50.05 ± 3.51 a	89.36 ± 1.76 a	96.07 ± 0.28 a

Values are mean ± standard errors. Different letters in a column indicate significant differences among different elements at $p < 0.05$

Effect of straw return on active soil organic C and N fraction

Active soil C and N fractions are sensitive to agricultural management and are regarded as important indicators of soil C and N dynamics (Martínez et al. 2017). It has been well documented that straw return can significantly increase the soil active C and N fractions (Mi et al. 2019; Dai et al. 2021). This study had the similar findings that straw incorporation greatly increased the content of DOC, MBC, DON and MBN in the 0–20 cm soil layer compared to no straw return treatments (Table 3). The enhanced content was probably caused by the carbon and energy available during straw decomposition and enhanced microbial activity, which may facilitate the conversion of crop straw carbon to soil active organic carbon and inorganic nitrogen to DON (Recous et al. 1995; Powlson et al. 2012; Liu et al. 2014). Additionally, straw incorporation promoted maize and rice growth and increased crop residual biomass (Table 1). Xu et al. (2011) reported that additional DOC and DON could be imported into the soil through root exudation of unstable C and decomposition of dead roots. These provide a favorable substrate condition for the direct formation of a soil active organic carbon and nitrogen pool.

In our study, straw return played a more important role in enhancing DOC, MBC, and MBN, while N fertilizer application showed a greater contribution to DON (Table 3). Previous studies have shown that straw incorporation is more effective in increasing soil active carbon and nitrogen content than nitrogen fertilizer application alone (Li et al. 2019; Yu et al. 2020). These results are consistent with the present study. Compared with N fertilizer application, the better increasing effect on DOC, MBC and MBN content of straw return mainly derived from direct C and N inputs. Another reason could be that incorporation of straw improved the soil physicochemical properties, enhancing the crops absorption and conversion of organic N to mineralized N (Fan et al. 2017). Conversely, N fertilize application mainly increased soil DON and MBN, but had no significant effect on microbial community and soil organic C pools (Zhao et al. 2016). Overall, these observations indicate that straw return enhanced soil active C and N fractions under the maize-rice rotation system. This result is also supported by the correlation between straw return and the active C and N pools in the SEM analysis (Fig. 3). However, the markedly enhanced DOC and DON by straw return might increase risk of water eutrophication by leaching and drainage from the paddy. Some proper measures should be considered to alleviate such problems caused by the straw return.

Effect of straw return on particulate C and N fraction

The particulate fractions have different sensitivity and responsiveness to agricultural practices (Guo et al. 2019). Among them, iPOM is regarded as the slow fraction, intra-SC and free-SC as the passive fractions (Brown et al. 2014). Our study showed that soil mass, C, and N retention are mainly stored in the iPOM fraction, which is in line with Dou et al. (2016) who reported that the C in iPOM accounted for 65–87% of the SOC in afforested soils. Changes in C and N following the straw return differed between the particulate fractions (Table 4). Firstly, significantly higher soil masses proportion of iPOM and intra-SC fraction occurred after the straw return. The similar findings were found under maize-wheat double cropping system with straw return mode by Zhao et al. (2018). This may be because the entry of straw into the soil promotes microbial activity in these fractions, facilitating the compounding of straw residues and soil particles to form soil microaggregates (Zhao et al. 2018) in favor to separate more iPOM and intra-SC, and concurrently to significantly reduce mass portion of free-SC fraction (Table 4). However, C and N content in iPOM were significantly reduced by the straw return relative to the control (Table 4), which was inconsistent with the report by Zhao et al. (2019) on increase of C and N content in iPOM induced by straw return under maize-wheat cropping system. We inferred that the faster growing in mass of iPOM under straw return might bind more soil mineral in microaggregates and thus diluted C concentration in it in the present experimental conditions. Anyway, it needs further to be examined the reasons under such changes. Nonetheless, C and N stocks in iPOM fraction significantly increased by 16.6% and 10.4% under S2Nck treatment mainly due to greater increment in mass of iPOM fraction relative to the S0Nck treatment (Table 4). This finding is thoroughly in common with previous reports (Li et al. 2016; Zhao et al. 2019).

Both intra-SC and free-SC are passive C and N pools, but intra-SC is more stable than free-SC because of the combination of physical and chemical protection (Lal 2018). Silt and clay particles are the basic structural units of soil aggregates, where trends in C and N content are closely related to changes in the mass of microaggregates (Qiu et al. 2020). The C and N content and retention of intra-SC were enhanced after straw return, while free-SC was the opposite except for the N content (Table 4). In slight contrast to other studies, no effect on free-SC was observed despite increased C concentration in intra-SC by crop residues (Brown et al. 2014; Huang et al. 2018). The variation in C and N content was mainly associated with the mass of intra-SC and free-SC fractions after straw incorporation under our experiment (Table 4). Whereas, straw return reduced the mass and C and N retention of free-SC, probably due to the rapid decomposition of maize straw and the promotion of the binding of free silt-clay particles to organic molecules, forming micro- and macroaggregates (e.g. increase in mass of iPOM and intra-SC fractions). Collectively, the notably enhanced C and N storage in iPOM and intra-SC suggests a tendency for straw return to promote C and N sequestration. Furthermore, structural equation modeling demonstrated straw incorporation could substantially increase nitrogen use efficiency and yields through enhancing labile and slow soil C and N pools (Fig. 3).

Effect of straw return on NUE

Straw incorporation greatly increases the AE and PFPN for rice and maize (Fig. 1), similar to the research of Xu et al. (2018) and Chen et al. (2020). Previous reports have shown that straw return improved the soil N content and N uptake, and reduces the soil N leaching (Yang et al. 2015; Huang et al. 2021). Besides, the decomposition of straw released C, N, P, and K into the soil and improved the soil nutrient status (Tables 2, 5, 6), which in line with the report by Yadvinder et al. (2010). According to the SEM analysis (Fig. 3), straw return can increase the soil C and N pool thus further improving PFPN. These findings provided supports to reduce fertilizer application rate for maize-rice rotation. The estimated PRP for maize and rice was 12.5% and 61.5% of that of the conventional N application amount (Fig. 2). The higher PRP in rice season may be explained by the rapid decomposition of maize straw relative to rice straw and the significantly increase in DON and MBN (Table 3). Therefore, straw return has the potential to increase NUE and replace fertilizer N due to increased availability of soil N.

Conclusions

Straw return had a profound impact on grain yields and soil C and N fractions in a maize-rice cropping system. Over the three experimental years, straw return sustained the release of C, N, P, and K nutrients during the crop growing season, significantly improved available soil nutrients, and thus obviously increased grain yield in maize and rice. Meanwhile, straw return substantially enhanced soil DOC, MBC and MBN, markedly increased C and N storage in iPOM and intra-SC, which favored the enhancement of soil quality in maize-rice rotation systems. Furthermore, straw return was effective in improving the NUE of maize-rice rotation. Overall, this study presents that straw return enhances soil C and N fractions and thus increases NUE, and provides supporting for rational reduction in N fertilizer application coupling with straw incorporation under a maize-rice rotation in tropical or subtropical regions.

Declarations

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Author contributions

YW conducted soil particulate fractions measurements, data analyses and was the the primary author of the text. MQ performed field sampling and laboratory analysis; MZ was the PI on the grant that funded the study, who contributed to overall project design, implementation and the manuscript writing. TL and JY assisted in the experiment and data analysis. All authors read and approved the final manuscript.

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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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

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Figures

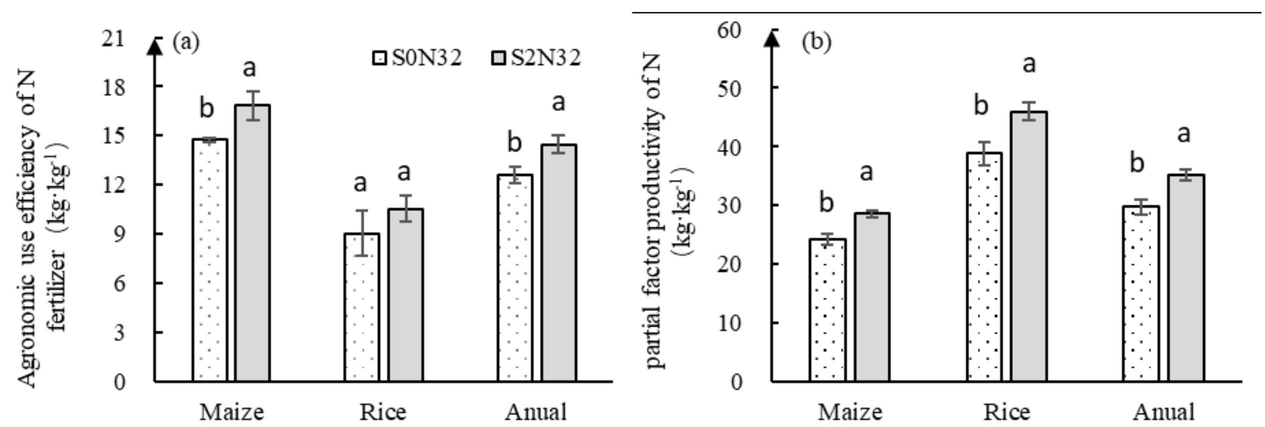

Figure 1

Agronomic N efficiency (a) and partial factor productivity of N (b) of crops under the maize-rice rotation in 2019. Error bars denote the standard error. Different letters above the column indicate significant differences among both treatments at *p*<0.05

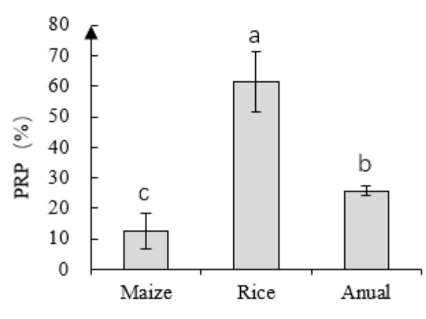

Figure 2

The potential reduction proportion in fertilizer-N induced by straw return (PRP) under the maize-rice rotation in 2019. Error bars denote the standard error. Different letters above the column indicate significant differences among different crop seasons at *p*<0.05

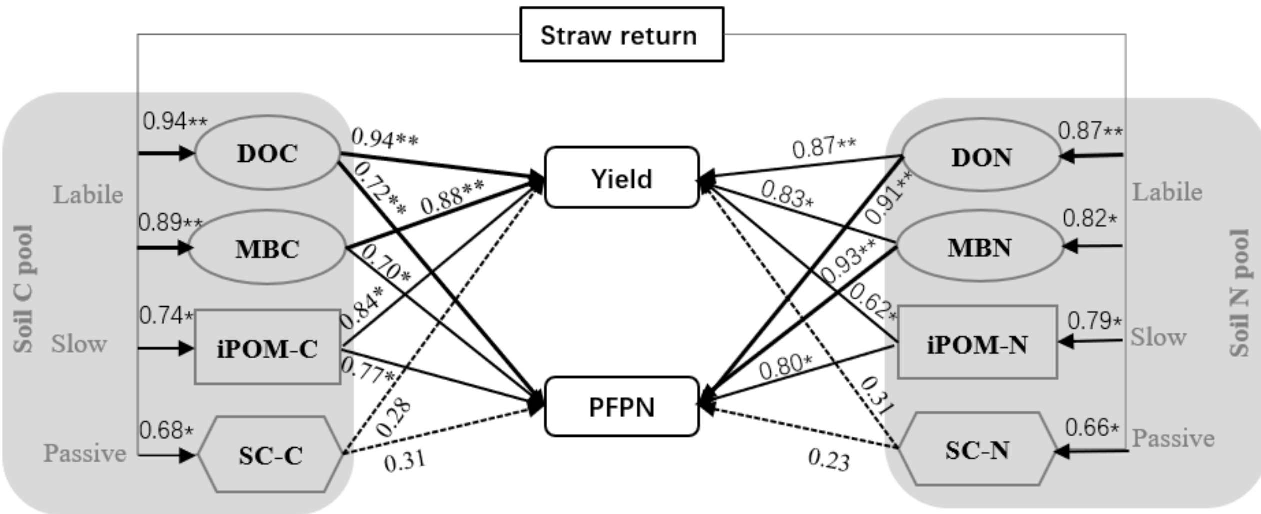

Figure 3

Structural equation modeling of the correlations among soil C pool, N pool, yield, and PFPN (χ^2 = 7.730; p = 0.388; CFI=0.969; GFI=0.933; RMSEA=0.04). The numbers listed above the arrows are the standardized path coefficients (*, $p \leq 0.05$ **, $p \leq 0.01$). The magnitude of each path coefficient is represented by the thickness of the arrow. PFPN, partial factor productivity of N; DOC(N), dissolved organic carbon (nitrogen); MBC(N), microbial biomass carbon (nitrogen); iPOM-C(N), intra-microaggregate POM-C(N); SC-C(N), silt and clay associated C(N)

Supplementary Files

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