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ORIGINAL PAPER

Maize Straw and Nitrogen Fertilizer Alter Soil Carbon and Nitrogen Mineralization during the Fallow Period in the Oasis Farmland area

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Abstract

Combining straw with nitrogen fertilizer is an important strategy that influences soil fertility and crop yield. N availability may further affect carbon mineralization (C_{min}) and nitrogen mineralization (N_{min}) in the soil by influencing the microbial decomposition of straw. The effects of straw return on carbon mineralization (C_{min}) and nitrogen mineralization (N_{min}), as well as the apparent soil organic carbon balance (C_{ab}) in agricultural fields at different nitrogen (N) levels, have not been widely studied in semi-arid oasis areas. Therefore, we conducted an incubation experiment in the Minqin oasis area to assess the soil C_{min}, N_{min}, and C_{ab} characteristics during the fallow period. A 141-day in-situ incubation experiment was established with the following six treatments: (i) soils were treated with low nitrogen (S0N1) or high nitrogen (S0N2) respectively; (ii) soils were treated without nitrogen (S1N0), low nitrogen (S1N1) and high nitrogen (S1N2) incorporated into maize straw respectively; (iii) soil only (S0N0, refer as CK). Nitrogen (N) sources came from urea ($CO(NH_2)_2$). The results showed that (1) Maize straw incorporation significantly increased soil cumulative C_{min} (6.83 g kg^{-1}) as compared to the non-straw application (1.01 g kg^{-1}) during 141 days of incubation. (2) Compared to S0N0, straw incorporated into N fertilizer (S1N0, S1N1, S1N2) significantly increased the potential mineralized carbon (C_0) content and mineralization rate (dC_{min}/dt) ($P < 0.05$), but the effect on potential N mineralization (N_0) appeared to be reversed, with N_{min} being more affected by N addition. (3) C_{ab} found a maximum in the S1N1 treatment (3.57 g kg^{-1}), which was five times higher than the treatment without added straw, 40% higher than in S1N0, and 46% higher than in S1N2, not proportional to the added N treatment. (4) Soil temperature and soil moisture contributed more to soil C_{min} and N_{min} during the fallow period, reaching 26.9% for C_{min} and 40.29% for N_{min}. It can be concluded that straw return incorporated into nitrogen will greatly affect soil carbon and nitrogen mineralization in the Minqin oasis area, which in turn affects soil nitrogen use efficiency and organic carbon balance.

Keywords Oasis area · Carbon mineralization · Nitrogen mineralization · Straw return · Nitrogen

1 Introduction

Crop straw, a carbon-rich, nutrient-dense agricultural waste, contains high levels of N, P, K, and micronutrient elements essential for crop growth (Jin et al. 2020; Li et al. 2019; Wang et al. 2020). Numerous studies have shown

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that the practice of straw return has a positive impact on increasing the storage of organic carbon and nitrogen in the soil (Bakht et al. 2009; Mao et al. 2023), protecting the ecological environment of farmland, enhancing the physical and chemical properties of soil, and ultimately leading to an increase in crop yield (Malhi et al. 2011). Straw return is becoming an increasingly popular method in China to prevent straw burning and air pollution.

Straw incorporation with nitrogen (N) fertilization is an important strategy influencing soil fertility and crop productivity. Previous studies have found that compared with sole straw incorporation or sole nitrogen fertilizer application, the combined application was more conducive to increasing soil organic carbon (SOC) sequestration (Meng et al. 2017) and improving crop yield and nutrient utilization (Su et al. 2014). This is mainly because the availability of nitrogen affects the microbial decomposition of straw, which may further affect carbon mineralization (C_{min}) and nitrogen mineralization (N_{min}) in the soil (Li et al. 2013; Raiesi, 2006). However, how exactly the interaction of the two affects soil C_{min} and N_{min} has been reported to depend largely on soil type (Muhammad et al. 2011). It also found that under the long-term input of crop residues combined with N fertilizer, SOC sequestration might decrease (Khan and Timney 2007) or remain unchanged (Abdalla et al. 2014) and affect crop growth and development (Kumar et al. 2018). Because crop straw, such as maize straw, has a high C/N ratio hindering the coupling of the straw and nitrogen fertilizer, leading to an imbalance in the soil C/N ratio (Li et al. 2019), increasing soil C_{min} (Li et al. 2017; Sui et al. 2022; Zang et al. 2016) and resulting in reducing SOC sequestration (Meng et al. 2021). C_{min} is also strongly related to N_{min} in the soil through the activity of the microbial reservoir and the C/N ratio of the substrate (Guo et al. 2018). Therefore, proper straw incorporation and nitrogen fertilizer management are crucial to improving fertilizer utilization and reducing N losses (Meng et al. 2021). In addition, most research on straw return and N fertilization has primarily concentrated on the growing season, neglecting the effects of unused N conversion and the impact on C_{min} during straw decomposition in the fallow period (Collier et al. 2017; Hou et al. 2012; Meng et al. 2021). Further research is needed to fully understand the impact of straw return and N fertilization on soil health and nutrient cycling during the fallow period.

The amount of organic carbon stored in soils is the net balance between the rate of soil organic carbon inputs and the rate of its mineralization (Rees et al. 2005). The apparent soil organic carbon balance (C_{ab}) can characterize the surplus of SOC in the farming system under straw return conditions, with values greater than 0 indicating an accumulation of SOC and vice versa, indicating a decrease in SOC (Lal 2015; Mamta et al. 2023). Optimizing agricultural management can increase soil carbon by increasing carbon inputs and/or decreasing carbon yields. Lu et al (2009) suggested that straw return and nitrogen fertilizer addition can sequester 5.96 and 9.76 Tg C per year, respectively. However, it has also been suggested that corn straw return may reduce crop yields due to nitrogen immobilization (Al-Kaisi et al. 2017), and that the added corn straw, as an available carbon substrate for soil microorganisms, increases soil CO_2 emissions (Fan et al. 2020), which in turn affects the C_{ab}. Furthermore, the findings of Nuria et al. (2017) indicate the need to incorporate fallow period cover crops to improve production systems. However, as an important part of carbon sequestration and emission reduction initiatives, C_{ab} has been relatively little studied by specific agricultural practices, and there are few studies related to fallow periods.

Minqin is located at the lower reaches of the Shiyang River and constitutes an indispensable part of the Hexi Corridor. It is a typical irrigated agricultural area in northwestern China (Zhang et al. 2022), soil nitrogen is generally high in this region, and tends to increase incrementally all the time. Moreover, there has been much controversy about whether straw is returned to the field in arid and semi-arid areas, and it is not yet known whether high nitrogen residues are beneficial to soil carbon and nitrogen mineralization and carbon sequestration after straw is returned to the field. In this region, most of the farmland has an idle period of 4–6 months after the current year’s crop harvest and before planting the next year's crop. There is a relative lack of research on soil C_{min} and N_{min} characteristics after straw return to the field during this period and apparent soil organic carbon balance after straw successive return to the field under different nitrogen levels. To fill this knowledge gap, the objectives of this study were to (i) assess the influence of straw return incorporated into different N levels on soil C and N mineralization characteristics during the fallow period, and (ii) determine the apparent soil organic carbon balance related to different N levels under straw return in the Minqin oasis area. The results of this study can provide a theoretical basis for nitrogen fertilizer reduction in semi-arid wind-eroded areas by exploring the trend of fertilizer application suitable for oasis areas through targeting the problems of high nitrogen fertilizer residue and increasing nitrogen fertilizer application year by year in oasis areas and combining with the practice of straw return to the field; as well as whether straw return to the field and moderate nitrogen application are beneficial to soil fertility enhancement and carbon sequestration through short-term experiments. We hypothesized that straw return with N fertilization would affect soil carbon and nitrogen mineralization and carbon surplus during fallow periods by influencing soil biological and geothermal conditions.

2 Materials and Methods

2.1 Study Sites

This study was conducted in Minqin County, Gansu Province, China (103º07′ 00.16″E, 38º37′10″N), which is located in the lower reaches of the Shiyang River basin in the Hexi Corridor and bounded by the Tenggeli and Badanjaran Deserts (Feng et al. 2011). With a mean annual temperature of 7.8℃, mean annual rainfall of 113.2 mm, most of which falls between July and September, and mean annual evaporation of 2,646 mm, the area is characterized by a typically arid continental climate. Uneven rainfall leads to severe seasonal dryness in spring and/or winter. The soils at the study site are irrigated desert soils according to the Chinese soil classification scheme (Gao et al. 2022) and similar to Anthropic Camborthids according to Soil Taxonomy (Jiang et al. 2017). Other relevant environmental conditions and agricultural production in the study area were described by Feng et al. (2011).

2.2 Experimental Design and Sampling

The simulated experiment was conducted in Minqin Oasis farmland from Oct 2018 to Feb 2019 after the maize was harvested. The collected moist samples (18% ± 5.82%) were ground and sieved through a 4-mm mesh (equal to 2.5 kg of dry weight), placed into a PVC incubation tube (the diameter is 20 cm, and the height is 15.5 cm), sealed the bottom of the PVC tube with a hard plastic plate, and then incubated in the local farmland for 141d. The experiment was set up with six treatments: (i) soils were treated with low N (S0N1) or high N (S0N2) respectively; (ii) soils were treated without N (S1N0), low N (S1N1) and high N (S1N2) incorporated into maize straw respectively; (iii) soil only (S0N0, referred to as CK). Each was replicated three times in a randomized block arrangement. The soil's basic physical and chemical properties are shown in Table 1. Straw from maize was crushed and screened until < 1 mm and corn stover was added at a uniform rate of 1% with the following physicochemical properties: pH 5.39; TOC 45.23%; TN 1.54%; P 0.31%; K 0.51%. The amount of exogenous carbon was added to simulate the number of maize stalks and roots remaining after the removal of above-ground stalks at maturity. Nitrogen was uniformly added from urea (46% N), of which low nitrogen was 50 mg kg^{-1}, high nitrogen was 200 mg kg^{-1}, and all treatments were uniformly added with 100 mg kg^{-1} P and 200 mg kg^{-1} K from $Ca(H_2PO_4)_2\cdot H_2O$ and KCl. The sampling periods were 0d, 7d, 14d, 21d, 51d, 81d, and 141d, and the soil auger was used for top-down penetrating sampling, and the samples were immediately refrigerated at 4 °C after processing for the determination of various physicochemical indexes.

Table 1 Basic physical and chemical properties of the soil before incubation

SOC (g kg^{-1})	TN (g kg^{-1})	AN (mg kg^{-1})	AP (mg kg^{-1})	AK (mg kg^{-1})	pH
7.35	0.51	25.22	12.26	127.93	8.40

The values of each index were taken from the mean of replicates ($n = 12$). *SOC* Soil organic carbon, *TN* Soil total nitrogen, *AN* Soil alkaline nitrogen, *AP* Soil fast-acting phosphorus, *AK* Soil fast-acting potassium

2.3 Soil Analysis

2.3.1 Analysis of Soil Physicochemical Properties and Enzyme Activity

Soil water content (SWC; %) was obtained by drying fresh soil samples taken at different incubation periods in an oven at 105℃ for 24 h. The pH of the soil was determined by shaking and mixing at a water-to-soil ratio of 1:2.5 and then using a pH meter (PHS-3C, Shanghai, China). Soil temperature (LT) was determined by a soil temperature tester (TPJ-21-G, Zhejiang, China) before soil sampling (Yuan et al. 2023a, b). The potassium dichromate oxidation method determined soil organic C (SOC). Total N (TN) was determined by K_2SO_4–$CuSO_4$–Se (100:10:1) distillation method (Sui et al. 2022). Soil samples were soaked in 2 M KCl, shaken at 200 rpm for 1 h, and analyzed for NH_4^+-N and NO_3^--N using an auto-flow injection system (Auto-Analyzer AA3, Germany) (Yuan et al. 2023a, b). Soil enzyme activities were determined for each incubation period for urease (URE) activity (expressed as the mass of NH_4^+-N in 1 g of soil after 24 h), protease (PRO) activity (expressed as the mass of NO_3^--N released by enzymatic protein digestion from 1 g of soil after 24 h), and 3,5-dinitro salicylic acid colorimetric method to determine cellulase (CEL) activity (expressed as the amount of glucose produced per 1 g of soil after 3 days) (Glaze-Corcoran et al. 2020; Wang et al. 2019).

2.3.2 Soil C and N Mineralization Measurement

To study soil CO_2 emissions, we use the LI-8100A(USA) soil respirometer to measure soil respiration and then calculate CO_2 emissions per unit area from respiration intensity, which in turn calculates the amount of carbon mineralized during the incubation period. The respiration intensity and CO_2 are measured before each sample is taken. Soil N mineralization we characterized by changes in inorganic N (NH_4^+-N + NO_3^--N) content (Kumar et al. 2018).

The potential mineralized carbon and nitrogen are calculated based on the first-order dynamic equation simulation as follows (Stanford and Smith 1972):

$$C_{min} = C_0 (1 - e^{-kt}) \tag{1}$$

$$N_{min} = N_0 (1 - e^{-kt}) \tag{2}$$

where, C_{min} and N_{min} are cumulative C and N mineralized, respectively, in time t (day), C_0 and N_0 are potentially mineralizable C and N, and k is the first-order mineralization rate constant.

Mineralization rates of C (dC_{min}/dt) and N (dN_{min}/dt) were determined by differentiating Eqs. (1) and (2) respectively as follows:

$$dC_{min}/dt = (C_0 \cdot k) \cdot e^{-kt} \tag{3}$$

$$dN_{min}/dt = (N_0 \cdot k) \cdot e^{-kt} \tag{4}$$

The mineralization quotient was calculated as the ratio of potentially mineralizable carbon to soil organic carbon (C_0/SOC). The active nitrogen fraction was calculated by dividing the potentially mineralizable nitrogen by the total nitrogen (N_0/TN).

The formula for calculating the apparent balance of soil organic carbon (C_{ab}) is as follows:

$$C_{ab} = (TOC_1 + E_{CO_2}) - TOC_2 \tag{5}$$

where, TOC_1 denotes the organic carbon content of the soil at the end of the incubation, E_{CO2} denotes the cumulative CO_2 emissions during the incubation period, and TOC_2 denotes the organic carbon content of the soil before incubation. Straw carbon from the straw addition treatment was uniformly added to the soil organic carbon content at 4.523 g kg^{-1}.

2.3.3 Statistical Analysis

Before conducting statistical analyses, all variables were checked for normality and homoscedasticity, and if these assumptions were not met, the data were log-transformed. Of course, this basic data processing was performed in SPSS 22.0 (IBM, Armonk, NY, USA). We could analyze soil physicochemical properties, cumulative mineralization of carbon and nitrogen, and mineralization rate. A nonlinear regression method was used to fit the cumulative mineralization of carbon and nitrogen (mg/kg) and incubation time (d) data to a first-level kinetic model using SPSS. The equation has two unknowns (C_0, N_0, and k) and is usually estimated by an iterative method, which is used to fit the data to a nonlinear equation in the SPSS package and to estimate the values of C_0, N_0, and k. We also conducted a two-factor mixed model repeated measures ANOVA using soil incubation sampling time as an effect between treatments and straw return with N fertilizer treatment as an effect within subjects to test the effects of time, straw return with N fertilizer, and their interactions on pH, soil water content (SWC), soil organic carbon (SOC), total nitrogen (TN), SOC: TN ratio (C/N), soil nitrate nitrogen (NO_3^--N), soil ammoniacal nitrogen (NH_4^+-N), soil temperature (LT), protease (PRO), cellulase (CEL), urease (URE), C_{min} rate, and N_{min} rate. Correlations between soil C_{min} or N_{min} rates and soil abiotic or biotic controls were investigated in R software (V4.2.3, R Core Team 2023) using Pearson correlation analysis. The random forest algorithm (Breiman 2001) was applied to estimate the relative importance of soil physicochemical properties and biological factors on soil C_{min} and N_{min} rates for all sampling periods. For this process, we ran the random forest algorithm 100 times to assess the increase in mean square error (lnMSE); thus assessing the importance of each driver on soil C_{min} and N_{min} rates. The random forest algorithm was executed using the R package *randomForest*. The R package *rfPermute* was used to check the P-value of the importance of each driver factor (Archer 2013). Finally, structural equation modeling (SEM) was further used to assess the direct and indirect effects of the drivers identified by the Random Forest analysis on soil C_{min} and soil N_{min} rates (Yuan et al. 2023b). All mapping was performed in R software (V4.2.3, R Core Team 2023).

3 Results

3.1 C and N Mineralization

The highest soil carbon mineralization (7.00 g kg^{-1}) was observed in the S1N1 treatment and the lowest in the S0N1 treatment (1.00 g kg^{-1}) (Fig. 1a). Straw addition had a significant effect on carbon mineralization at different N levels. N mineralization (N_{min}) also varied significantly throughout the incubation period with straw addition under different N levels (Fig. 2a). But soil N mineralization was lowest in the S1N0 treatment (0.17 g kg^{-1}) and highest in the S0N2 treatment (0.60 g kg^{-1}) (Fig. 1b). Both straw return and N application had a significant effect on soil N mineralization (Fig. 2b). Straw addition with high and low N fertilization resulted in a curvilinear relationship between soil carbon mineralization (C_{min}) and incubation time during the fallow period.

3.2 C and N Mineralization Kinetics

The carbon and nitrogen mineralization curve patterns were well-fitted in the first-level kinetic model ($R^2 = 0.98$–0.99). The highest carbon mineralization rate

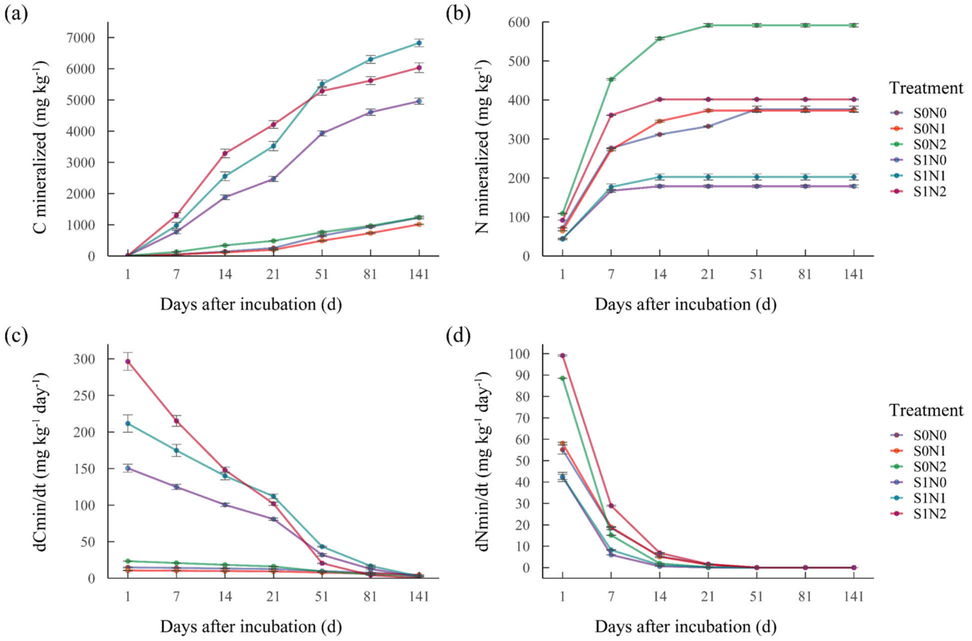

Fig. 1 The effect of each treatment on the cumulative mineralization (**a**, **b**) of soil carbon and nitrogen and mineralization rate (**c**, **d**) at different periods. S0N0: no return; S0N1: low nitrogen without straw return; S0N2: high nitrogen without straw return; S1N0: straw return without nitrogen; S1N1: straw return with low nitrogen; S1N2: straw return with high nitrogen

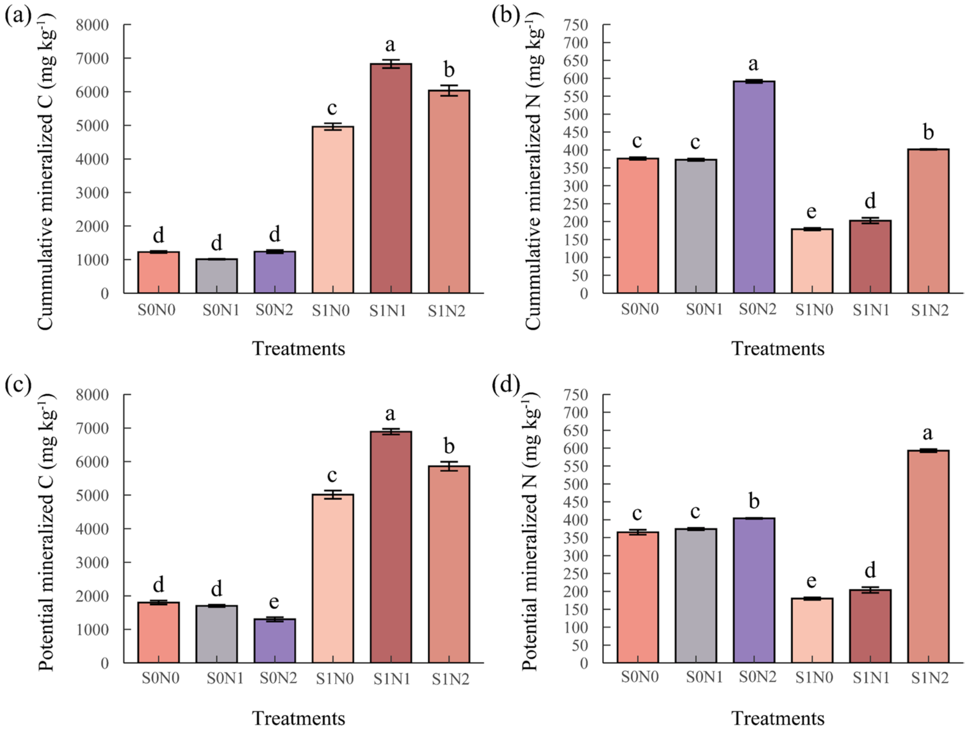

Fig. 2 The effect of each treatment on soil carbon and nitrogen accumulation (**a**, **b**) and potential mineralization (**c**, **d**) in different periods. S0N0: no return; S0N1: low nitrogen without straw return; S0N2: high nitrogen without straw return; S1N0: straw return without nitrogen; S1N1: straw return with low nitrogen; S1N2: straw return with high nitrogen. Error bars represent the mean (± SE) standard error at $P < 0.05$

was found in the S1N1 treatment, while the lowest carbon mineralization rate was found in the S0N1 treatment (Fig. 1c). The highest nitrogen mineralization rate was found in S0N2, while the lowest nitrogen mineralization rate was found in S1N0 treatment (Fig. 1d). The mineralization rates of C and N decreased after 51 days of incubation (Fig. 2c and d). Similar to the actual carbon and nitrogen mineralization patterns (C_{min}, N_{min}, C_{min}/N_{min}), potential mineralized of carbon and nitrogen indicators (C_0, N_0, C_0/N_0) were also significantly different among treatments ($P < 0.05$, Table 2).

The carbon mineralization rate constant (k_C) was highest in the S1N2 treatment and lowest in the S0N1 treatment. The nitrogen mineralization rate constant (k_N) was highest in the S1N0 treatment and lowest in the S0N0 treatment (Table 2). The mineralization quotient (C_0/SOC) differed significantly

Table 2 Cumulative mineralized C (C_{min}) and N (N_{min}), potential mineralizable C (C_0) and N (N_0), rate constant (k_C and k_N), mineralization quotient (C_0/SOC and N_0/TN), and mineralized carbon-to-nitrogen ratio (C_{min}/N_{min} and C_0/N_0) under different treatments. S0N0: no return; S0N1: low nitrogen without straw return; S0N2: high nitrogen without straw return; S1N0: straw return without nitrogen; S1N1: straw return with low nitrogen; S1N2: straw return with high nitrogen

Treatments	C_{min} /N_{min}	C_0/N_0	K_C (day^{-1})	k_N(day^{-1})	C_0/SOC (%)	N_0/TN (%)
S0N0	3.27 ± 0.12d	4.94 ± 0.18d	0.008	0.182	24.77 ± 0.46d	42.63 ± 1.42b
S0N1	2.72 ± 0.04d	4.55 ± 0.08d	0.006	0.187	23.08 ± 0.55d	39.01 ± 2.48b
S0N2	2.09 ± 0.06d	3.22 ± 0.15d	0.018	0.294	17.66 ± 0.88e	37.95 ± 0.48b
S1N0	27.78 ± 0.72b	27.92 ± 0.94b	0.031	0.327	43.42 ± 1.37c	18.77 ± 0.53c
S1N1	33.77 ± 1.34a	33.87 ± 0.94a	0.032	0.273	59.19 ± 1.42a	20.03 ± 1.01c
S1N2	15.04 ± 0.41c	9.88 ± 0.17c	0.053	0.205	50.32 ± 0.92b	48.54 ± 1.85a

Lowercase letters mean a significant difference at 0.05 level among different practices. The standard error of the mean was calculated for each treated value (± SE, $n = 3$)

among treatments (Table 2), with the highest quotient in S1N1 and the lowest in S0N2. Correlations between the soil's different C and N states were estimated (Table 3). A significant relationship was found between C_{min} and C_0 (r = 0.995), and N_{min} and N_0 (r = 0.682). The rate constant k_C was positively correlated with C_0 (r = 0.809), while the rate constant k_N was negatively correlated with N_0 (r = -0.588).

3.3 Apparent Balance of Soil Organic Carbon

All three treatments with straw addition significantly increased soil organic carbon content compared to N fertilizer addition only (S0N1 and S0N2) ($P < 0.05$, Table 4), and S1N0 significantly increased soil organic carbon content compared to S1N1 and S1N2 ($P < 0.05$, Table 4). The S1N0, S1N1, and S1N2 increased the cumulative release of soil C significantly, and the highest cumulative release of C was observed in S1N1 (Table 4). Compared with N fertilizer only (S0N1, S0N2), S1N1 and S1N2 significantly improved the apparent balance of soil organic carbon (C_{ab}), and S1N1 increased mostly, reaching 3.57 gkg^{-1}, and large amounts of N fertilizer without external carbon supplementation (S0N2) during the incubation period significantly reduced the C_{ab} and was not conducive to organic carbon accumulation.

4 Discussion

Our results showed that straw return significantly affected soil C_{min} (increase by 1.00–7.00 g kg^{-1}) and N_{min} (increase by 0.17–0.60 g kg^{-1}) and increased SOC sequestration, these results are also similar to previous studies (Zhang et al. 2021). This improvement can be explained by the increase of soil microbial and enzymatic activities, our study confirmed that cellulase activity and protease activity had a significant effect on soil carbon mineralization (C_{min}) with a contribution of 24.91% (Figs. 3 and 4). Moreover, the addition of straw stimulates microorganisms to secrete more cellulase

Table 3 Pearson correlation coefficients of soil carbon and nitrogen pools under different experimental treatments. SOC: Soil organic carbon; C_{min}: Mineralizable carbon; C_0: Potentially mineralizable carbon; k_C: Carbon rate constant; TN: Total nitrogen; N_{min}: Mineralizable nitrogen; N_0: Potentially mineralizable nitrogen; k_N: Nitrogen rate constant; C_0/SOC: Mineralization quotient of C; N_0/TN: Mineralization quotient of N

Parameters	C_{min}	C_0	K_C	SOC	C_0/SOC	N_{min}	N_0	K_N	TN	N_0/TN
C_{min}	1	0.995**	0.851**	0.976**	0.984**	-0.628**	-0.165	0.346	0.458	-0.432
C_0		1	0.809**	0.968**	0.996**	-0.682**	-0.201	0.3	0.405	-0.45
k_C			1	0.860**	0.771**	-0.225	0.29	0.251	0.737**	-0.027
SOC				1	0.944**	-0.668**	-0.194	0.416	0.442	-0.468
C_0/SOC					1	-0.702**	-0.206	0.235	0.362	-0.433
N_{min}						1	0.682**	-0.243	0.256	0.719**
N_0							1	-0.588*	0.577*	0.925**
K_N								1	0.067	-0.744**
TN									1	0.228
N_0/TN										1

* Correlation is significant at $P < 0.05$ level

** Correlation is significant at $P < 0.01$ level

Table 4 Apparent balance of organic carbon between different treatment groups. S0N0: no return; S0N1: low nitrogen without straw return; S0N2: high nitrogen without straw return; S1N0: straw return without nitrogen; S1N1: straw return with low nitrogen; S1N2: straw return with high nitrogen

Treatments	Soil organic carbon (g kg^{-1})	Carbon sequestration (g kg^{-1})	The proportion of carbon sequestration (%)	Organic carbon apparent balance (g kg^{-1})
S0N0	6.79 ± 0.08c	-	-	0.50 ± 0.06c
S0N1	6.98 ± 0.11c	-	-	0.49 ± 0.03c
S0N2	6.85 ± 0.15c	-	-	0.26 ± 0.02c
S1N0	10.49 ± 0.25a	3.70 ± 0.32a	47.80 ± 3.2a	2.54 ± 0.37b
S1N1	9.62 ± 0.44b	2.63 ± 0.43b	32.09 ± 4.9b	3.57 ± 0.20a
S1N2	9.57 ± 0.10b	2.72 ± 0.12b	35.63 ± 0.96b	2.44 ± 0.52b

Lowercase letters mean a significant difference at 0.05 level among different practices. The standard error of the mean was calculated for each treated value (± SE, $n = 3$)

and protease activity enzymes. The priming effect has a positive effect on increasing C_{min} rates and decreasing SOC content (Wang et al. 2014; Zhang et al. 2012), and it is through this effect that straw addition in turn accelerates SOC mineralization in agricultural fields (Fig. 5), and this acceleration lasts for several days (Li et al. 2022; Xu et al. 2016).It is well known that seasonal changes are usually accompanied by temperature and precipitation changes, and these changes have been identified as key factors affecting soil C_{min} and N_{min} rates (Carson and Zeglin 2018; Risch et al. 2020). In our study, the C_{min} and N_{min} rates were found to level off after 51 days of incubation, which can be explained by the inhibitory effect of gradually decreasing the temperature on soil C_{min} rates (Fig. 3, 4 and 5), consistent with results from Yuan et al (2023a, b). Especially in low-fertility soils (such as research areas), microorganisms require nitrogen fixation and thus break down more SOC or straw to obtain nutrients, resulting in a more sensitive Q_{10} (Kan et al. 2020a; Moinet et al. 2020). These results are crucial to exploring the effects of climate factors on soil carbon emissions from agricultural lands (Ren et al. 2023).

In the literature, N addition has been shown to have inhibitory (Lu et al. 2011; Mo et al. 2008; Ouyang et al. 2008), stimulatory (Allen and Schlesinger 2004; Tu et al.

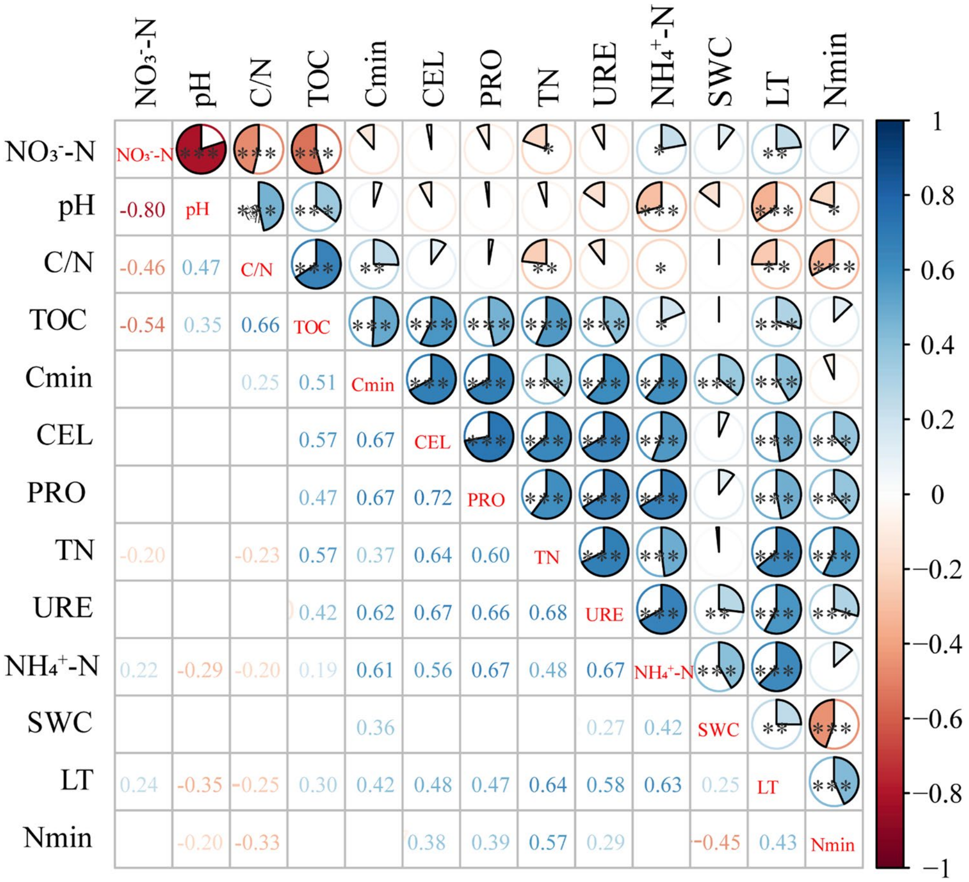

Fig. 3 Relationships between soil carbon and nitrogen mineralization and physicochemical properties. C_{min}: C mineralization rate; N_{min}: N mineralization rate; LT: soil temperature; SWC: saturated water content; TN: total nitrogen; NO_3^--N: nitrate nitrogen; NH_4^+-N: ammonia nitrogen; SOC: soil organic carbon; C/N: carbon to nitrogen ratio; CEL: cellulose activity; PRO: protease activity; URE: urease activity. * Correlation is significant at $P < 0.05$ level. ** Correlation is significant at $P < 0.01$ level

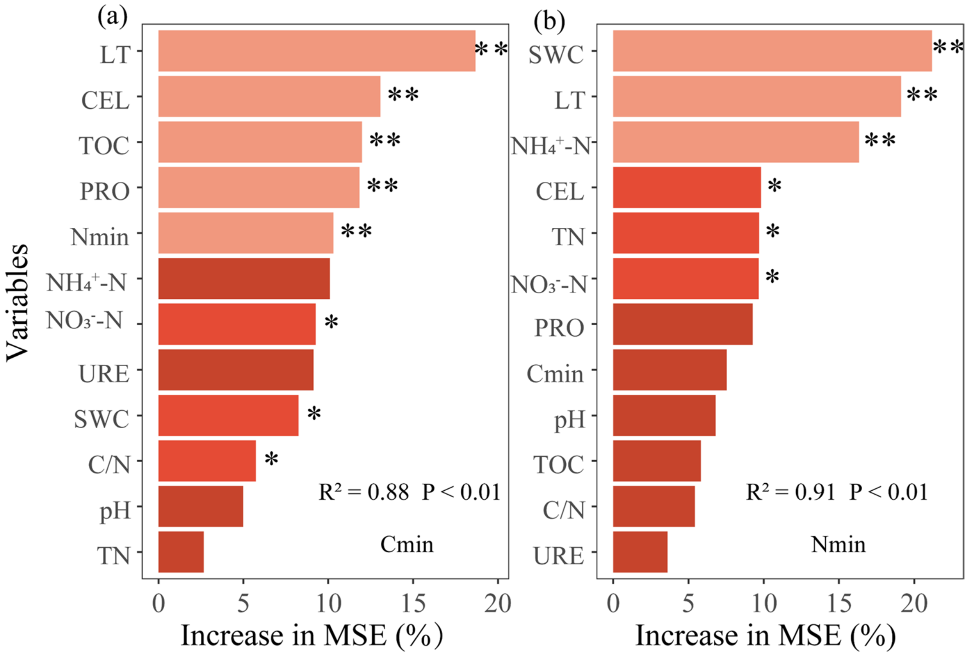

Fig. 4 Relative contributions of drivers to soil C_{min} (**a**) and N_{min} (**b**) rates for all soil sampling dates. The significance of the predictor variables was estimated using the percentage increase in mean square error (MSE; %) of 100 runs of the random forest model. Cmin: C mineralization rate; Nmin: N mineralization rate; LT: soil temperature; SWC: saturated water content; TN: total nitrogen; NO_3^--N: nitrate nitrogen; NH_4^+-N: ammonia nitrogen; SOC: soil organic carbon; C/N: carbon to nitrogen ratio; CEL: cellulose activity; PRO: protease activity; URE: urease activity. * Correlation is significant at $P < 0.05$ level. ** Correlation is significant at $P < 0.01$ level

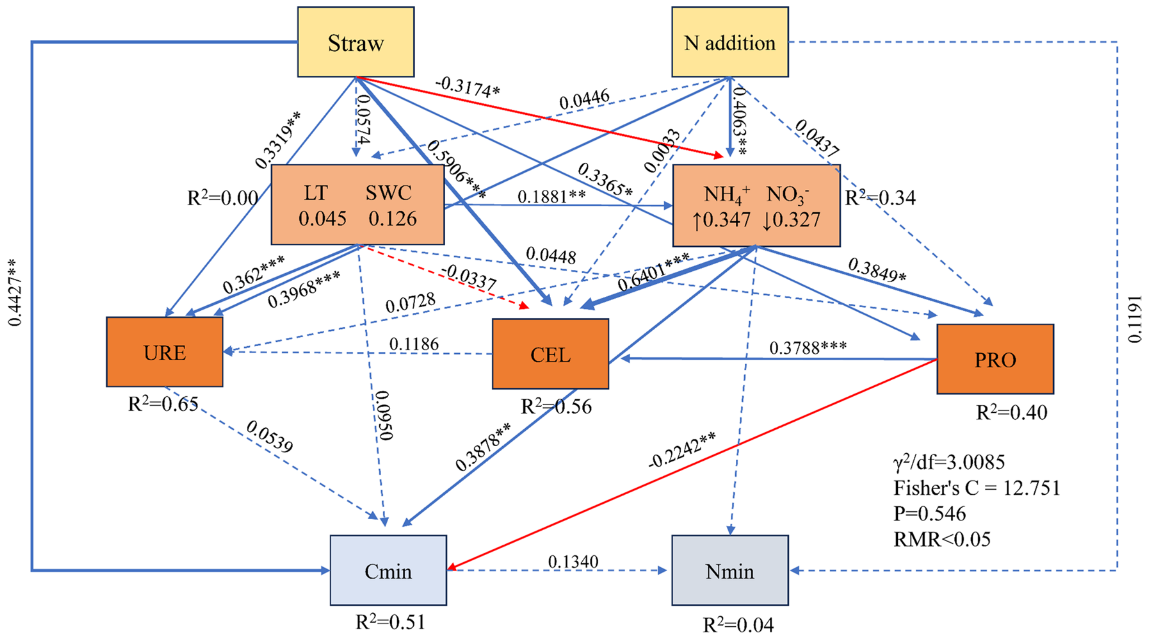

Fig. 5 Structural equation modeling (SEM) analysis of the direct and indirect effects of identified soil abiotic and biotic factors on soil C_{min} and N_{min} rates and their relationships. Cmin: C mineralization rate; Nmin: N mineralization rate; LT: soil temperature; SWC: saturated water content; NO_3^--N: nitrate nitrogen; NH_4^+-N: ammonia nitrogen; CEL: cellulose activity; PRO: protease activity; URE: urease activity. Path coefficients (correlation coefficients) along the arrows are normalized by the mean value of each parameter. The symbols "↑" as well as "↓" indicate significant positive or negative relationships between variables and rates of added straw and N addition. Blue and red arrows indicate significant positive and negative relationships, respectively. The arrow width indicates the strength of the relationship. Dashed arrows indicate no significant relationship. Numbers adjacent to arrows are path coefficients. Percentages given close to variables indicate the variance explained by the model (R^2). Significance levels are indicated: $*P < 0.05$, $**P < 0.01$ and $***P < 0.001$

2013), and no effects (Groffman and Fisk 2011) to soil C_{min}. According to our study, no significant differences in C_{min} were found in the N addition alone (Fig. 2a), however, the structural equation model showed that N incorporated into maize straw directly or indirectly affected soil C_{min} and N_{min} related to the contribution of soil inorganic nitrogen (ammonia nitrogen and nitrate nitrogen) and urease (Fig. 5). Probably because soil microorganisms need N supply to decompose straw C (Feng and Zhu 2021; Huang et al. 2017), especially in N-poor soil environments (e.g., Minqin oasis area), microorganisms compete with the soil for N, with increased N supply, soil microorganisms have enough N to sustain autotrophic life activities and thus increase respiration, which affects soil C_{min} and N_{min} rate. Moreover, N addition affects soil C_{min} by influencing microbial community structure (Thiessen et al. 2013), and the maximum rate of N_{min} occurs during that time to meet the microbial demand (Aljerib et al. 2022; Moreno-Cornejo et al. 2014). In addition, our results suggest that N addition does not consistently accelerate soil C_{min}, and excessive N supply affects soil pH and inhibits microbial growth and decomposition of crop residue (Chen et al. 2018; Ding et al. 2019).

Quantitative information on C_{min} and N_{min} in soils is essential to better assess N availability and losses of C and N from soils. First-order kinetic equations have been widely used to describe C_{min} and N_{min}, with potentially C mineralizable (C_0) and N mineralizable (N_0) determined by equations that are measures of reactive or unstable and readily decomposable SOC and N, respectively (Kan et al. 2020b; Kumar et al. 2018; Sarker et al. 2018). These parameters can be used to determine the effects of agricultural practices and tillage on C sequestration and short-term nutrient turnover or fertility. We found that straw returning matched nitrogen fertilization had significant effects on C_0, it is worthwhile to note that straw return with high N application (S1N2) is more conducive to increasing C_0 in the study area (Fig. 4). However, N addition alone had little effect on C_0, N_0 increasing with increasing N additions. These results imply that the inorganic N fertilizer will accelerate the decomposition of straw with a high C/N ratio (Shaukat et al. 2011), but the overall change in N_{min} was proportional to the amount of nitrogen applied and the N transformation was more susceptible to soil N level than exogenous carbon sources. Generally, soil C_0 depends on a variety of factors such as microbial activity, soil organic carbon, and other soil physicochemical properties, and therefore, the greater C_0 measurements identified in the standardized laboratory assay conflict with in situ C_{min} measurements (Rieke et al. 2022), their functioning in soil remains poorly understood. We also found that C_0 was positively related to the rate constant (k_C) and the N_0 was inversely related to the rate constant (k_N), and those results were inconsistent with previously reported in other studies (Marinari et al. 2010). This may be due to the complexity of the soil system and does not account for all locations (Mohanty et al. 2013). We also found a significant positive correlation between C_{min} and C_0, and N_{min} and N_0, which is consistent with previous reports (Kumar et al. 2018), implying that each of them can reflect the different kinetics of C_{min}.

The apparent soil organic carbon balance (C_{ab}) can characterize the surplus of SOC in the farming system under straw return conditions, with values greater than 0 indicating an accumulation of SOC and vice versa, indicating a decrease in SOC (Lal 2015; Mamta et al. 2023). From the changes in SOC during the incubation, all three treatments with straw addition combined with N significantly increased SOC content compared to N fertilizer addition only ($P < 0.05$), meanwhile, the cumulative release of soil carbon increased significantly with the addition of straw and N, and the highest cumulative release of carbon was observed with the addition of 50 mg kg^{-1} of N fertilizer (Fig. 2), which indicated that the moderate addition of N fertilizer accelerated the decomposition of straw and increased the release of SOC (Collier et al. 2017). In addition, sequestered carbon accounted for 32.09%-47.8% of the carbon released from straw decomposition, indicating that nearly half of the carbon released from straw decomposition was sequestered by the soil in the treatments with straw addition alone during the on-farm recreation period, which was 15.71% and 12.18% higher than the treatments with low and high N application, respectively, these results are similar to the previous finding by Yuan et al (2023a, b). Compared with N addition alone (S0N0, S0N1, and S0N2), the addition of straw significantly improved the C_{ab}, and low N addition increased the most compared to others. It can be seen that no or moderate addition of nitrogen fertilizer during straw return helps to improve the accumulation of SOC, while the application of high nitrogen fertilizer is detrimental to the accumulation of SOC. The reason may be that soil acidification caused by excessive nitrogen application may lead to loss of soil carbonate, which further reduces the total soil carbon stock (Liu et al. 2020). Likewise, the application of large amounts of nitrogen fertilizer (S0N2) without external carbon supplementation during the recreational period significantly reduces the C_{ab} and is detrimental to the accumulation of SOC. Therefore, to improve the current nitrogen supply capacity of the soil and maintain the soil C pool, wise nitrogen application strategies need to be developed through the integration of organic and inorganic resources (Ahmad et al. 2021; Allen and Schlesinger 2004; Marinari et al. 2010; Mo et al. 2008; Yang et al. 2015).

5 Conclusion

In semi-arid oasis farmland, compared to CK (S0N0), maize straw return significantly increased soil C_{min} and C_0 and decreased N_{min} and N_0 during 141-days in-situ incubation. Straw incorporated into N fertilizer (S1N0, S1N1, S1N2) significantly increased C_{min} and C_{min} rate (dC_{min}/dt) ($P < 0.05$), but the effect on N_0 appeared to be reversed, with N_{min} being more affected by N addition. The rationing of low N incorporated into straw return (S1N1) is more beneficial to the C_{ab} and reduces N loss. Overall, appropriate nitrogen fertilizer additions combined with the straw return are beneficial to local soil carbon sequestration and emission reduction, providing an advantage for soil organic carbon (SOC) balance.

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Declarations

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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