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Effects of different returning method combined with decomposer on decomposition of organic components of straw and soil fertility

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ABSTRACT

In view of the problems of low straw decomposition rates and reduced soil fertility in southern Liaoning, China. Using nylon mesh bags method, the decomposition rules of cellulose, hemicellulose and lignin in straw and straws and the dynamic changes of soil organic carbon (SOC), soil microbial biomass carbon (MBC) and soil dissolved organic carbon (DOC) contents were analyzed after 15, 35, 55, 75, 95, 145 and 365 days of returning. At 365 days after return to the field, rotating tillage + straw decomposing agent(refer to decomposer)(RT+S) was the most favorable for straw decomposition and its components, straw decomposition proportion reached 73.25%, and the decomposition proportion of lignin, cellulose and hemicellulose were the highest, being 35.49%, 84.23% and 85.50%, respectively. DOC content in RT+S treatment was higher than in other treatments at each stage, SOC content reached 18.02 $g \cdot kg^{-1}$ at 145d, which was higher than other treatments. The improvement effect of deep turning + deep rotary tillage + straw decomposing agent (PT+S) treatment on microbial biomass carbon (MBC) was the best, followed by RT+S treatment. Our results suggest that the straw and its organic components decomposition proportion could be increased by adding straw decomposing agent, the straw decomposition proportion and the SOC content of various forms were significantly increased with the RT+S treatment.

Introduction

The total amount of straw in China is large, and the annual output has exceeded 900 million tons[1]. With inappropriate disposal of agricultural waste presenting a major threat to the environment[2]. Crop straw burning has numerous detrimental effects on soil and air quality[3]. Straw is an important biomass resource and should be used rationally. Returning straw to the field is important for soil fertilization[4], as it not only improves soil structure, but also soil organic carbon storage[5,6]. It is well known that straw incorporation is beneficial to the concentration and storage of SOC[7], while nutrient availability in the soil, conversely, influences the straw decomposition rate[8].Tillage methods, air temperature, and precipitation affect soil temperature, moisture, porosity and microbial activity[9-11], and these affect crop straw soil decomposition and nutrient changes, and ultimately, soil fertility[12]. Soil temperature and moisture especially, have been identified as key environmental factors regulating soil organic matter and straw decomposition[13-16]. Returning straw to the field under different tillage methods leads to different soil layer ranges, and environmental temperature and straw moisture status, which affects straw decomposition processes and forms of soil organic carbon[17]. Presently, there are two main ways of returning straw to the field: mulching and burying. No-tillage mulching has the least soil disturbance, and increasing crop residue could reduce soil erosion[18-20]. However, straw decomposition rate when placed on the soil surface is lower than when buried in the soil[21,22]. Under the condition of straw burying, the decomposition process is different due to different straw depth[23]. Studies have shown that, in no tillage straw returning treatment, straw was exposed to the air, lack of full contact with soil and water, low microbial activity and low decomposition intensity of straw. Rotary tillage straw returning treatment, straw and soil fully mixed, soil ventilation and water permeability is good, 0-20 cm temperature is higher than no tillage mulch, which is conducive to soil microbial decomposition of straw, thus promoting the decomposition of straw[24].

To promote straw decay and ensure normal production of the next crop, a straw decomposing agent is sometimes applied. A straw decomposition agent is a type of microbial agent composed of a variety of microbial communities, which can accelerate degradation through the catabolism of fungi, bacteria and actinomycetes to decompose cellulose hemicellulose and lignin into small molecular organic compounds and minerals[25]. The agent can prevent or reduce the adverse effect of excessive straw retention on crop growth, thus stabilizing and increasing soil nutrient content and significantly increasing straw decomposition rate[26].

Presently, there are many reports on the effects of tillage methods on straw decomposition and soil fertility indexes, but few on decomposition characteristics of straw organic components and the dynamic changes of different forms of soil organic carbon under different straw return methods combined with a decomposing agent. Therefore, we studied: (1) influences of return methods and decomposition agent on decomposition characteristics of straw and its components and the dynamic changes of soil organic carbon content , and (2) regulation of straw decomposition rules, to provide a reference for the rational utilization of local straw.

Materials and methods

Site Description. The experimental was conducted in Gengzhuang Town, Haicheng(40°48´ N, 122° 37´ E), Liaoning Province from 2019 to 2020. This area is belonged to the conti-nental monsoon climate zone of warm temperate zone, the annual average tempera-ture is above 10 ℃, the annual accumulated temperature is 3 000-3 100 ℃, the frost-free period is about 170 days, and the annual rainfall is 600-800 mm. The soil type is brown soil. Before the experiment, the concentration of soil organic matter, total ni-trogen, available nitrogen, available phosphorus, available potassium, and soil bulk density in 0-20cm surface layer were 12.01 g·kg^{-1}, 0.89 g·kg^{-1}, 129.6 mg·kg^{-1}, 25.96 mg·kg^{-1}, 117.94 mg·kg^{-1}, and 1.53 g·cm^{-3}, respectively. The components and nutrient contents of corn straw were shown in Table 1, The average temperature and precipita-tion from May 2019 to May 2020 are shown in Figure 1.

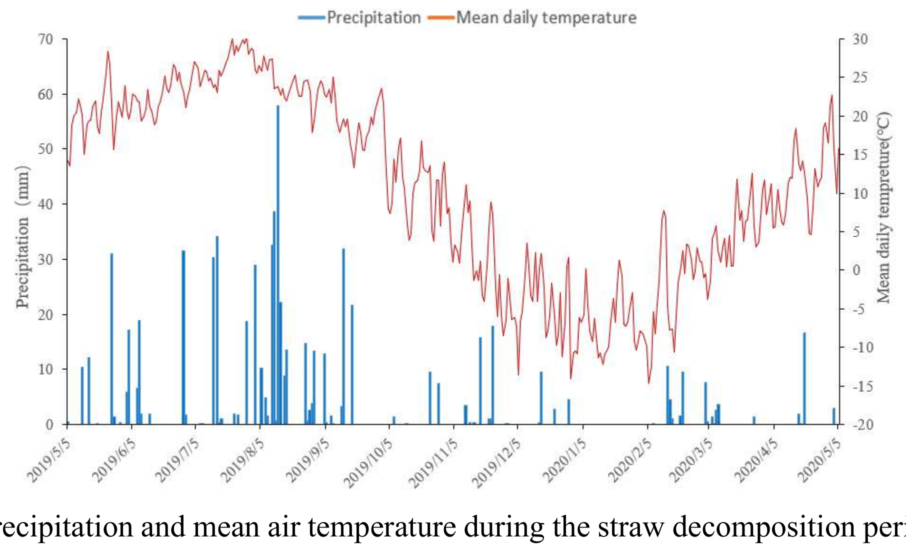


Figure 1. Daily precipitation and mean air temperature during the straw decomposition period from May 2019 to May 2020.

Table 1. Initial component content of corn straw.

Cellulose %	Hemicellulose %	Lignin %	C %	N %	P %	K %
32.14	34.37	10.25	36.90	0.92	0.22	0.86

Experimental design and management. We adopted a split plot design, with the main plot as the cultivation method, and with three cultivation options: no-tillage, deep turning + deep rotary tillage and rotary tillage. Then, when adding straw as a decomposing agent, two methods were used: adding straw decomposing agent and not adding it. Our experimental approach included six treatments: No-tillage mulching and straw return to the field + straw decomposing agent; no-tillage mulching and straw return to the field + no straw decomposing agent; rotating tillage and straw return to the field + straw decomposing agent; rotating tillage and straw return to the field + no straw decomposing agent; deep turning + deep rotary tillage and straw return to the field + straw decomposing agent; and deep turning + deep rotary tillage and straw return to the field + no straw decomposing agent. Each treatment was replicated 3 times, located in random blocks, with a total plot area of 68.4 m^2. At the same time as the previous year's corn harvest, straw was returned to the field, crushed to about 10 cm long, spread evenly on the ground. No-tillage mulching and straw return to the field is the direct no-tillage maize sowing operation in spring; in deep turning + deep rotary tillage treatment, deep turning is used to loosen the soil to a depth of 35 cm, and then the straw is mixed into the soil through deep rotary tillage (a depth of 30 cm); and rotating tillage involves mixing straw into the soil with a rotary tiller to a depth of 20 cm and then raking it flat.

Using the nylon net bag method (mesh bags were 5 cm × 6 cm, small; 15 cm × 20 cm, medium; and large, 25 cm × 35 cm; each size with an aperture of 100 mesh), we simulated three return modes. Soil added to the net bags was taken from the top 0-20 cm prior to sowing in 2019, in the corresponding plots of each treatment. Corn stalks were added at a ratio of 5:4 per stem and leaf (dry weight of stem and leaf of corn stalks in mature stage), and crushed to 2 cm long. In no-tillage treatment, 10 g straw was added to the medium mesh bag, in the rotary tillage and deep turning + deep rotary tillage treatment, 10 g straw was evenly divided into five parts and put into five small net bags, then the five small net bags were evenly mixed into the soil of the outer large net bag and sealed, and the compactness between the inner net bag and the soil in the outer net bag was adjusted.

Net bag layout was determined according to different treatment tillage patterns, and bags were placed in the field on seeding day in 2019. Deep turning + deep rotary tillage was achieved by ploughing furrows 30 cm long, 15 cm wide, and 35 cm deep between corn rows in corresponding plots, large net bags were buried vertically in the furrows, filled with soil and compacted, so that return depth and straw distribution were basically the same as deep turning + deep rotary tillage in the field. Rotating tillage was achieved by ploughing furrows 30 cm long, 15 cm wide, and 20 cm deep between corn rows in the corresponding treatment plot, the packed net bags were tilted in the furrows, filled with soil and moderately compacted, the top end of the net bags was level with the ground surface, which is basically consistent with the return depth of rotary tillage and straw distribution in actual field production. No-tillage mulching treatments involved laying the net bags containing straw on the ground and covering the four corners with soil to prevent the net bag from being blown away by the wind. The decomposing agent addition treatments involved evenly spraying c. 6.5 ml straw decomposing agent on the straw surface before bagging.

In all treatments we applied the same amount of N, P and K (N 240 $kg \cdot hm^{-2}$, P_2O_5 74 $kg \cdot hm^{-2}$ and K_2O 89 $kg \cdot hm^{-2}$). The nitrogen fertilizer was urea, the phosphate fertilizer superphosphate, and the potassium fertilizer, potassium chloride. The brand of straw decomposition agent is Gainby and the model number is d-68 (created by NORDOX company and produced by Beijing Shifang Biotechnology Co., Ltd.). Straw decomposing agent dosage was 1.5 $kg \cdot hm^{-2}$, diluted with water 100 times, and the effective viable bacteria number was $\geqslant$ 50 $million \cdot g^{-1}$.

Sampling and Analysis Methods. On the 15th, 35th, 55th, 75th, 95th, 145th and 365th day after the nylon net bags were placed in the field plots, 3 bags were randomly sampled from each plot. For each net bag, we first washed the surface soil off with tap water, then washed the sample with distilled water 3 times, dried it at 60°C, weighed it and then ground it to deter-mine the decomposition rate of straw and its components. At the same time, 200 g of soil from each soil bag was taken for the determination of soil SOC, MBC and DOC. Content of cellulose, hemicellulose and lignin in straw were determined following

Van's method[27], using a SLQ-6A semi-automatic crude fiber analyzer (Shanghai Fiber Testing Instrument Co., Ltd.).

The following formula was used to calculate decomposition rate of straw and its components. M_0 is the initial straw or cellulose (hemicellulose, lignin) mass, g, and M_t is the straw or cellulose (hemicellulose, lignin) mass at time t, g.

$$\text{Decomposition proportion (\%)} = \frac{M_0 - M_t}{M_0} \times 100 \tag{1}$$

The following formula was used to calculate the straw carbon release proportion. C_0 is the initial straw carbon content, g, C_t is the straw carbon content at time t, g.

$$\text{Straw carbon release proportion (\%)} = \frac{C_0 - C_t}{C_0} \times 100 \tag{2}$$

The following formula was used to calculate the straw and its components decomposition rate. M_{365} is the quality of straw or cellulose (hemicellulose, lignin) mass on the 365th day, mg·d^{-1}.

$$\text{Decomposition rate (mg·d}^{-1}\text{)} = \frac{M_0 - M_{365}}{365} \tag{3}$$

The relationship of the straw decomposition proportion(%) changes over time was fitted as follows:

$$y_t = a + b \times \exp(-kt) \tag{4}$$

where y_t is the proportion of the straw decomposition proportion at time t, %; t is the decomposition time of straw; k is the decomposition rate constant calculated using the least-squares method; a and b are constants.

SOC concentrations (g·kg^{-1}) was determined using the $K_2Cr_2O_7$ - H_2SO_4 digestion method[28]. Soil MBC content was determined using the Chloroform fumigation extraction method[29]. Two fresh soil samples were weighed, and then one of them was placed in a vacuum dryer with chloroform added, and pumped until the chloroform boiled violently, and after a period of time, the dryer cover was opened, the container containing chloroform removed, and the lid replaced. Another portion of soil was placed in a vacuum dryer without chloroform as a control. Then, 20 g each of fumigated and unfumigated soil samples were weighed, 50 mL 0.5 mg·L^{-1} K_2SO_4 was added, extracted by vibration for 0.5 h, filtrate was pumped by 0.45 μm organic filter membrane, and then the filtrate was directly analyzed and detected using a TOC organic carbon analyzer. Based on the difference of organic C content between fumigated and unfumigated soil extracts, the microbial biomass carbon was obtained by multiplying the coefficient by 2.64. For the determination of soil DOC content, we used a slightly modified method of Jones [30] and Hu Haiqing [31]. We made a leaching solution with 0.5 mol·L K_2SO_4, weighed 10 g over 2 mm sieve of air dried soil, added the soil to the leaching solution to create a soil mass ratio of 2.5:1, and then applied a shock temperature for 1 h (220 r·min^{-1}). Then, after filtering, the filtrate was centrifuged for 20 min (3800 r·min^{-1}), filtered with a 0.45 μm organic membrane, and the filtrate subjected to TOC organic carbon analysis meter tests.

Data analysis. In this experiment, Excel 2016 (Microsoft Corporation, New Mexico, USA) software was used to collate and analyze the data, and SPSS 19.0 (SPSS Inc., Chicago, Illinois, USA) statistical software was used to conduct variance analysis, LSD multiple analysis comparison and nonlinear regression analysis on the data. Duncan's multiple range test was used to compare the treatment means at a 95% confidence level. Graphs were drawn using Origin 9.0 (Originlab, Northampton, USA).

Results

Decomposition of straw and its components. From May to September 2019, the temperature and rainfall were higher, than from September 2019 to May 2020 (Fig. 1), and under the influence of temperature and moisture, the straw decomposition proportion in the early period was higher (0-95 days, 11.35-62.70%), while at the late stage it was lower (95-356 days, 42.35-73.25%, Fig. 2a). The decomposition proportion of straw and its organic components were higher for tillage than no-tillage mulching (Table 2). Moreover, decomposition proportion for rotary tillage was higher than deep turning + deep rotary tillage. At 365 days, the straw decomposition proportion under no-tillage mulching was 50.25-52.35%, under deep turning + deep rotary tillage 61.90-66.90%, and under rotary tillage 70.55-73.25% treatments, respectively.

The first-order kinetic curve was used to fit the straw decomposition decomposition line chart (Fig. 2b), it was found that the fitting degree of each treatment was good. It took 291.5 days, 148 days, 90.3 days, 74 days, 64.5 days and 60.4 days for NT, NT+S, PT, PT+S, RT and RT+S to decompose the straw to 50%, respectively.

Under the same tillage method, the addition of decomposing agent promoted straw decomposition over the entire experiment, but its influence did not exceed the influence of tillage. The decomposition of cellulose, hemicellulose, and lignin in the straw was consistent with that of the straw, and straw decomposition proportion under deep turning + deep rotary tillage and rotary tillage was higher than that under no-tillage mulching. Under the same tillage pattern, the decomposition proportion of straw organic components treated with decomposition agent was significantly higher than that without it. At 365d, the lignin decomposition proportion was lower than that of cellulose and hemicellulose. The decomposition proportion of lignin, cellulose and hemicellulose were 27.14-36.89%, 56.56-85.53% and 64.17-86.50%, respectively. The straw and cellulose and hemicellulose decomposition proportion under rotary tillage and deep turning + deep rotary tillage were higher than those under no-tillage mulching (Table 2, Fig. 3).

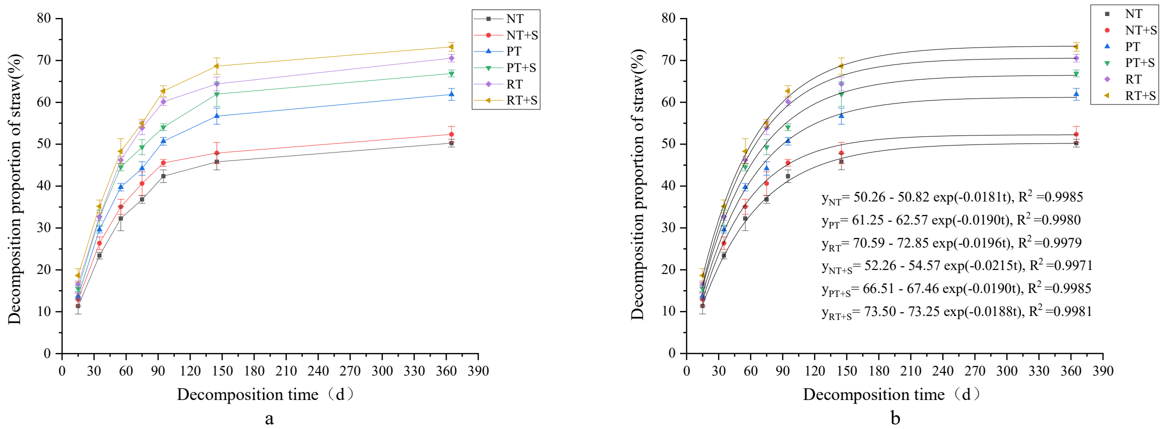
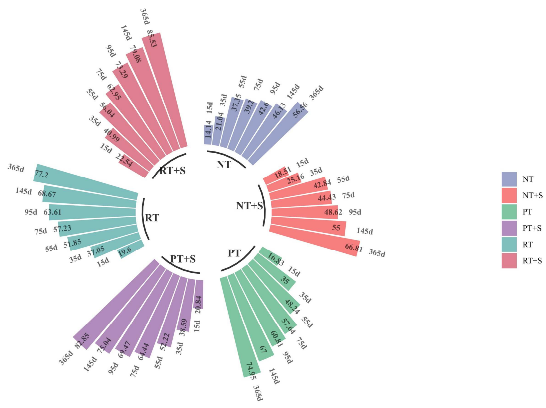
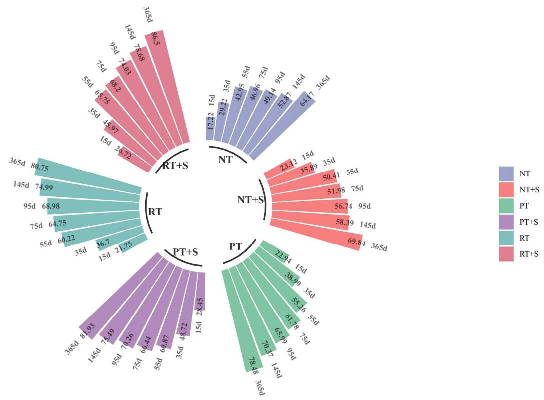


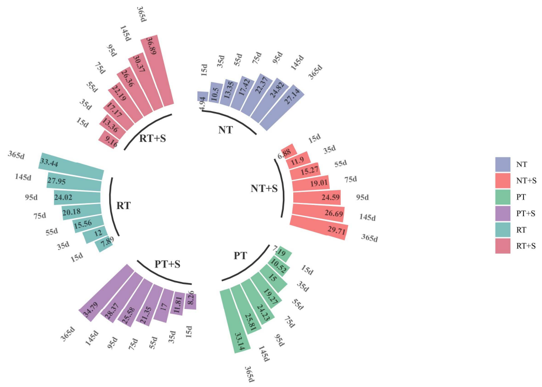
Figure 2. a, Straw decomposition proportion original curve; **b**, Fitting curve by using the first order dynamic equation. NT = no-tillage mulching and straw return to the field + no straw decomposing agent; NT+S = no-tillage mulching and straw return to the field + straw decomposing agent; PT = deep turning + deep rotary tillage + no straw decomposing agent; PT+S = deep turning + deep rotary tillage + straw decomposing agent; RT = rotating tillage + no straw decomposing agent; RT+S = rotating tillage + straw decomposing agent. The same below.



Decomposition proportion of cellulose
a



Decomposition proportion of hemicellulose
b



Decomposition proportion of lignin
c

Figure 3. a, **b**, **c** are the circular barplots of the decomposition proportion of cellulose, hemicellulose and lignin in straw at 15, 35, 55, 75, 95, 145 and 365 days.

Straw carbon release. Trends in straw carbon release proportion and straw decomposition proportion were basically the same, being initially fast, and slow in later stages. Average carbon release proportion of straw under rotary tillage mode was higher than under the other two tillage treatments. Carbon release rates of straw between the three treatments was as follows: rotary tillage > deep turning + deep rotary tillage > no-tillage (Table 2). At 365 days, the carbon release proportion of each treated straw was 49.44-71.05%. For the same return method, adding straw decomposition agent promoted carbon release. RT+S treatment had the highest proportion of straw carbon release in each time period among different return methods (Fig. 4a)

First-order dynamics curve was used to fit the straw carbon release proportion line chart(Fig. 4b). The time for NT+S, PT, PT+S, RT and RT+S treatments to release 50% of straw carbon was 152 days, 93 days, 73.7 days, 59 days and 58.8 days, respectively. It is worth mentioning that the straw carbon release proportion of NT treatment did not reach 50% within 365 days.

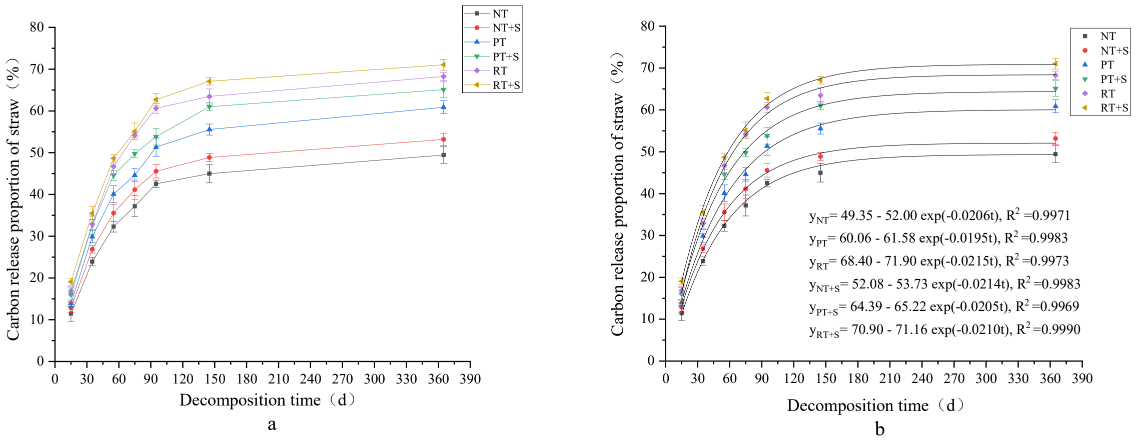


Figure 4. a, Straw carbon release proportion original curve; **b**, Fitting curve by using the first order dynamic equation.

Table 2. Straw decomposition and carbon release rates under different return methods. F: Methods of returning farmland; Tr: processing. Different letters after the mean indicate a significant difference between treatments. *, ** and *** indicate a significance difference at 0.05, 0.01 and 0.001 levels, respectively. NS means no significant difference.

Treatment	Farming method	Straw decomposition rate (mg·d^{-1})	Cellulose decomposition rate (mg·d^{-1})	Hemicellulose decomposition rate (mg·d^{-1})	Lignin decomposition rate (mg·d^{-1})	C releasing rate (mg·d^{-1})
No decomposing agent	NT	13.8±0.10 c	4.7±0.10 b	6.0±0.20 b	0.8±0.01 c	3.6±0.02 c
	PT	17.0±0.04 b	6.5±0.08 a	7.4±0.20 a	0.9±0.01 b	6.2±0.05 b
	RT	19.3±0.06 a	6.6±0.10 a	7.5±0.10 a	2.1±0.03 a	6.9±0.07 a
Decomposing agent	NT	14.4±0.02 c	5.7±0.20 b	6.6±0.10 b	0.8±0.02 c	5.17±0.08 c
	PT	18.3±0.30 b	7.4±0.10 a	8.1±0.20 a	1.0±0.02 b	6.6±0.10 b
	RT	20.1±0.20 a	7.4±0.03 a	8.1±0.30 a	2.4±0.07 a	7.17±0.80 a
F		32.6***	4.1***	2.8***	2.6***	4.0***
Tr		2.4***	2.2***	1.1**	0.04***	0.3***
F×Tr		0.176*	0.01	0.009	0.009***	NS

Dynamic changes in soil organic carbon and soil microbial biomass carbon. On the 35th to 55th day after straw return, SOC content of each treatment decreased gradually, and reached 11.27-12.13 g·kg^{-1} on the 55th day. From 55d to 95d, SOC content changes were consistent with straw carbon release proportion, which showed a rapid increase. RT+S treatment SOC content was higher than other treatments on the 95th day (17.51 g·kg^{-1}), and remained at the highest level of all treatments until maize harvest time at 145d (18.02 g·kg^{-1}). For the same mode of straw return to the field, SOC content of the treatments with the addition of decomposing agent significantly higher than without it (Fig. 5).

Overall MBC content changes were consistent with those for SOC, that is, initial decline from the 35th day after straw return to the field, and then increasing from the 55th day, and remaining at a higher level for a long time. From 35d to 145d, PT+S and RT+S treatment MBC content was always at the highest level and higher than other treatments, but there was no significant difference between the two treatments. NT treatment MBC content was lower than in other treatments. Under the same return method, MBC content in the treatments with straw decomposing agent were higher than those without it(Fig. 5).

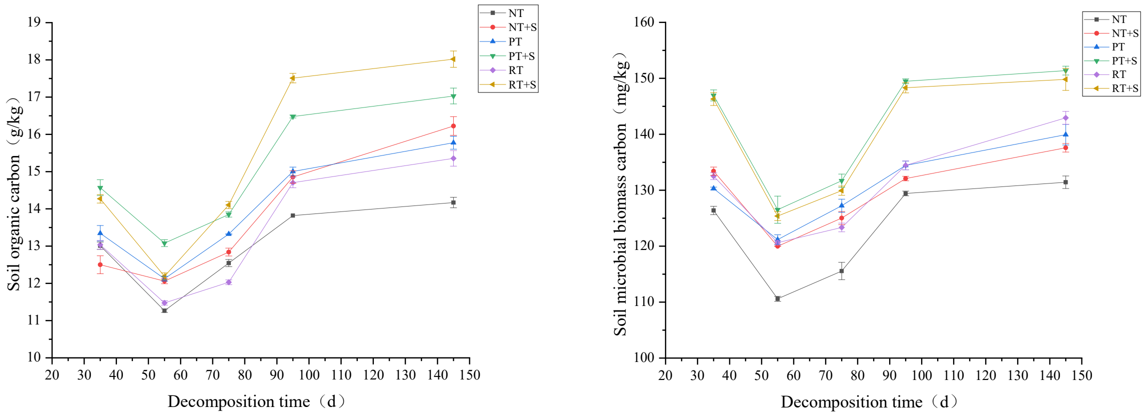


Figure 5. Changes of soil organic carbon and microbial biomass carbon under different returning modes.

Changes in soil soluble organic carbon. Generally, both the straw return method and the decaying agent had effects on soil DOC content: rotary tillage > deep turning + deep rotary tillage > no-tillage; and straw decomposing agent addition > no straw decomposing agent. After straw was returned to the field, soil DOC content of all treatments increased rapidly with the rapid decomposition of straw and release of straw carbon, reaching a maximum of 114.29-135.29 mg·kg^{-1} on the 95th day. From 95d to 145d, soil DOC content of all treatments began to decrease gradually. During the 35d to 145d decay period, soil DOC content in RT+S and PT+S treatments was generally at a higher level, and RT+S was higher, than other treatments. NT treatment soil DOC content was always the lowest, and the soil DOC content of NT+S increased (Fig. 6).

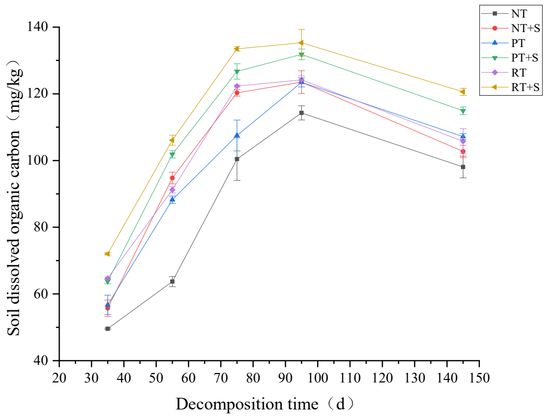


Figure 6. Changes of soil soluble organic carbon under different returning modes.

Discussion

Effects of returning methods and climate on straw decomposition. The straw decomposition process is affected by air temperature and precipitation, decomposition and nutrient release of returned maize straw requires optimum temperature and soil moisture conditions[32,33]. Studies have shown that in the early stage of field return, non-structural and easily decomposed substances such as soluble carbohydrates, organic acids and amino acids are released rapidly, providing a large number of carbon sources and nutrients for soil microorganisms, increasing their numbers, and enhancing their activity, thus accelerating the decomposition of straw organic components[34]. In our experiment, with increasing temperature and rainfall for the 0-95d after straw return to the field, overall decomposition proportion, carbon release proportion and cellulose, hemicellulose, and lignin decomposition proportion of all treatments were similar, that is, they increased rapidly (Fig. 1), our finding was consistent with the work of Yang et al[35]. During the 95d-145d period, a drop in temperature and precipitation occurs, microbial decomposition activity slows down, due to the perishable nature of straw, components such as cellulose and hemicellulose gradually decline, refractory organic components such as lignin proportion increase, so straw decomposition gradually slows, and late decomposition proportion is significantly reduced[36]. Under different tillage methods, the soil layer of returned straw varies, and the soil temperature, water and oxygen content are also different, which further affects soil microbiology characteristics and straw decomposition rate[23]. In this study, the straw decomposition rate of the two treatments of overburying and returning to the field was significantly higher than that of the no-tillage mulching treatment. This was because the straw was fully mixed with the soil, which was conducive to microbial decomposition, making full use of soil moisture and nutrients, promoting straw decomposition[37]. Under no-tillage mulching, straw is exposed to the air and not in full contact with soil and water, the decomposing agent is exposed to the ground, and microorganisms are unable to play a role, thus affecting straw decomposition. Studies have shown that under no-tillage mulching, the microbial activity was low, however, biodegradation is the main driver of straw decomposition under wet soil conditions [38]. In deep turning + deep rotary tillage treatments, some straw is about 30 cm below the soil surface, and organic materials tend to decompose anaerobically at this depth. Our results showed that an aerobic environment was beneficial to crop straw degradation, while anaerobic conditions inhibited aerobic soil microorganism activity under similar soil moisture content[15]. Under anaerobic conditions, the relative content of refractory components such as lignin in crop straw increased, which reduced straw degradation rate[39]. Straw return depth under rotary tillage was relatively shallow, it is more easily exposed to oxygen, so straw decomposition rate was higher than under deep turning + deep rotary tillage.

Effects of return method and decomposing agent on soil carbon form dynamics. From 35d to 55d after straw returning, the contents of MBC and SOC in soil decreased and were the lowest in the whole period at 55d. This is because the addition of exogenous organic matter stimulates the original organic matter in the soil, promoting the decomposition of soil organic carbon [40], which results in the decrease of soil organic carbon content at this stage. During this process, soil microorganisms also need abundant nitrogen to meet their reproductive needs. At this time, the maize jointing stage is at the peak of nitrogen absorption, and the C/N ratio increases significantly, which inhibits the reproduction of microorganisms, leading to a decrease of soil microbial biomass carbon content[41]. In straw return after 55d-95d, temperature and precipitation are at their annual maximum(Fig. 1), which can enhance microorganism diversity and activity, and improve straw decomposition proportion, thus improving straw carbon release proportion, significantly increasing the distribution of soil organic carbon soil, and rapidly increasing soil MBC and total organic carbon content[17,42]. Spedding[43] found that the soil MBC of straw returned to the field increased by 61% compared with that of non-return. After 95 days of straw return to the field, straw decomposition proportion gradually slowed down, and the MBC and total organic carbon content tended to be stable. On the 95d, the order of SOC content of each treatment from high to low was RT+S, PT+S, NT+S, PT, RT, NT, indicating that decomposing agent addition significantly improved SOC, and rotating tillage combined with decomposing agent had the most improved SOC content. The effects of straw return on SOC and carbon forms are affected by many factors, such as soil moisture, temperature and biochemical characteristics, which differ depending on the method of straw return and soil depth[44]. The trend in soil DOC content was consistent with straw decomposition rate 35 to 95 days after straw return, but after 95 days, with the straw decomposition proportion and straw carbon release became slow, temperature and rainfall became slow, the content of soil DOC decreases accordingly. In the RT+S treatment from 35d to 95d, DOC content was significantly higher than in other treatments, followed by PT+S treatment. The accumulation effect of SOC, DOC and MBC contents under rotary tillage and deep turning + deep rotary tillage was better than that under no-tillage mulch. Correlative studies also showed that treatments with added decomposing agent significantly increased soil active organic carbon, MBC and DOC[45]. Straw decomposing agent is rich in microorganisms such as cellulose, hemicellulose and lignin-degrading bacteria, which can increase the diversity, activity and quantity of soil microbial community structure, and thus accelerate the decomposition process of straw components[46]. Therefore, to accelerate the decomposition process of returned straw and improve the decomposition proportion of its organic components, straw decomposing agent can be added at the same time as the straw.

Conclusion

Among the three returning models, rotary tillage and deep turning + deep rotary tillage had better effect on straw decomposition and carbon release proportion of returning straw than no tillage. This conclusion can also be verified by calculating the half-life of straw decomposition proportion and carbon release proportion through the fitting curve of the first-order dynamic equation. RT+S treatment had the highest proportion of straw decomposition and straw carbon release in each sampling period. In each sampling period of 95d-365d, the decomposition proportion of cellulose, hemicellulose and lignin in RT+S treatment was the highest. The SOC content of various forms were significantly increased with the RT+S treatment. On the 145d, the contents of DOC and SOC in RT+S treatment were the highest, and MBC content was lower than that in PT+S treatment and higher than other treatments. Under the same return method, straw decomposition proportion, straw organic component decomposition proportion, and straw treated with decomposing agent carbon release proportion were all higher than treatments without decomposing agent. SOC, DOC and MBC contents in the treatments with added decomposing agent were higher than in treatments without it. in the short term, in order to speed up the decomposition rate of returning straw and improve the content of various forms of soil carbon, rotary tillage returning mode can be adopted, and the straw decomposition agent can be sprayed on the surface of returning straw at the same time.[1]

References

1. Bi, Y., Wang, Y. & Gao, C. Straw Resource Quantity and its Regional Distribution in China. *Journal of Agricultural Mechanization Research*, DOI: https://doi.org/10.13427/j.cnki.njyi.2010.03.031 (2010).
2. Fu & B. Blue Skies for China. *Science* **321**, 611, DOI: https://doi.org/10.1126/science.1162213 (2008).
3. Liu, T., He, G. & Lau, A. Statistical evidence on the impact of agricultural straw burning on urban air quality in China. *Science of The Total Environment* **711**, 134633, DOI: https://doi.org/10.1016/j.scitotenv.2019.134633 (2019).
4. Jiajiang *et al.* The effects of different types of crop straw on the transformation of pentachlorophenol in flooded paddy soil. *ENVIRONMENTAL POLLUTION* **233**, 745-754, DOI: https://doi.org/10.1016/j.envpol.2017.10.114 (2018).
5. Lugato, E., Berti, A. & Giardini, L. Soil organic carbon (SOC) dynamics with and without residue incorporation in relation to different nitrogen fertilisation rates. *Geoderma* **135**, 315-321, DOI: https://doi.org/10.1016/j.geoderma.2006.01.012 (2006).
6. Yan, X., Akiyama, H., Yagi, K. & Akimoto, H. Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change Guidelines. *Glob.biogeochem.cycles* **23**, - , DOI: https://doi.org/10.1029/2008GB003299 (2009).
7. Zhang, P. *et al.* Effects of straw incorporation on the stratification of the soil organic C, total N and C:N ratio in a semiarid region of China. *Soil and Tillage Research*, DOI: https://doi.org/10.1016/j.still.2015.04.008 (2015).
8. Puttaso, A., Vityakon, P., Saenjan, P., Trelo-Ges, V. & Cadisch, G. Relationship between residue quality, decomposition patterns, and soil organic matter accumulation in a tropical sandy soil after 13 years. *Nutrient Cycling in Agroecosystems* **89**, 159-174, DOI: https://doi.org/10.1007/s10705-010-9385-1 (2011).

9. Latifmanesh, H. *et al.* Integrative impacts of rotational tillage on wheat yield and dry matter accumulation under corn-wheat cropping system. *Soil & Tillage Research* **184**, DOI: https://doi.org/10.1016/j.still.2018.07.008 (2018).
10. Latifmanesh, H. *et al.* Integrative impacts of soil tillage on crop yield, N use efficiency and greenhouse gas emission in wheat-corn cropping system. *International Journal of Plant Production* **10**, 317-333, DOI: https://doi.org/10(3):317-334 (2016).
11. Tangyuan, N., Bin, H., Nianyuan, J., Shenzhong, T. & Zengjia, L. Effects of conservation tillage on soil porosity in maize-wheat cropping system. *Plant Soil & Environment* **55**, 327-333, DOI: https://doi.org/10.1111/j.1365-3059.2009.02047.x (2009).
12. Muhammad, W., Vaughan, S. M., Dalal, R. C. & Menzies, N. W. Crop residues and fertilizer nitrogen influence residue decomposition and nitrous oxide emission from a Vertisol. *Biology and Fertility of Soils* **47**, DOI: https://doi.org/10.1007/s00374-010-0497-1 (2011).
13. Devêvre, O. C. & Horwáth, W. R. Decomposition of rice straw and microbial carbon use efficiency under different soil temperatures and moistures. *Soil Biology and Biochemistry* **32**, DOI: https://doi.org/10.1016/S0038-0717(00)00096-1 (2000).
14. Huang, S., Sun, Y., Yu, X. & Zhang, W. Interactive effects of temperature and moisture on CO2 and CH4 production in a paddy soil under long-term different fertilization regimes. *Biology & Fertility of Soils* **52**, 285-294, DOI: https://doi.org/10.1007/s00374-015-1075-3 (2016).
15. Jia, X., Shao, M. a., Wei, X. & Li, X. Response of soil CO 2 efflux to water addition in temperate semiarid grassland in northern China: the importance of water availability and species composition. *Biology and Fertility of Soils* **50**, DOI: https://doi.org/10.1007/s00374-014-0901-3 (2014).
16. Sain, P. & Broadbent, F. E. Decomposition of Rice Straw in Soils as Affected by Some Management Factors. *Journal of Environmental Quality* **6**, DOI: https://doi.org/10.2134/jeq1977.00472425000600010021x (1977).
17. Zhang, G. *et al.* Effect of rice straw application on stable carbon isotopes, methanogenic pathway, and fraction of CH4 oxidized in a continuously flooded rice field in winter season. *Soil Biology & Biochemistry* **84**, 75-82, DOI: https://doi.org/10.1016/j.soilbio.2015.02.008 (2015).
18. Bayer, C., Mielniczuk, J., Amado, T., Martin-Neto, L. & Fernandes, S. V. Organic matter storage in a sandy clay loam Acrisol affected by tillage and cropping systems in southern Brazil. *Soil & Tillage Research* **54**, 101-109, DOI: https://doi.org/10.1016/S0167-1987(00)00090-8 (2000).
19. Bolliger, A., Magid, J., Amado, J., Neto, F. S. & Neergaard, A. D. Taking Stock of the Brazilian "Zero‐Till Revolution": A Review of Landmark Research and Farmers' Practice. *Advances in Agronomy* **91**, 47-110, DOI: https://doi.org/10.1016/S0065-2113(06)91002-5 (2006).
20. Calegari, A. *et al.* Impact of Long‐Term No‐Tillage and Cropping System Management on Soil Organic Carbon in an Oxisol: A Model for Sustainability. *Agronomy Journal* **100**, DOI: https://doi.org/10.2134/agronj2007.0121 (2008).
21. Christensen, B. T. Barley straw decomposition under field conditions: Effect of placement and initial nitrogen content on weight loss and nitrogen dynamics. *Soil Biology & Biochemistry* **18**, 523-529, DOI: https://doi.org/10.1016/0038-0717(86)90010-6 (1986).
22. Douglas, C. L., Allmaras, R. R., Rasmussen, P. E., Ramig, R. E. & Roager, N. C. Wheat Straw Composition and Placement Effects on Decomposition in Dryland Agriculture of the Pacific Northwest. *Soil Science Society of America Journal* **44**, DOI: https://doi.org/10.2136/sssaj1980.03615995004400040035x (1980).
23. Latifmanesh, H., Deng, A., Li, L., Chen, Z. & Zhang, W. How incorporation depth of corn straw affects straw decomposition rate and C&N release in the wheat-corn cropping system. *Agriculture Ecosystems & Environment* **300**, 107000, DOI: https://doi.org/10.1016/j.agee.2020.107000 (2020).
24. Jiang, X., Chi, S., Yun, W., Ning, T. & Li, Z. Effect of less tillage and no-tillage patterns on decomposition of returned maize straw in wheat/maize system. *Transactions of the Chinese Society of Agricultural Engineering* **25**, 247-251, DOI: https://doi.org/10.3969/j.issn.1002-6819.2009.10.045 (2009).
25. Swift, M. J., Heal, O. W. & Anderson, J. M. Decomposition in terrestrial ecosystems. *Studies in Ecology* **5**, 2772-2774, DOI: https://doi.org/10.1063/1.1615673 (1979).

26. Witt, C. *et al.* Crop rotation and residue management effects on carbon sequestration, nitrogen cycling and productivity of irrigated rice systems. *Plant & Soil* **225**, 263-278, DOI: https://doi.org/10.1046/j.1365-2915.1998.00116.x (2000).
27. Soest, P. J. V. Use of detergents in the analysis of fibrous feeds. 2. A rapid method for the determination of fiber and lignin. *Journal - Association of Official Analytical Chemists* **49**, 546-551, DOI: https://doi.org/10.1093/jaoac/73.4.491 (1963).
28. Dikgwatlhe, S. B., Chen, Z. D., Lal, R., Zhang, H. L. & Chen, F. Changes in soil organic carbon and nitrogen as affected by tillage and residue management under wheat–maize cropping system in the North China Plain. *Soil & Tillage Research* **144**, 110-118, DOI: https://doi.org/10.1016/j.still.2014.07.014 (2014).
29. Vance, E. D., Brookes, P. C. & Jenkinson, D. S. An extraction method for measuring soil microbial biomass C. *Soil Biology and Biochemistry* **19**, 703-707, DOI: https://doi.org/10.1016/0038-0717(87)90052-6 (1987).
30. Jones, DL, Willett & VB. Experimental evaluation of methods to quantify dissolved organic nitrogen (DON) and dissolved organic carbon (DOC) in soil. *SOIL BIOL BIOCHEM* **2006,38(5)**, 991-999, DOI: https://doi.org/10.1016/j.soilbio.2005.08.012 (2006).
31. Hu, H., Xin, L. & Long, S. Research Review on Soil Active Organic Carbon Fractionation and Analytical Methods. *Forest Engineering*, DOI: https://doi.org/10.16270/j.cnki.slgc.2012.05.026 (2012).
32. Gregorich, E. G. *et al.* Litter decay controlled by temperature, not soil properties, affecting future soil carbon. *Global Change Biology*, DOI: https://doi.org/10.1111/gcb.13502 (2016).
33. Wetterstedt, J. M., Persson, T. & Gren, G. I. Temperature sensitivity and substrate quality in soil organic matter decomposition: results of an incubation study with three substrates. *Global Change Biology* **16**, DOI: https://doi.org/10.1111/j.1365-2486.2009.02112.x (2010).
34. Powell, J. R. *et al.* Effects of genetically modified, herbicide-tolerant crops and their management on soil food web properties and crop litter decomposition. *Journal of Applied Ecology* **46**, 388-396, DOI: https://doi.org/10.1111/j.1365-2664.2009.01617.x (2009).
35. Yang, F. K., He, B., Zhang, L., Zhang, G. & Gao, Y. An Approach to Improve Soil Quality: a Case Study of Straw Incorporation with a Decomposer Under Full Film-Mulched Ridge-Furrow Tillage on the Semiarid Loess Plateau, China. *Journal of Soil Science and Plant Nutrition* **20**, DOI: https://doi.org/10.1007/s42729-019-00106-y (2019).
36. Wang, X. B., Cai, D. X., Hoogmoed, W. B., Oenema, O. & Perdok, U. D. Potential Effect of Conservation Tillage on Sustainable Land Use: A Review of Global Long-Term Studies. *Pedosphere* **16**, 587-595, DOI: https://doi.org/10.1016/S1002-0160(06)60092-1 (2006).
37. Lu, Y., Fu, L., Lu, Y., Hugenholtz, F. & Ma, K. Effect of temperature on the structure and activity of a methanogenic archaeal community during rice straw decomposition. *Soil Biology and Biochemistry*, DOI: https://doi.org/10.1016/j.soilbio.2014.10.031 (2015).
38. Liu, S. *et al.* The role of UV-B radiation and precipitation on straw decomposition and topsoil C turnover. *Soil Biology and Biochemistry*, DOI: https://doi.org/10.1016/j.soilbio.2014.06.009 (2014).
39. Wang, J., Chen, X. & Wei, J. L. Decomposition of Rice Straw and Corn Straw Under Aerobic and Anaerobic Conditions. *Journal of Agricultural Resources and Environment*, DOI: https://doi.org/10.13254/j.jare.2016.0180 (2017).
40. Pan, Q. *et al.* Influences of 6-year Application of Biochar and Biochar-based Compound Fertilizer on Soil Bioactivity on Brown Soil. *Acta Agriculturae Boreali-Sinica*, DOI: https://doi.org/10.7668/hbnxb.2016.03.033 (2016).
41. Hui-Jie, L. U., Hong-Bo, H. E., Zhang, X. D. & Zheng, L. C. Dynamic of Amino Acid N in Different Grow Seasons of Maize in Different Management. *Chinese Journal of Soil Science*, DOI: https://doi.org/10.19336/j.cnki.trtb.2012.01.007 (2012).
42. Chen, L. *et al.* Effects of straw amendment and moisture on microbial communities in Chinese fluvo-aquic soil. *Journal of Soils & Sediments* **14**, 1829-1840, DOI: https://doi.org/10.1007/s11368-014-0924-2 (2014).
43. Spedding, T. A., Hamel, C., Mehuys, G. R. & Madramootoo, C. A. Soil microbial dynamics in maize-growing soil under different tillage and residue management systems. *Soil Biology & Biochemistry* **36**, 499-512, DOI: https://doi.org/10.1016/j.soilbio.2003.10.026 (2004).

44. Balota, E. L., Calegari, A., Nakatani, A. S. & Coyne, M. S. Benefits of winter cover crops and no-tillage for microbial parameters in a Brazilian Oxisol: A long-term study. *Agriculture Ecosystems & Environment* **197**, 31–40, DOI: https://doi.org/10.1016/j.agee.2014.07.010 (2014).
45. Insam, H., Mitchell, C. C. & Dormaar, J. F. Relationship of soil microbial biomass and activity with fertilization practice and crop yield of three ultisols. *Soil Biology & Biochemistry* **23**, 459-464, DOI: https://doi.org/10.1016/0038-0717(91)90010-H (1991).
46. Yang, Z. X., Zhou, H. P., Guan, C. L., Xie, W. Y. & Li, C. Effect of straw decomposing inoculant on maize straw returning. Journal of Shanxi Agricultural ences, DOI: https://doi.org/10.3969/j.issn.1002-2481.2013.04.15 (2013).

Author contributions statement

Designed and performed most of the experiments, wrote the manuscript and analyzed the data, X.W., X.W. (Xuexin Wang),; helped with the data collection and analysis, K.C., P.G., Q.Y., N.L., Y.L(Yueling Fan)., X.Z. (Xiumei Zhan)., X.H. (Xiaori Han). All authors read and approved the manuscript.

Additional information

The authors declare no conflict of interest.

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Figures

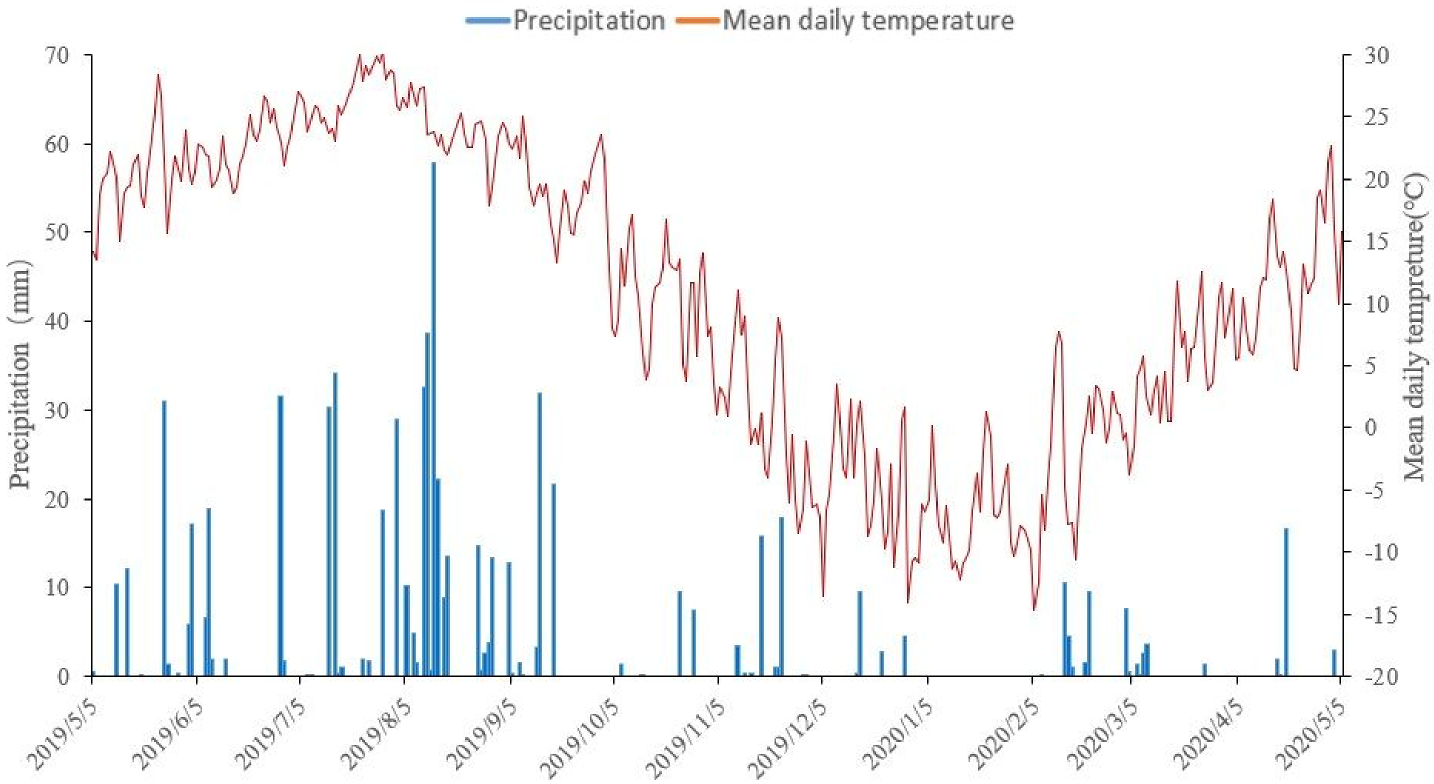

Figure 1

Daily precipitation and mean air temperature during the straw decomposition period from May 2019 to May 2020.

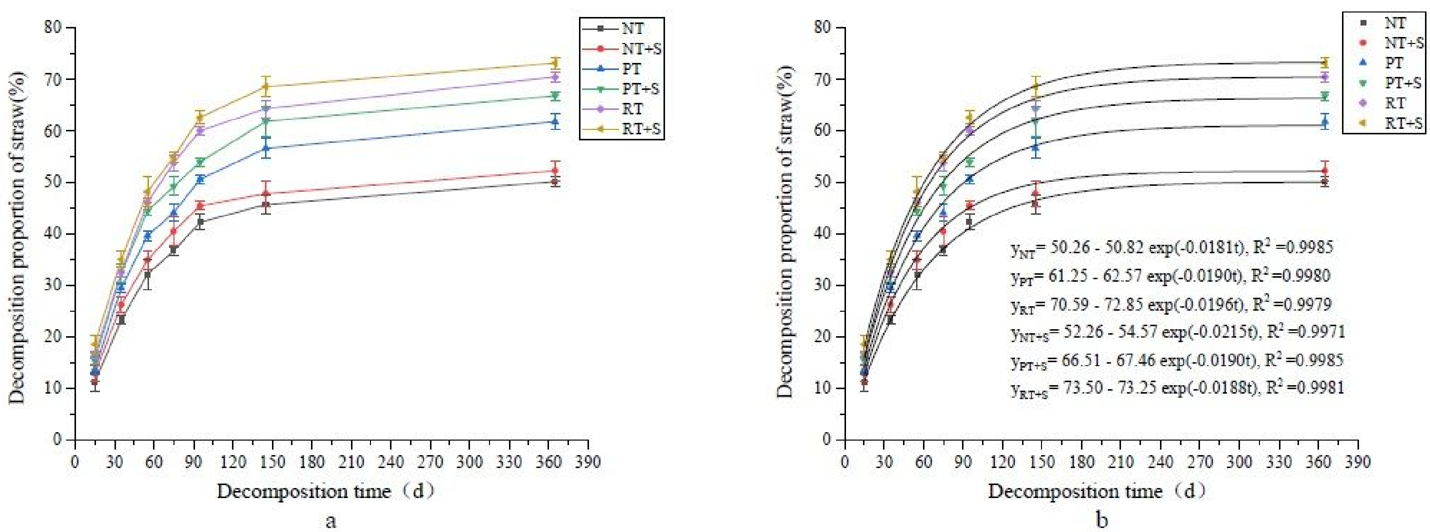

Figure 2

a, Straw decomposition proportion original curve; b, Fitting curve by using the first order dynamic equation. NT = no-tillage mulching and straw return to the field + no straw decomposing agent; NT+S = no-tillage mulching and straw return to the field + straw decomposing agent; PT = deep turning + deep rotary tillage + no straw decomposing agent; PT+S = deep turning + deep rotary tillage + straw decomposing agent; RT = rotating tillage + no straw decomposing agent; RT+S = rotating tillage + straw decomposing agent. The same below.

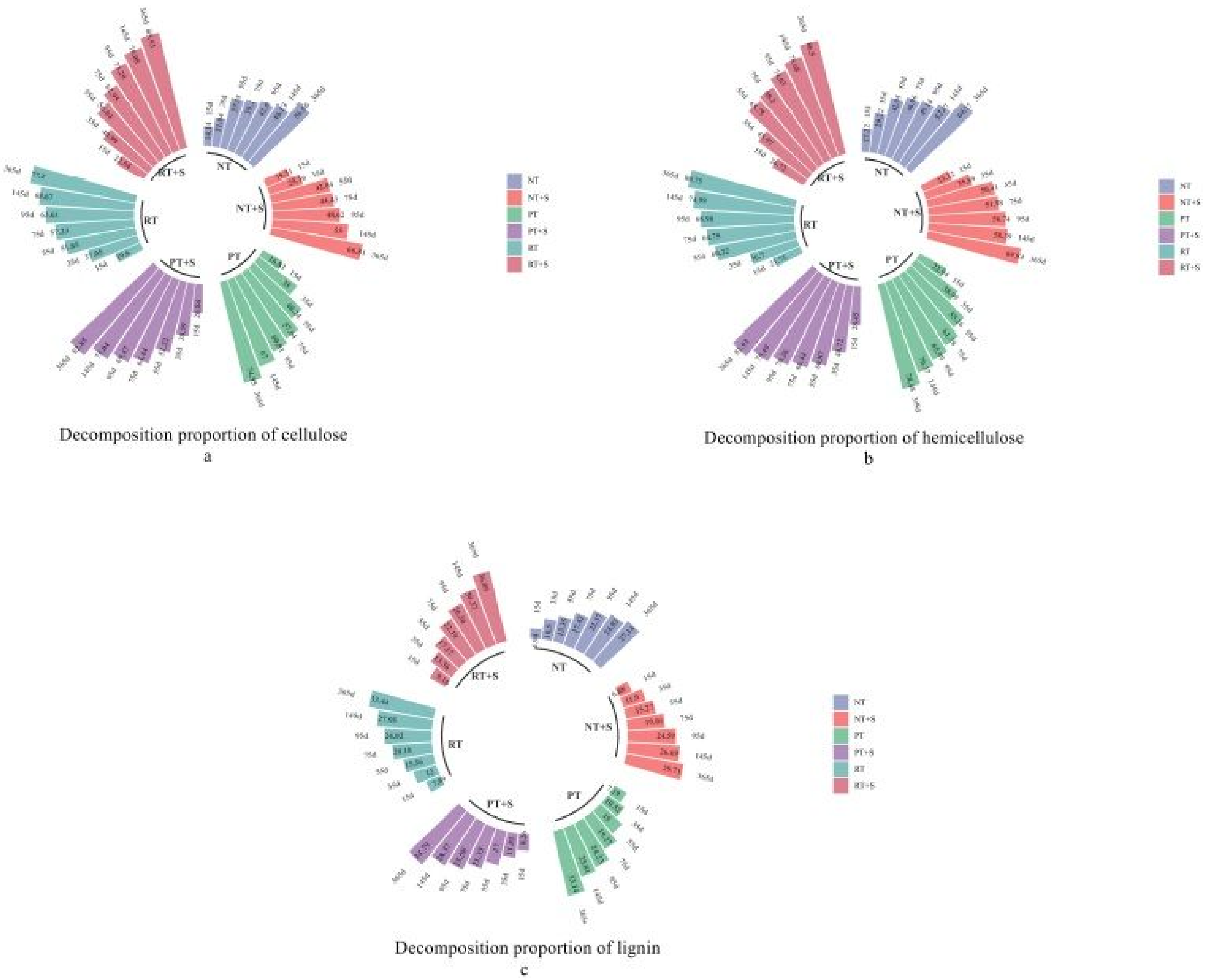

Figure 3

a, b, c are the circular barplots of the decomposition proportion of cellulose, hemicellulose and lignin in straw at 15, 35, 55, 75, 95, 145 and 365 days.

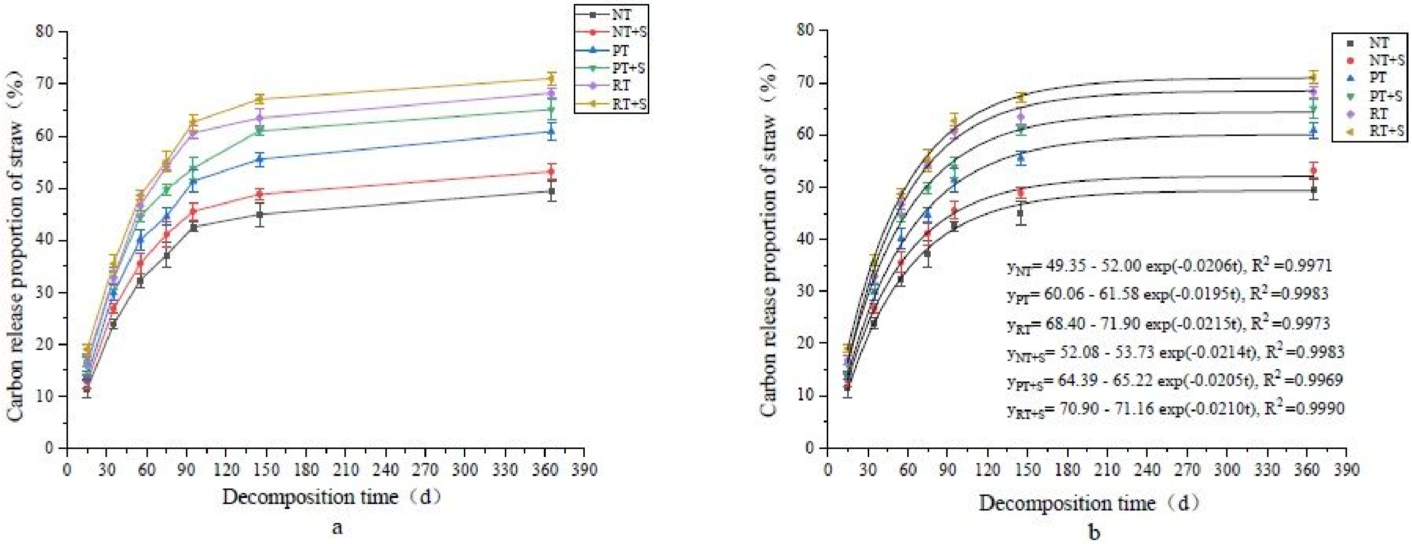

Figure 4

a, Straw carbon release proportion original curve; b, Fitting curve by using the first order dynamic equation.

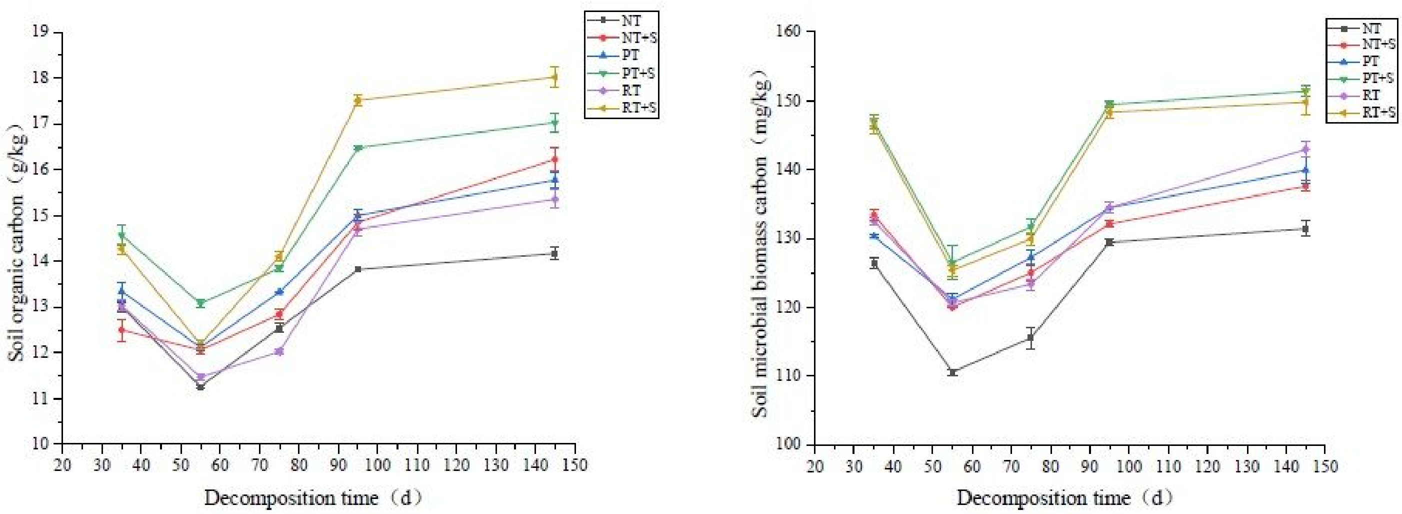

Figure 5

Changes of soil organic carbon and microbial biomass carbon under different returning modes.

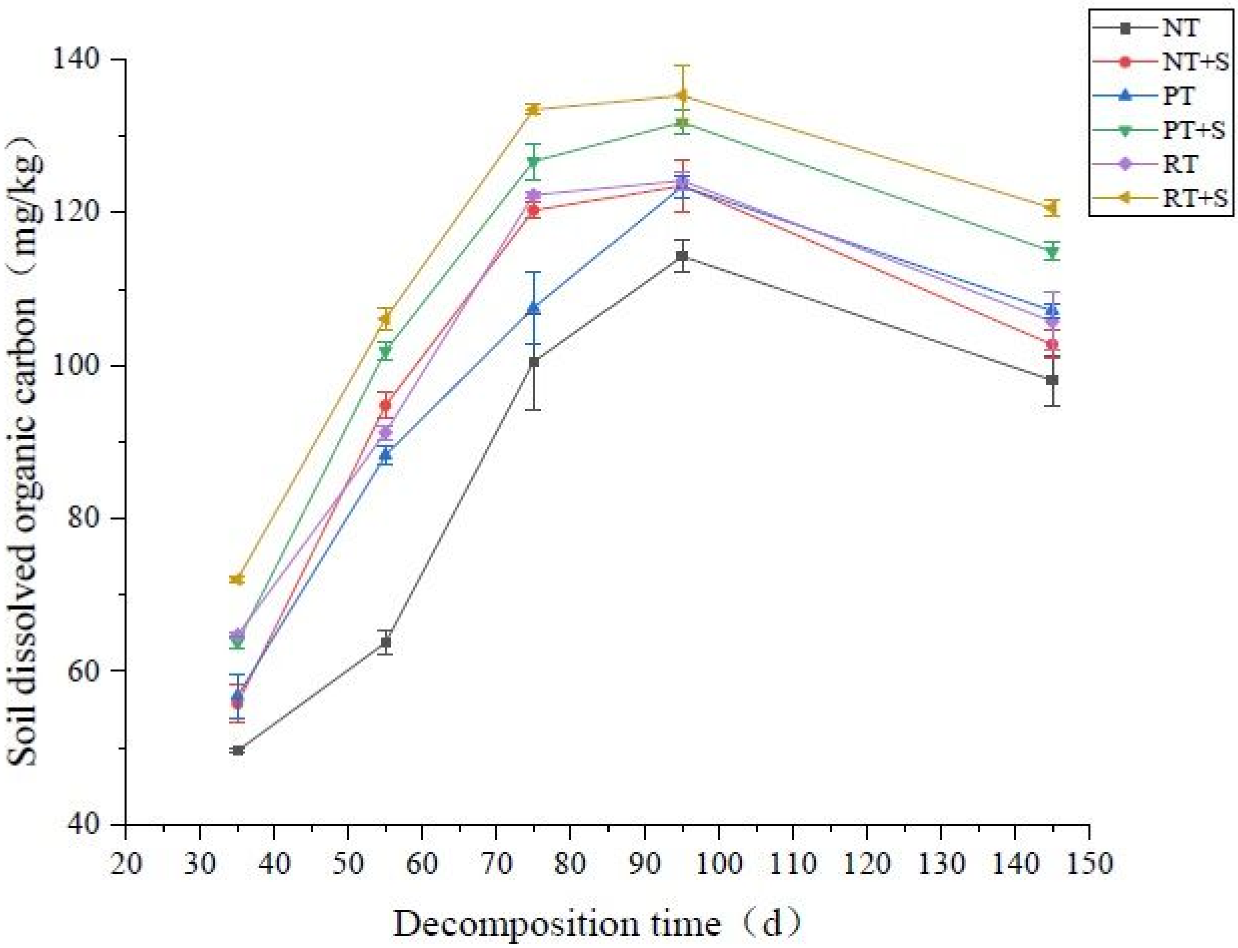

Figure 6

Changes of soil soluble organic carbon under different returning modes.