



Decomposition characteristics of organic materials and their effects on labile and recalcitrant organic carbon fractions in a semi-arid soil under plastic mulch and drip irrigation

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Abstract: Labile organic carbon (LC) and recalcitrant organic carbon (RC) are two major fractions of soil organic carbon (SOC) and play a critical role in organic carbon turnover and sequestration. The aims of this study were to evaluate the variations of LC and RC in a semi-arid soil (Inner Mongolia, China) under plastic mulch and drip irrigation after the application of organic materials (OMs), and to explore the effects of OMs from various sources on LC and RC by probing the decomposition characteristics of OMs using *in-situ* nylon mesh bags burying method. The field experiment included seven treatments, i.e., chicken manure (CM), sheep manure (SM), mushroom residue (MR), maize straw (MS), fodder grass (FG), tree leaves (TL) and no OMs as a control (CK). Soil LC and RC were separated by Huygens D's method (particle size-density), and the average soil mass recovery rate and carbon recovery rate were above 95%, which indicated this method was suitable for carbon pools size analysis. The LC and RC contents significantly ($P<0.01$) increased after the application of OMs. Moreover, LC and RC contents were 3.2%–8.6% and 5.0%–9.4% higher in 2016 than in 2015. The applications of CM and SM significantly increased ($P<0.01$) LC content and LC/SOC ratio, whereas they were the lowest after the application of TL. However, SOC and RC contents were significantly higher ($P<0.01$) after the applications of TL and MS. The correlation analysis indicated the decomposition rate of OMs was positively related with LC content and LC/SOC ratio. In addition, lignin, polyphenol, WOM (total water-soluble organic matter), WHA (water-soluble humic acid), HSL (humic-like substance) and HAL (humic acid-like) contents in initial OMs played important roles in SOC and RC. *In-situ* nylon mesh bags burying experiment indicated the decomposition rates of CM, SM and MS were significantly higher than those of MR, FG, and TL. Furthermore, MS could result in more lignin derivatives, WHA, and HAL polymers in shorter time during the decomposition process. In conclusion, the application of MS in the semi-arid soil under a long-term plastic mulch and drip irrigation condition could not only improve soil fertility, but also enhance soil carbon sequestration.

Keywords: organic materials; labile organic carbon; recalcitrant organic carbon; decomposition characteristics; plastic mulch; drip irrigation; Inner Mongolia

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1 Introduction

Soil organic carbon (SOC) plays an important role in supplying plant nutrients, enhancing cation exchange capacity, improving soil aggregation and water retention, and supporting soil biological activity (Loveland and Webb, 2003; Lal, 2004; Sparling and Schipper, 2004; Haynes, 2005). At the same time, SOC is an index of sustainable land management (Nandwa, 2001) and is critical in determining response to N and P fertilization. Although labile organic carbon (LC) fraction accounts for a small part of total SOC, but it directly involves in soil biochemical processes and plays a vital role in soil health (Haubensak et al., 2002; McLauchlan and Hobbie, 2004; Cookson et al., 2005). Separation techniques of LC can be classified as physical, chemical, and biological methods. Especially, chemical method is more common used in previous studies. LC fractions included water-soluble organic carbon (WOC), dissolved organic carbon (DOC), microbial biomass carbon (MBC), particulate organic carbon (POC), and the permanganate oxidized carbon (POXC) have been identified by chemical method (Meng et al., 2013; Plaza-Bonilla et al., 2014). However, physical method does less damage to organic carbon structure than that of chemical method, and the separation of components can reflect the structure and function of undisturbed SOC (Zhang et al., 2011). According to carbon cycle characteristics in Markov Chain Monte Carlo (MCMC) model (Müller et al., 2004), Huygens et al. (2007) have recently improved the soil separation method of Meijboom et al. (1995). They asserted SOC could be divided into LC and recalcitrant organic carbon (RC), which could be directly determined by this physical method. LC and RC are two important components of SOC, and their ratios to SOC (i.e., LC/SOC and RC/SOC) could be used as indicators to describe SOC turnover and sequestration (Yu et al., 2015).

Management strategies to research the variation of SOC components have recently received much attention (Knoblauch et al., 2011; Du et al., 2013; Troy et al., 2013). One important strategy for sustainable agriculture production systems was the application of organic materials (OMs) into soils (Schmidt et al., 2011). Gougoulas et al. (2014) and Liu et al. (2016) have shown that the application of OMs contributed lots to LC content, which was mainly due to the OMs inputted into soil provide carbon source for soil microbial. Liang (2012) and Chen et al. (2015) also found that the application of OMs could significantly affect the contents of MBC, POC, and DOC. Moreover, Li et al. (2016) indicated that soil DOC and MBC contents after the applications of straw, mushroom residue, and manure were significantly improved. A lot of studies have been conducted on the effects of the application of OMs on LC fractions using the chemical method; For example, Singh et al. (2009) found that the quality of OMs had an important influence on short-term soil carbon dynamic. The amounts of SOC and LC were closely related to the types and properties of exogenous OMs (Manna et al., 2005). However, relatively few attempts have been made on LC and RC fractions separated by Huygens D's method (2007) and the relationship between chemical compositions of OMs and SOC fractions. Integrating the water saving of drip irrigation and evaporation reducing of plastic film mulch was more suitable for improving the water utilization efficiency, especially in semi-arid areas in western China. In recent years, the application areas of plastic mulch and drip irrigation in Inner Mongolia have been about 4.686×10^5 hm². Jiang et al. (2014) and Yin et al. (2014) found that plastic film mulch could change the physical, chemical and biological properties of soils, as well as improve the decomposition of soil organic matter and the transformation and release of soil nutrients, thus increasing soil nutrient availability and soil fertility. Li et al. (2007) found that the biomass and yield of corn increased after plastic film mulch, which resulted in the increase of corn residue returned into soil. Li et al. (2009) also found that plastic film mulch promoted the decomposition of organic carbon and in turn decreased the light fraction organic carbon content of topsoil. In a word, lots of studies were carried out to research the effects of plastic mulch and drip irrigation on LC in different soils. However, little information is available in the effects of plastic mulch and drip irrigation on LC and RC.

The aim of this study was to evaluate the variations of LC and RC separated by Huygens D's method in a semi-arid soil under plastic mulch and drip irrigation after the application of six

different origins of OM_s, including natural organic materials (maize straw, fodder grass, and tree leaves), livestock manures (chicken manure and sheep manure), and half-decomposed organic materials (mushroom residue). In addition, *in-situ* nylon mesh bags burying experiment was conducted to explore the decomposition characteristics and variations in the chemical compositions of different OM_s. We hypothesized that the application of OM_s would increase SOC, LC, and RC contents, and affect the turnover and sequestration of SOC in a semi-arid soil under plastic mulch and drip irrigation condition. Moreover, the decomposition rate and chemical compositions of OM_s would play important roles in SOC fractions.

2 Materials and methods

2.1 Experimental site

The experiment was conducted in Tumuji Town (46°17'N, 123°00'E), which is located at Jalaid Banner, Hinggan League, Inner Mongolia, China, and belongs to semi-arid areas. The annual average temperature is 4.0°C, the mean annual precipitation is 300–450 mm, and the frost-free period is approximate 150 d. The average annual hours of sun exposure is 2592 h, and the total amount of solar radiation is 5362.46 MJ/(m²·a). The effective accumulated temperature ≥10°C is about 2700°C–3300°C. The soil is classified as Chernozem, with a pH of 8.2 and containing 19.8 g/kg of organic matter, 6.55 mg/kg of available phosphate, 51.36 mg/kg of available potassium, and 84.82 mg/kg of available nitrogen.

2.2 Experimental design and soil sampling

2.2.1 Field experiment with the application of OM_s

The field experiment was conducted in May 2015 and 2016. The OM_s used including chicken manure (CM), sheep manure (SM), mushroom residue (MR), maize straw (MS), fodder glass (FG), tree leaves (TL), and with no OM_s as control (CK). CM and SM were collected from chicken-breeding farm and sheep-breeding farm, respectively. MR was the residue of edible fungus culture medium produced with corn as raw material. MS was maize straw, and TL was poplar leaves. FG was collected from Jalaid Banner pasture. The basic properties of initial OM_s were shown in Table 1. The variety of maize used was XianYu 335. The area of each plot was 5 m×10 m. The field was randomly designed with three replicates for each treatment. The mechanized coated drip irrigation cultivation technique was used in planting process. OM_s were fertilized to ridge artificially after ridging both in 2015 and 2016. The height of the ridge was 10 cm. The inputted quantity of carbon was 7719 kg C/hm² and each organic material treatment was equivalent in 2015 and 2016. The application rates were 33,151 kg/hm² for CM, 27,708 kg/hm² for SM, 22,953 kg/hm² for MR, 18,000 kg/hm² for MS, 22,265 kg/hm² for FG, and 19,415 kg/hm² for TL. Each plot was fertilized with urea (210 kg N/hm²), superphosphate (67 kg P/hm²) and potassium chloride (87 kg K/hm²). Soil samples were collected from the junction of ridge and furrow in 0–20 cm depth in October 2015 and 2016. Five samples of each plot followed “S” method. Then the samples were air-dried and passed through a 2-mm sieve after removal of crop residues and stones.

2.2.2 Field experiment with *in-situ* nylon mesh bags burying

The field experiment with *in-situ* nylon mesh bags burying was conducted at the same time and the field management was similar to the application of OM_s. There were totally six treatments, i.e., CM, SM, MR, MS, FG, and TL. Every treatment consisted of three replicates, and each plot covered an area of 1.7 m×3.6 m. The raw materials of MR, TL, CM, and SM were crushed into crumbs, while materials of MS and FG were cut into segments in about 2–3 cm long. Each kind of OM_s was weighed 20 g and was placed into the 300 mesh nylon bags in a size of 20 cm×15 cm and then sealed. Totally, 24 parts of nylon mesh bags were buried in each plot. Nylon mesh bags were tiled with no overlaps directly below the drip irrigation belt at 20-cm intervals in 10 cm deep soil. Three nylon mesh bags from each plot were randomly collected at 30, 60, 90, 120, 150, 180,

360, and 540 days after burial, which were carried back to the laboratory and set aside after clearing up.

Lignin and cellulose were measured by Van Soest acid detergent fiber (Van Soest, 1963). Organic C was measured by an exogenous thermal process with potassium dichromate (Walkley and Black, 1934). Polyphenol was measured by ferrous tartrate (Turkmen et al., 2006). Total N was determined by Kjeldahl method. The water-soluble organic matter and humic-like substance fractions were extracted according to the method of Wu et al. (2004).

Table 1 Basic properties of the initial organic materials

Index	Chicken manure (CM)	Sheep manure (SM)	Mushroom residue (MR)	Maize straw (MS)	Fodder grass (FG)	Tree leaves (TL)
Organic C (g/kg)	232.84±2.30 ^c	278.58±2.01 ^d	336.29±3.34 ^c	428.85±2.56 ^a	346.68±4.18 ^c	397.57±1.21 ^b
Total N (g/kg)	15.19±0.61 ^a	9.82±0.38 ^b	11.06±0.53 ^b	6.13±0.72 ^c	16.75±1.05 ^a	8.72±0.68 ^{bc}
C/N	15.33±0.82 ^c	28.37±1.64 ^c	30.42±1.33 ^c	69.96±1.51 ^a	20.70±0.97 ^d	45.59±1.36 ^b
Lignin (%)	2.29±0.33 ^c	2.60±0.75 ^c	6.90±0.42 ^c	5.30±0.18 ^d	8.49±0.83 ^b	11.50±0.67 ^a
Cellulose (%)	7.02±0.93 ^c	20.53±1.24 ^c	12.76±1.55 ^d	37.81±2.17 ^a	25.64±2.00 ^b	13.47±0.64 ^d
Hemicellulose (%)	4.16±0.22 ^d	14.13±0.72 ^b	4.35±0.21 ^d	23.68±1.15 ^a	16.25±1.07 ^b	8.89±0.58 ^c
Polyphenol (%)	0.69±0.05 ^b	0.75±0.08 ^b	0.72±0.09 ^b	0.88±0.07 ^b	0.81±0.04 ^b	1.05±0.03 ^a
Lignin/N	1.51±0.32 ^d	2.65±0.19 ^d	6.24±0.24 ^{cd}	8.65±0.43 ^b	5.07±0.41 ^{cd}	13.19±0.92 ^a
Quality class	IM	IM	IM	IM	IM	IM

Note: IM, intermediate quality. Data with the same lowercase letter within the same row do not differ significantly at the 5% level according to the least significant difference test. Mean±standard error.

2.3 Separation method of labile organic carbon (LC) and recalcitrant organic carbon (RC)

The extracted soil was subjected to LC and RC fractions using the Huygens D's method. Each sample was treated three times and the specific steps were listed as follows: 50 g air-dried soil passing through a 2-mm sieve was placed on the 0.25-mm sieve, and then wet by deionized water. Put the set of sieves (0.25-, 0.15- and 0.05-mm sieves) into the wet sieve barrel and added water to immerse the soil on the top of the 0.25-mm sieve, then wet-sieve it with a sieving machine in 30 min. Size fractions lying on sieves of 0.25-mm and 0.15-mm were washed into a bucket and swirled with injected deionized water. Upper turbid liquid was poured out and collected until the washing solution was clear to separate the macro organic matter (>0.15 mm MOM) and mineral fraction (>0.15 mm MF) by decantation. Then, we collected the MOM, MF, 0.05–0.15 mm fraction and <0.05 mm fraction (centrifuged with 3000 r/min in 5 min). Each fraction was oven-dried at 55°C and weighed. Dried soils were grounded with planetary ball mill and normally stored for further carbon analysis.

LC was carbon content in terms of MOM in 1 kg of original soil. RC was the sum of carbon content in terms of MF, 0.50–0.15 mm fraction and <0.05 mm fraction in 1 kg of original soil. Mass recovery referred to the percentage of the sum of different soil grades weight comprising total soil weight (50 g). In other words, carbon recovery meant the sum of carbon content in different soil grades which represented the carbon content in the total amount of soil.

2.4 Data and statistical analyses

Decomposition percentage (%)=(mass of initial OMs–mass of residue OMs)/mass of initial OMs×100%, (1)

Cellulose decomposition percentage (%)=(content of initial OMs–content of residue OMs)/content of initial OMs×100%. (2)

Residual quantities of OMs in decomposition process were fitted by exponential equation:

$$y=a+b\times e^{-k\times t}, \quad (3)$$

where y (g) is residual quantity at time t ; k is constant of decomposition rate calculated by the least-squares method, indicating the decomposing speed level; b (g) is mass lost; and a (g) is asymptote value of y when t is ∞ .

$$C \text{ released quantities} = (C_0 \times M_0 - C_t \times M_t) \times 10^{-3}, \quad (4)$$

where C_0 is C content of initial OMs (g/kg); M_0 is mass of initial OMs (g); C_t is C content of OMs at time t (g/kg); and M_t is mass of OMs at time t (g).

C released quantities from OMs in decomposition process were fitted by the first-order kinetic equation:

$$C_t = C_0 \times (1 - e^{-k_0 \times t}), \quad (5)$$

where k_0 is constant of carbon decomposition rate calculated by the least-squares method.

The results were initially collected with Excel 2010 (Microsoft, Redmond, WA, USA). All analyses were carried out with three replicates. The data were analyzed in the analysis of variance (ANOVA) procedure. Multiple comparisons were made under Duncan's new multiple ranges test (DMRT). Significant differences between treatments were determined at 95% and 99% levels of probability. Graphical material was prepared using Origin 2007 (Originlab, Northampton, USA).

3 Results

3.1 Soil organic carbon (SOC)

Compared with CK, the SOC contents increased significantly ($P < 0.01$) after the application of OMs (Fig. 1). Both in 2015 and 2016, SOC contents followed the descending order $TL > MS > FG > MR > SM > CM$, whereas SOC contents after the application of OMs in 2016 were 6.7%–12.6% higher than those in 2015. Compared with CK, SOC contents after the applications of TL and MS respectively increased 39.5% and 36.2% in 2016. SOC contents after the application of TL were 9.5%, 15.0%, 19.2%, and 20.7% higher than those of FG, MR, SM and CM in 2016 ($P < 0.01$). Meanwhile, SOC contents after the application of MS were 6.9%, 12.2%, 16.3%, and 17.8% higher than those of FG, MR, SM and CM in 2016, respectively ($P < 0.01$). However, SOC content after the application of TL was 2.5% higher than that of MS ($P < 0.05$) in 2016.

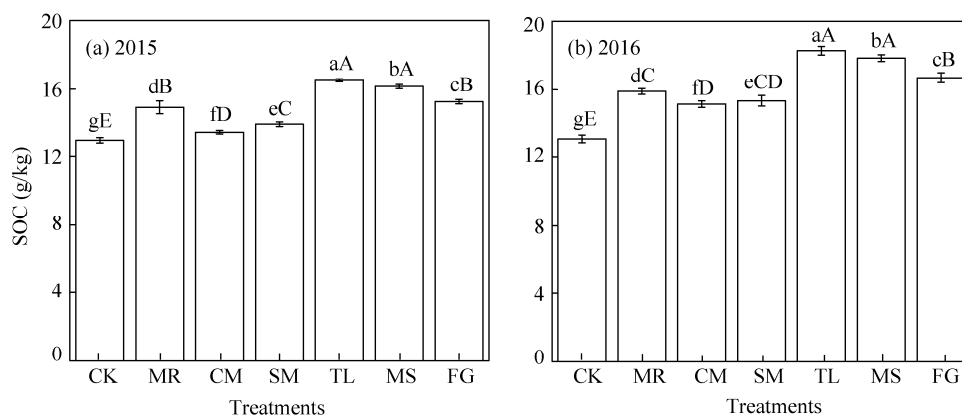


Fig. 1 Soil organic carbon (SOC) contents after the application of OMs (organic materials) in 2015 and 2016. The error bars mean standard deviations. The different lowercase and capital letters above the bars mean the significances at $P < 0.05$ and $P < 0.01$ levels in the same year among different fertilization treatments. CK, control; MR, mushroom residue; CM, chicken manure; SM, sheep manure; TL, tree leaves; MS, maize straw; FG, fodder grass. Abbreviations are the same as follows.

3.2 Labile organic carbon (LC) and recalcitrant organic carbon (RC)

The average mass recovery rate and carbon recovery rate were 95.53% (94.51%–96.32%) and 95.87% (94.54%–96.25%), respectively after separation. The separation method was simple and suitable for carbon pools size analysis, for the errors were controlled at a reasonable range.

Compared with CK, the LC and RC contents significantly increased ($P<0.01$) after the application of OMs (Table 2). Moreover, LC and RC contents were 3.2%–8.6% and 5.0%–9.4% higher in 2016 than in 2015, respectively. Compared with CK, LC contents in soil after the applications of CM and SM increased the most, and were 28.9% and 30.7%, respectively in 2016. Furthermore, LC contents in soil after the applications of MS, MR and FG were 10.8%, 9.4% and 8.5% higher than that of TL ($P<0.01$) in 2016, respectively. Compared with CK, RC contents after the applications of TL and MS, respectively increased 38.4% and 33.0% in 2016. RC contents after the application of TL were 11.7%, 17.0%, 21.8%, and 27.5% higher than those of FG, MR, SM and CM in 2016, respectively ($P<0.01$). RC contents after the application of MS were 7.3%, 12.3%, 17.0%, and 22.4% higher than those of FG, MR, SM and CM in 2016, respectively ($P<0.01$). RC content after the application of TL was 4.2% higher than that of MS ($P<0.01$) in 2016.

Table 2 LC and RC contents after the application of OMs in 2015 and 2016

SOC component	Year	CK	MR	CM	SM	TL	MS	FG
LC (g/kg)	2015	1.10±0.01 ^{eE}	1.40±0.02 ^{cC}	1.49±0.01 ^{aA}	1.43±0.01 ^{bB}	1.31±0.01 ^{dD}	1.40±0.02 ^{cC}	1.34±0.01 ^{cC}
	2016	1.19±0.03 ^{dC}	1.46±0.06 ^{bB}	1.54±0.02 ^{abA}	1.56±0.03 ^{aA}	1.34±0.02 ^{cB}	1.48±0.05 ^{bB}	1.45±0.04 ^{bB}
RC (g/kg)	2015	11.32±0.09 ^{IE}	13.08±0.24 ^{dC}	11.53±0.10 ^{IE}	12.06±0.12 ^{eD}	14.68±0.06 ^{aA}	14.26±0.11 ^{bB}	13.34±0.08 ^{cC}
	2016	11.60±0.23 ^{gG}	13.73±0.15 ^{dD}	12.59±0.11 ^{IE}	13.19±0.11 ^{0E}	16.06±0.18 ^{1aA}	15.42±0.14 ^{2bB}	14.37±0.26 ^{9cC}

Note: SOC, soil organic carbon; LC, labile organic carbon; RC, recalcitrant organic carbon; OMs, organic materials. The different lowercase and capital letters within the same row indicate the significances at $P<0.05$ and $P<0.01$ levels in the same year among different fertilization treatments. Mean±standard error.

Two-way ANOVA revealed that OMs treatments and years were both the main factors influencing SOC, LC, and RC contents (Table 3). The interactions between OMs treatments and years were significant for SOC and RC contents; however, it was not significant for LC content.

Table 3 Significant effects of OMs treatments, years and their interactions on SOC, LC and RC contents

Main effect	SOC			LC			RC		
	Mean square	F value	Sig.	Mean square	F value	Sig.	Mean square	F value	Sig.
OMs treatment (O)	14.58	316.42	**	0.094	115.71	**	12.30	511.94	**
Year (Y)	17.02	369.54	**	0.051	62.52	**	9.56	398.06	**
O×Y	0.472	10.25	**	0.002	1.90	NS	0.206	8.57	**

Note: ** indicates significance at $P<0.01$ level; NS, not significant.

3.3 Ratios of labile organic carbon and recalcitrant organic carbon to soil organic carbon (LC/SOC and RC/SOC)

Allocation proportions of LC fractions were obviously different after the application of OMs (Fig. 2). Compared with CK, LC/SOC ratio after the applications of CM and SM significantly ($P<0.01$) increased 31.7% and 21.7% in 2015, and significantly ($P<0.01$) increased 11.5% and 11.6% in 2016, respectively. LC/SOC ratio significantly ($P<0.01$) decreased after the application of TL in 2015, and significantly ($P<0.01$) decreased after the applications of TL and MS in 2016. However, compared with CK, RC/SOC ratio after the applications of CM and SM reduced and had no significant differences in 2015 and 2016. Compared with six kinds of OMs, RC/SOC ratio after the application of TL was the highest, and followed by the MS.

3.4 Pearson's correlation coefficient (r) between chemical compositions of OMs and SOC fractions

A correlation analysis was conducted to explore the relationships between chemical compositions of OMs and SOC fractions (Table 4). As a result, the most important chemical compositions of SOC content were the lignin ($r=0.709$, $P<0.01$), WOM ($r=0.754$, $P<0.01$), WHA ($r=0.652$, $P<0.05$), HSL ($r=0.685$, $P<0.05$), polyphenol ($r=0.655$, $P<0.05$), and HAL ($r=0.619$, $P<0.05$) in

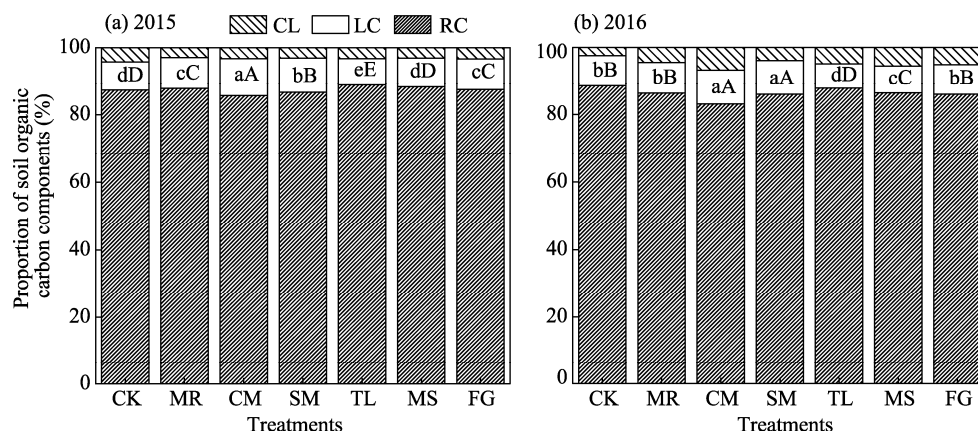


Fig. 2 Proportion of soil organic carbon components after the application of OMs in 2015 and 2016. CL, carbon loss quantities in separation; LC, labile organic carbon; RC, recalcitrant organic carbon. The different lowercase and capital letters indicate significances at $P<0.05$ and $P<0.01$ levels among different fertilization treatments.

OMs. LC content showed a negative relationship with C/N ratio ($r = -0.817$, $P<0.01$) and WHA ($r = -0.640$, $P<0.01$). RC content showed a positive relationship with lignin ($r = 0.633$, $P<0.05$), polyphenol ($r = 0.642$, $P<0.05$), lignin/N ratio ($r = 0.627$, $P<0.05$), WOM ($r = 0.733$, $P<0.01$), WHA ($r = 0.750$, $P<0.01$), HSL ($r = 0.747$, $P<0.01$) and HAL ($r = 0.725$, $P<0.01$). The most important factor affecting the LC/SOC ratio was C/N ratio ($r = -0.718$, $P<0.01$). Lignin ($r = 0.647$, $P<0.05$) and lignin/N ratio ($r = 0.738$, $P<0.01$) played important roles in RC/SOC ratio. In addition, a positive relationship was found between decomposition rates of OMs and LC content ($r = 0.507$, $P<0.05$), and LC/SOC ratio ($r = 0.734$, $P<0.01$).

Table 4 Pearson's correlation coefficient (r) between chemical compositions of OMs and SOC fractions in 2016

SOC fraction	SOC	LC	RC	LC/SOC	RC/SOC
Organic C	0.350	0.231	0.483	0.118	0.181
Total N	0.133	0.243	0.076	0.396	0.119
C/N	0.005	-0.817**	0.092	-0.718**	0.399
Cellulose	0.309	0.493	0.303	0.271	0.418
Hemicellulose	0.348	0.392	0.369	0.331	0.278
Lignin	0.709**	0.411	0.633*	0.456	0.647*
Polyphenol	0.655*	0.411	0.642*	0.318	0.408
Lignin/N	0.514	0.459	0.627*	0.504	0.738**
WOM	0.754**	-0.169	0.773**	0.266	-0.049
WLOM	0.286	0.182	0.292	0.260	0.320
WHA	0.652*	-0.640*	0.750**	0.099	-0.231
HSL	0.685*	-0.344	0.747**	0.036	-0.088
FAL	0.520	0.333	0.514	0.148	-0.220
HAL	0.619*	-0.240	0.725**	-0.100	0.086
Decomposition rate	0.218	0.507*	0.262	0.734**	-0.055

Note: LC/SOC, ratio of labile organic carbon to soil organic carbon; RC/SOC, ratio of recalcitrant organic carbon to soil organic carbon; WOM, total water-soluble organic matter; WLOM, water-soluble litter-molecular organic matter; WHA, water-soluble humic acid; HSL, humic-like substance; FAL, fulvic acid-like; HAL, humic acid-like. r values were coefficients based on the results of Pearson's correlation analysis ($n=21$). * and ** indicate significances at $P<0.05$ and $P<0.01$ levels, respectively. Decomposition rate of OMs was calculated by the contents of organic carbon dividing 540 days.

3.5 Residual quantities and carbon released quantities of OMs in decomposition process

The decomposition process of OMs could be divided into three stages, 0–90 days for a “quick decomposition period”, 90–180 days for a “slow decomposition period”, and 180–540 days for a

“stable decomposition period” (Fig. 3). In 90 days, decomposition rate of OM_s was over 70%. In 540 days, residual quantities of CM, SM and MS decreased to 5.69, 6.11, and 6.53 g from the initial 20 g, whereas those of MR, FG, and TL decreased to 8.05, 8.84, and 10.32 g, respectively. Moreover, the decomposition rates of CM, SM, and MS (71.55%, 68.16%, and 68.21%) were higher than those of MR, FG, and TL (58.64%, 55.28%, and 47.95%), respectively.

The trends of quantities of carbon released from OM_s were first quickly increased and then tended to stable in decomposition process (Fig. 4). Quantity of carbon released from MS was higher than those of other OM_s in each period. In 90 days, quantities of carbon released from OM_s were over 65%. In 540 days, quantities of carbon released from MS, TL, MR, FG, SM, and CM were 6.38, 4.85, 4.71, 4.64, 4.37, and 3.80 g, respectively.

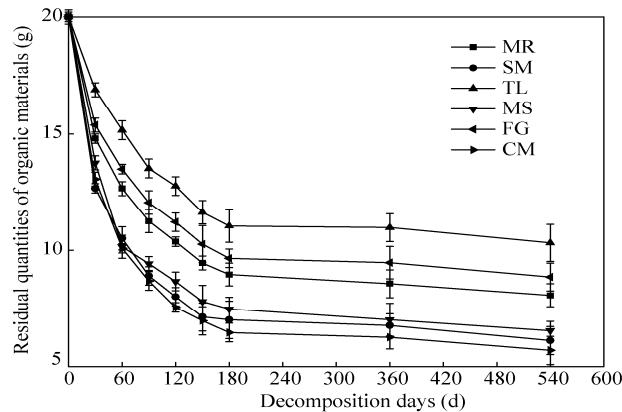


Fig. 3 Dynamic changes of residual quantities of OM_s in decomposition process under different treatments. Error bars mean standard deviations.

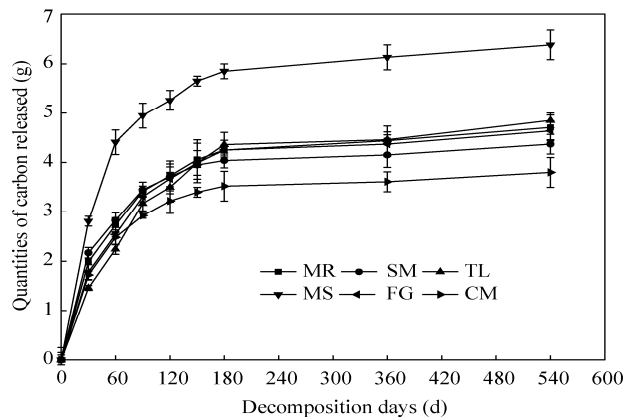


Fig. 4 Dynamic changes of quantities of carbon released from OM_s in decomposition process under different treatments. Error bars mean standard deviations.

The changes of residual quantities of OM_s in decomposition process could be fitted by the first-order kinetic equation ($y = a + b \times e^{-k \times t}$) (Table 5), with a higher correlation ($R^2 > 0.98$). k values of CM, SM and MS were higher, and required 61, 63 and 69 days to decompose one half, respectively. However, k values of MR, FG, and TL were lower than those of other OM_s, and required 117, 161 and even 590 days to decompose one half, respectively. The changes of quantities of carbon released from OM_s in decomposition process could be fitted by the first-order kinetic equation $C_t = C_0 \times (1 - e^{-k_0 \times t})$, with a higher correlation ($R^2 > 0.98$). C_0 value of MS was the highest (6.11), and followed by TL (4.75), whereas those of CM and SM were lower (3.66 and 4.18, respectively). k_0 value of SM was the highest (0.0203), and followed by MS (0.0194) and CM (0.0189), whereas that of TL was the lowest (0.0117).

Table 5 Fitted equation of residual quantities and carbon released quantities of OM_s and decomposition days

Treatment	$y=a+b \times e^{-k \times t}$				$C_t = C_0 \times (1 - e^{-k_0 \times t})$		
	a	b	k	R^2	C_0	k_0	R^2
MR	8.40	11.34	0.0162	0.9919	4.52	0.0160	0.9914
CM	6.12	13.67	0.0206	0.9945	3.66	0.0189	0.9950
SM	6.67	13.06	0.0218	0.9879	4.18	0.0203	0.9899
TL	10.64	9.56	0.0127	0.9916	4.75	0.0117	0.9923
MS	7.06	12.81	0.0209	0.9897	6.11	0.0194	0.9922
FG	9.16	10.62	0.0151	0.9912	4.51	0.0146	0.9950

Note: R^2 is determination coefficient; y is residual quantity at time t ; k is constant of decomposition rate calculated by the least-squares method, indicating the decomposing speed level; b is mass lost; a is asymptote value of y when $t \rightarrow \infty$. C_t is quantities of carbon released from organic material at time t ; C_0 is carbon mineralization potentials; k_0 is constant of carbon decomposition rate calculated by the least-squares method.

3.6 Residual quantities of cellulose and lignin of OM_s in decomposition process

The trends of residual quantities of cellulose contents were quickly declined and then tended to stable in decomposition process, which were almost the same with the trends of residual quantities of OM_s (Fig. 5). Cellulose contents of FG and TL quickly decomposed in 0–60 days, whereas those of MS, MR, CM, and SM quickly decomposed in 0–90 days. In 540 days, cellulose decomposition percentages of OM_s followed the descending order MS>CM>FG>MR>TL>SM, and reached to 64.87%, 62.67%, 62.44%, 55.93%, 51.36% and 50.14%, respectively.

Residual quantities of lignin contents of OM_s increased in the early decomposition. Lignin contents of MS, CM, and SM increased mainly in 0–60 days, whereas those of TL, FG, and MR mainly increased in 0–90 days. Compared with lignin contents of initial OM_s, in 540 days, lignin contents of TL, MS, MR, FG, SM and CM increased 26.77%, 21.36%, 19.14%, 16.09%, 11.84% and 10.68%, respectively.

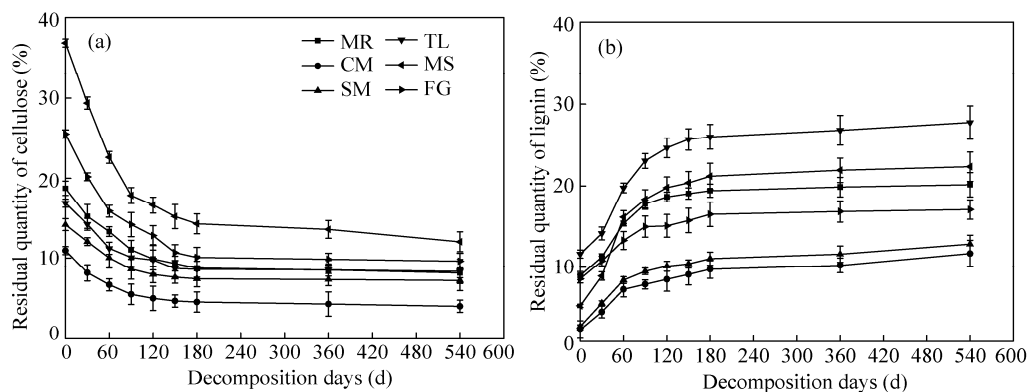


Fig. 5 Dynamic changes of residual quantities of cellulose (a) and lignin (b) contents of OM_s in decomposition process

3.7 Water-soluble organic matter of OM_s in decomposition process

Dynamic changes of water-soluble organic matter (WLOM) of OM_s in decomposition process were presented in Table 6. WLOM contents of OM_s basically declined in decomposition process, and only MS and TL increased in 90 days. WOM and WHA contents of OM_s showed rising trends in 90 days, and WOM contents of MS, FG and MR significantly increased and sustained a longer time, whereas those of CM, SM and TL slightly increased and sustained a shorter time, in addition, WHA contents of MS increased the most compared with those of other OM_s.

3.8 Humic-like substance of OM_s in decomposition process

Dynamic changes of humic-like substance of OM_s in decomposition process were shown in Table 7. There were rising trends of HSL and HAL contents in decomposition process. HSL and HAL contents of MS increased in 60 days, and reached the maximum values in 90 days. Moreover, HSL and HAL contents of MS were obviously higher than those of other OM_s in each period. HSL and

HAL contents of CM, SM, MR, TL, and FG increased in 90 days, and those of TL, MR and FG had a large increase.

Table 6 Dynamic changes of water-soluble organic matter of OMs in decomposition process

OMs	Components	Decomposition days (d)								
		0	30	60	90	120	150	180	360	540
MR	WOM	12.82±1.2	8.98±0.18	5.20±0.58	7.11±0.51	6.58±0.62	4.44±0.26	3.68±0.56	3.43±0.16	2.11±0.05
	WLOM	7.33±0.52	4.16±0.06	3.14±0.09	2.76±0.13	2.51±0.12	1.94±0.08	1.68±0.21	1.49±0.08	1.02±0.03
	WHA	5.49±0.26	4.82±0.17	2.06±0.10	4.35±0.18	4.07±0.21	2.51±0.26	2.00±0.16	1.93±0.11	1.09±0.08
CM	WOM	15.55±2.27	7.27±0.81	5.49±0.34	6.93±0.54	5.08±0.15	3.43±0.04	3.21±0.13	3.05±0.24	2.03±0.10
	WLOM	6.47±0.43	4.82±0.23	3.93±0.16	3.17±0.19	2.92±0.06	2.34±0.15	2.20±0.17	2.11±0.18	1.64±0.05
	WHA	9.07±1.24	2.45±0.03	1.56±0.07	3.76±0.27	2.16±0.07	1.09±0.09	1.01±0.08	0.94±0.06	0.39±0.03
SM	WOM	13.71±1.30	6.23±0.87	5.20±0.44	5.46±0.55	4.19±0.38	3.83±0.21	2.83±0.19	2.56±0.26	2.48±0.14
	WLOM	5.20±0.71	4.57±0.34	3.81±0.24	3.30±0.13	3.17±0.13	2.86±0.17	2.04±0.14	1.95±0.13	1.83±0.17
	WHA	8.50±0.47	1.66±0.08	1.40±0.07	2.16±0.08	1.02±0.04	0.97±0.05	0.79±0.06	0.61±0.08	0.65±0.02
TL	WOM	11.04±1.26	9.01±0.96	6.60±0.78	7.11±1.17	5.71±0.43	4.57±0.23	4.32±0.37	4.09±0.42	3.28±0.13
	WLOM	4.91±0.25	3.08±0.09	2.57±0.07	2.45±0.04	2.38±0.06	1.70±0.04	1.64±0.26	1.57±0.06	1.42±0.06
	WHA	6.13±0.53	5.93±0.37	4.03±0.26	4.66±0.54	3.33±0.45	2.87±0.28	2.68±0.22	2.52±0.08	1.86±0.17
MS	WOM	17.01±2.29	7.87±0.66	4.70±0.25	7.11±0.28	6.22±0.81	4.06±0.15	3.93±0.19	3.51±0.15	2.26±0.05
	WLOM	6.57±0.55	3.33±0.27	2.19±0.19	2.25±0.17	1.87±0.17	1.74±0.16	1.62±0.07	1.30±0.17	1.20±0.09
	WHA	10.44±2.22	4.54±0.25	2.51±0.15	4.86±0.35	4.35±0.26	2.32±0.14	2.31±0.18	2.21±0.11	1.06±0.08
FG	WOM	15.86±2.31	9.28±0.22	6.62±0.51	7.98±0.96	6.71±0.11	5.40±0.54	4.82±0.26	3.93±0.23	2.81±0.17
	WLOM	7.68±1.18	4.70±0.40	4.06±0.26	4.16±0.22	3.93±0.16	3.55±0.23	3.11±0.38	2.74±0.09	2.55±0.11
	WHA	8.19±1.14	4.58±0.38	2.56±0.06	3.82±0.16	2.78±0.04	1.85±0.07	1.71±0.06	1.19±0.04	0.26±0.03

Note: WOM, Total water-soluble organic matter; WLOM, water-soluble litter-molecular organic matter; WHA, water-soluble humic acid. Mean±standard error.

Table 7 Dynamic changes of humic-like substance of OMs in decomposition process

OMs	Components	Decomposition days (d)								
		0	30	60	90	120	150	180	360	540
MR	HSL	7.93±1.20	5.08±0.95	3.17±1.13	11.30±1.82	9.01±1.63	8.63±1.22	7.36±0.85	4.32±0.67	3.32±0.39
	FAL	4.47±0.29	4.06±0.32	2.79±0.16	4.95±0.33	4.70±0.18	4.19±0.24	3.93±0.29	3.55±0.15	2.91±0.16
	HAL	3.46±0.22	1.02±0.08	0.38±0.17	6.35±0.70	4.31±0.34	4.44±0.21	3.43±0.18	0.77±0.13	0.41±0.08
CM	HSL	6.16±1.30	4.19±0.23	2.67±0.06	7.62±1.27	7.87±0.83	7.36±0.91	6.28±0.54	3.05±0.11	2.05±0.05
	FAL	4.19±0.25	2.79±0.05	1.78±0.12	2.73±0.06	2.41±0.14	2.28±0.10	2.16±0.16	2.05±0.08	1.55±0.06
	HAL	1.97±0.06	1.40±0.03	0.89±0.05	4.89±0.23	5.46±0.46	5.08±0.45	4.12±0.31	1.00±0.14	0.50±0.03
SM	HSL	8.19±1.18	5.58±0.24	3.05±0.10	5.84±0.45	5.20±0.62	4.57±0.25	4.19±0.38	3.43±0.29	2.43±0.61
	FAL	2.16±0.13	1.78±0.06	1.27±0.11	1.52±0.04	1.90±0.15	1.78±0.09	1.65±0.03	1.40±0.04	1.03±0.05
	HAL	6.03±0.40	3.81±0.05	1.78±0.08	4.32±0.08	3.30±0.03	2.79±0.03	2.54±0.04	2.03±0.10	1.40±0.03
TL	HSL	10.28±1.21	8.50±0.79	5.08±0.47	15.86±1.27	10.53±1.21	9.90±1.27	8.96±1.19	6.09±0.23	4.09±0.16
	FAL	5.97±0.34	4.82±0.46	2.16±0.09	6.22±0.75	4.70±0.26	3.68±0.18	3.47±0.15	2.79±0.14	1.79±0.11
	HAL	4.32±0.26	3.68±0.35	2.92±0.13	9.65±0.76	5.84±0.24	6.22±0.84	5.49±0.46	3.30±0.27	2.30±0.08
MS	HSL	17.45±2.21	13.20±2.17	17.77±1.16	20.43±2.37	17.26±1.36	15.99±1.35	13.96±2.24	9.58±0.89	6.58±0.46
	FAL	9.90±1.90	7.87±0.72	6.73±0.17	7.62±0.20	7.23±0.61	5.97±0.46	4.82±0.11	3.46±0.16	2.49±0.07
	HAL	7.55±0.85	5.33±0.36	11.04±1.22	12.82±1.25	10.03±1.33	10.02±0.91	9.14±0.71	6.12±0.61	4.09±0.52
FG	HSL	14.91±1.17	1.93±1.23	7.36±1.21	14.47±1.30	11.45±1.21	10.77±1.34	8.78±1.19	7.50±0.88	5.50±0.63
	FAL	8.25±1.16	6.60±0.76	5.71±0.83	6.55±0.45	6.23±0.64	5.58±0.47	4.98±0.56	4.08±0.27	3.27±0.17
	HAL	6.66±0.64	5.33±0.31	1.65±0.06	7.92±0.78	5.22±0.57	5.19±0.41	3.80±0.16	3.42±0.13	2.23±0.03

Note: HSL, humic-like substance; FAL, fulvic acid-like; HAL, humic acid-like. Mean±standard error.

4 Discussion

Continuous application of OM_s could influence the levels of soil organic matter and the quality of some or all of its pools (Cadisch and Giller, 2000). Many studies have shown that OM_s played a positive role in altering soil environment and promoting SOC storage (Liu et al., 2005; Purakayastha et al., 2008; Banger et al., 2010). Wang (2014) found that LOC and POC contents after the application of straw were significantly higher in semi-arid soil than in sub-humid soil. Thus, the result illustrated that the effects of OM_s on labial organic carbon might be greater in the semi-arid soil. In this study, compared with no OM_s (CK), LC and RC contents in soil significantly increased ($P<0.01$) after the continuous application of OM_s for 2 years. Moreover, LC and RC contents were 3.2%–8.6% and 5.0%–9.4% higher in 2016 than in 2015, respectively, being consistent with the result of Wang (2014), who found that the SOC, light fraction organic carbon (LOC), and particulate organic carbon (POC) contents of straw treatment under plastic mulch were higher in 2010 than in 2009, and were significantly higher than that of no straw treatment.

The application of OM_s, and different sources and decomposing degrees of OM_s were all affected the SOC fractions under plastic film mulch (Li et al., 2009). Furthermore, Vanlauwe et al. (2005) indicated that short-term carbon dynamics was controlled by the quality parameters of OM_s inputted, such as lignin, N, and polyphenol contents and this funding was confirmed further by Mandal et al. (2007) and Singh et al. (2009), who suggested that the quality of OM_s was an important factor on agricultural soil carbon changes besides the amount of injected carbon. In this study, the amount of carbon inputted was equivalent in different OM_s treatments. Therefore, the variation of SOC fractions mainly depended on the nature of OM_s. Hence, a correlation analysis was conducted to explore the relationships between OM_s compositions and SOC fractions. Results indicated that the lignin and polyphenol contents in OM_s played important roles in SOC and RC contents in soil, which was consistent with the result of Gentile et al. (2010). Puttaso et al. (2013) found that lignin and polyphenols were more resistant and difficult to decompose compared with the cellulose and hemicellulose, and thus were benefited to the SOC improvement. Similarly, Trinsoutrot et al. (2000) indicated that the residues with higher concentrations of lignin and polyphenols might be more stable as an important component of SOC by biochemical processes due to the highly recalcitrant lignin. Moreover, in this study, we found that the most important factors affecting the SOC and RC contents can be attributing to the WOM, WHA, HSL, and HAL contents in OM_s.

The decomposition rate was an important index for its role in maintaining and improving soil organic matter distribution and soil fertility (Li et al., 2015). In this study, we found that the decomposition rate of OM_s was in the following descending order CM>SM>MS>MR>FG>TL, moreover, decomposition rates of CM, SM and MS were obviously higher than those of MR, FG and TL. Gao et al. (2010) and Liang et al. (2011) showed that water soluble organic carbon (WOC) contents in soil after application of animal manures were higher than those of straw. In this study, LC contents in soil after the applications of CM and SM were significantly higher than those of other OM_s, and followed by MS, whereas that of TL was the lowest. Similarly, LC/SOC ratios after the applications of CM and SM were higher, which implied that applications of CM and SM were more in favor of SOC mineralization and turnover. Moreover, the decomposition rate of OM_s was positively related with LC content and LC/SOC ratio. Therefore, applications of CM and SM significantly increased the LC contents and LC/SOC ratios mainly due to their higher decomposition rates. On the other hand, SOC and RC contents in soil after the applications of TL and MS were significantly higher than those of other OM_s, and RC/SOC ratios were similarly higher, which implied that applications of TL and MS were more in favor of SOC storage. The higher RC and SOC contents of TL and MS treatments can be attributed to the higher lignin/N ratio, lignin and polyphenols contents in TL and MS, which is not consistent with the result of Long et al. (2015), who found that SOC content of pig manure treatment in silt loam was significantly higher than those of straw treatment. The inconsistency might be attributed to the various soil type and environment.

Wang et al. (2014) and Liu et al. (2014) researched the decomposition rate of maize straw in a semi-arid and dryland soil under plastic film mulch condition using nylon mesh bags burying method, and they found that plastic film mulch could promote carbon mineralization. Therefore, application of OM_s in semi-arid soils under a long-term plastic film mulch condition is necessary. In this study, application of six kinds of OM_s significantly increased the SOC, LC, and RC contents. However, the variations of LC and RC contents, LC/SOC ratio, and RC/SOC ratio were significant different among the six kinds of OM_s treatments. For example, decomposition rate of MS was higher, and the WOM, WHA, HSL, and HAL contents in MS were the highest, and the more lignin derivatives, WHA, and HAL polymers were found in decomposition process. Thus, MS was recommended to use under plastic mulch and drip irrigation in semi-arid soils.

5 Conclusions

A two-year of field experiment has showed that LC and RC contents in soil after the continuous application of OM_s significantly increased. LC and RC contents were 3.2%–8.6% and 5.0%–9.4% higher in 2016 than in 2015. LC contents after the applications of CM and SM were significantly higher, and followed by MS, whereas that of TL was the lowest. In addition, LC/SOC ratios after the applications of CM and SM were significantly higher as well. SOC and RC contents in soil after the applications of TL and MS were significantly higher, whereas those of CM and SM were relatively lower. In addition, RC/SOC ratios after the applications of TL and MS were higher as well. In conclusion, the application of MS in the semi-arid soil under a long-term plastic mulch and drip irrigation condition could not only improve soil fertility, but also enhance soil carbon sequestration.

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