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Effects of straw mulching and plastic film mulching on improving soil organic carbon and nitrogen fractions, crop yield and water use efficiency in the Loess Plateau, China

Qin'ge Dong[a,b,c,1], Yuchen Yang[d,1], Kun Yu[a,c,e], Hao Feng[a,b,c,*]

[a] Institute of Soil and Water Conservation, Northwest A&F University, Yangling 712100, China
[b] Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling 712100, China
[c] Institute of Water-saving Agriculture in Arid Areas of China, Northwest A&F University, Yangling 712100, China
[d] College of Chemistry & Pharmacy, Northwest A & F University, Yangling 712100, China
[e] College of Water Resource and Architectural Engineering, Northwest A&F University, Yangling 712100, China

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ABSTRACT

A field experiment was conducted in the Loess Plateau of Northwest China to study the effects of plastic film mulching and straw mulching on soil water, soil organic carbon (SOC), total nitrogen (TN), microbial biomass carbon (MBC) and nitrogen (MBN), dissolved organic carbon (DOC) and nitrogen (DON), crop yield and water use efficiency under winter wheat (*Tricicum aestivum* L.)—summer maize (*Zea mays* L.) double-cropping system conditions using the following three cultural practices: (i) traditional plough with no mulching (CK), (ii) traditional plough with plastic film mulching (PM), and (iii) traditional plough with straw mulching (SM). Soil water contents were measured by the gravimetric method. SOC was determined using the dichromate oxidation method. TN was analyzed by the Kjeldahl method. MBC and MBN were determined using the chloroform fumigation extraction method. DOC and TDN were determined following Jones' procedures proposed by Jones and Willett (2006). The results showed that soil water was higher under the PM treatment than under the SM treatment and mainly changed in the upper 60 cm soil layer. Compared with the CK treatment, the concentrations of SOC and TN under the SM treatment were increased by 16.9% and 7.7% at the 0–10 cm soil depth, respectively, and the PM treatment had the similar SOC and TN concentrations. Compared with the CK treatment, soil C:N ratio was increased under the SM treatment by 6.2% ($P < 0.05$), and that under the PM treatment was decreased by 5.2% ($P < 0.05$) after three years. The concentrations of MBC under the PM and SM treatments were significantly increased by 42.0% and 24.1%, respectively, and MBN under the PM treatment was significantly increased by 5.6% at 0–10 cm soil depth after the maize season. Compared with the CK treatment, DOC was significantly increased by 21.0% under the SM treatment and decreased by 13.1% under the PM treatment, and DON was significantly increased by 10.5% under the SM treatment and decreased by 4.3% under the PM treatment at the 0–10 cm soil depth after the maize season. Relative changes of labile soil organic carbon and nitrogen fractions were more sensitive than that of SOC and TN. The relative decline or increase of labile soil organic carbon and nitrogen fractions was on average almost 13.6% for the mulching practices. Compared with the CK treatment, the average maize yields under the PM and SM treatments were increased by 26.4% and 9.8%, and the average wheat yields under the PM and SM treatments were increased by 21.3% and 7.4%, respectively. The average water use efficiencies under the PM and SM treatments were 24.5%, 8.8% in winter wheat and 22.9%, 6.3% in summer maize higher than that under the CK treatment, respectively. Our results suggested that plastic film mulching could be used as an effective practice to improve low soil quality with adequate nitrogen and increase crop yield and water use efficiency in the Loess Plateau, China.

1. Introduction

Different cultural practices may have different effects on the soil water and soil quality, and these effects may vary with soil type and climatic conditions (Lal, 2004; Huo et al., 2017). In the Loess Plateau of Northwest China, maize and wheat are both one of the most common

* Corresponding author at: Institute of Soil and Water conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling 712100, China.
E-mail address: nercwsi@vip.sina.com (H. Feng).
[1] These authors contributed equally to this work and should be considered co-first authors.

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grain crops (Li et al., 2004; Bu et al., 2013). However, soil degradation, inefficient water use, poor soil quality, and low-temperature stresses are the major constraints on crop production in this region (Fan and Zhang, 2000; Bai et al., 2009; Liu et al., 2009; Liang et al., 2010; Gao et al., 2016, 2018). Therefore, a number of techniques, including straw mulching, plastic film mulching, and rainwater harvesting, have been widely used in this region to improve soil quality and crop growth environments, thereby increasing crop yields (Li et al., 2004; Zhang et al., 2009; Liu et al., 2010; Bu et al., 2013; Li et al., 2013a,b).

In recent years, the practice of returning crop straw to the field has been widespread in winter wheat-summer maize double-cropping system in northwest China. This is mainly due to the increased use of machinery that leaves the crop straw on the land in response to a ban on straw burning made by the Chinese government. A lot of crop straw is burned directly and this has caused serious environmental pollution in the last decade (Xiao, 2012). Straw mulching is one practice for effective disposal that can decrease air pollution and provide soil organic matter (Soon and Lupwayi, 2012). Meanwhile, straw mulching can reduce evaporation loss from the soil surface, protect the surface from direct strike of raindrops, enhance soil aggregation, and promote biological activity (Salinas-Garcia et al., 2001; Blanco-Canqui and Lal, 2007; Chen et al., 2007; Blanco-Canqui and Lal, 2009; Sharma et al., 2011). Straw mulching can keep the soil warmer in winter and cooler in summer as well as reduce soil temperature oscillation (Chen et al., 2007). However, some researches present that low soil temperature caused by straw mulching froze wheat seedlings and roots during the winter, thereby negatively influenced germination and tillering (Gao et al., 2009). Therefore, straw mulching has not always been shown to increase, but decrease yields (Bonfil et al., 1999; Wang et al., 2002; Taa et al., 2004). Currently, plastic film mulching is widely used to increase soil temperature and reduce soil evaporation in vegetable and crop production in Northwest China. It is becoming a well-evolved technique for agriculture in arid, semiarid and sub-humid areas, especially where irrigation is not available and spring temperature is low (Dong et al., 2009). Plastic film mulching can increase topsoil temperature and prolong the reproductive growth period, which in turn enhances grain yield (Wang et al., 2009; Li et al., 2013a,b). However, the increases in both soil water and temperature can change the soil biological characteristics and may negatively impact on soil quality and sustainability (Li et al., 2004). It is known that the release of soil nutrients through decomposition of soil organic matter by microbes plays an important role in soil quality (Li et al., 2004). Therefore, it is necessary to critically examine the effects of straw mulching and plastic film mulching on soil organic matter to assess the changes in soil quality.

Soil organic carbon (SOC) and total nitrogen (TN) play a crucial role in the soil quality and fertility (Bauer and Black, 1994; Monaco et al., 2008; Zhao et al., 2015) because it significantly affects soil physical, chemical and biological properties, which can affect crop productivity and agro-ecosystems (Sainju et al., 2008). Maintenance of satisfactory level of SOC and TN are necessary for crop productivity and sustainable agro-ecosystems. However, it is difficult to detect the changes of SOC and TN in response to management practices in the short-term (Haynes, 2005; Gong et al., 2009). In contrast, labile soil organic carbon and nitrogen fractions (i.e., MBC, DOC, MBN, and DON) that turn over quickly can respond more rapidly to soil management than SOC and TN (Haynes, 2005; Schimel et al., 2007; Plaza-Bonilla et al., 2014). Therefore, SOC, TN, MBC, MBN, DOC and DON can be used to assess the effects of agricultural management practices on soil quality (Bremer et al., 1994; Gregorich et al., 1994; Dong et al., 2009; Plaza-Bonilla et al., 2014). Mulching practices may affect soil organic matter through decomposition and soil moisture preservation (Youkhana and Idol, 2009). However, little is yet known about the effects of different mulching practices on soil organic carbon and nitrogen fractions and crop yields in winter wheat-summer maize double-cropping system. In this study, we assumed that soil water, soil organic carbon and nitrogen fractions as well as crop yields would be affected by different mulching practices in winter wheat-summer maize double-cropping system. Therefore, the overall objectives of this study were to: (1) assess the effects of straw mulching and plastic film mulching practices on crop productivity in the Loess Plateau of Northwest China; (2) quantify SOC, TN, and labile soil organic C and N contents after 3-year field experiment to assess different mulching practices.

2. Materials and methods

2.1. Experimental site

Field experiments using a winter wheat-summer maize double-cropping system were conducted from June 2013 to June 2016 at the irrigation experimental station of the Key Laboratory of Agricultural Soil and Water Engineering sponsored by the Ministry of Education (34°18′N, 108°04′E, 506 m ASL) in Yangling, Shaanxi, China. The experimental site is located in the southern region of the Loess Plateau and belongs to a typical dry semi-humid area in northwest China. The average annual precipitation is 638 mm, with nearly 60% falling between July and October. The average annual sunshine hour is 2196 h, and the average annual air temperature is 13 °C. The precipitation distribution and daily mean air temperature were recorded throughout the year over the whole period of experiments (Fig. 1). The experimental soil was a silt clay loam with a mean bulk density of 1.45 g cm^{-3} and contained 11.17 g kg^{-1} total carbon and 0.95 g kg^{-1} total nitrogen in the 0–100 cm soil layer. The groundwater level was approximately 50 m.

2.2. Experimental design

The experimental field was cultivated with a winter wheat and summer maize double-cropping system for 20 years prior to the establishment of this experiment. This experiment had three treatments: (i) traditional plough with no mulching (CK), (ii) traditional plough with plastic film mulching (PM), and (iii) traditional plough with straw mulching (SM). The CK treatment comprised a flat, non-mulched plot. Winter wheat straw (3–5 cm in length) was applied at the rates of 4.0 t ha^{-1} in the summer maize plot and summer maize straw (3–5 cm in length) was applied at the rates of 4.0 t ha^{-1} in the winter wheat plot after the seeds were sown in the SM treatment. Plastic film (0.005 mm thick, 1.7 m wide) was mulched in the winter wheat and summer maize plots by hand after the seeds were sown in the PM treatment. The three treatments were arranged into a randomized complete block design with three replications. Each plot was 5 m long and 4 m wide. The chemical fertilizers consisted of 120 kg N ha^{-1} as $CO(NH_2)_2$ and 54 kg P ha^{-1} as Ca $(H_2PO_4)_2$ for maize and wheat, respectively, and were applied to the upper soil layer (0–20 cm) by rotary tillage for three treatments. In order to facilitate tillage, the roots for each plot were removed when the crop was harvested.

Maize seeds (cv.Qinlong-11) were sown at a density of 50,000 plants ha^{-1} on June 9, 2013, June 20, 2014, and June 15, 2015 after a rotary tillage, and the crops were harvested on September 28, 2013, October 12, 2014, and October 7, 2015. Three treatments involved alternating wide and narrow row spacing of 60 cm and 30 cm. The plots were irrigated with 80 mm water in 2013 due to low precipitation and not irrigated in 2014 and 2015. Wheat seeds (cv.Xiaoyan-22) were sown at a density of 150 kg ha^{-1} on October 16, 2013, October 18, 2014, and October 19, 2015, using a rotary tillage, and the crops were harvested on June 8, 2014, June 6, 2015, and June 5, 2016. Winter wheat was planted with 25 cm wide row space. The plots were irrigated with 60 mm water during the 2013–2014 and 2014–2015 growing seasons due to drought stress and not irrigated during the 2015–2016 growing season.

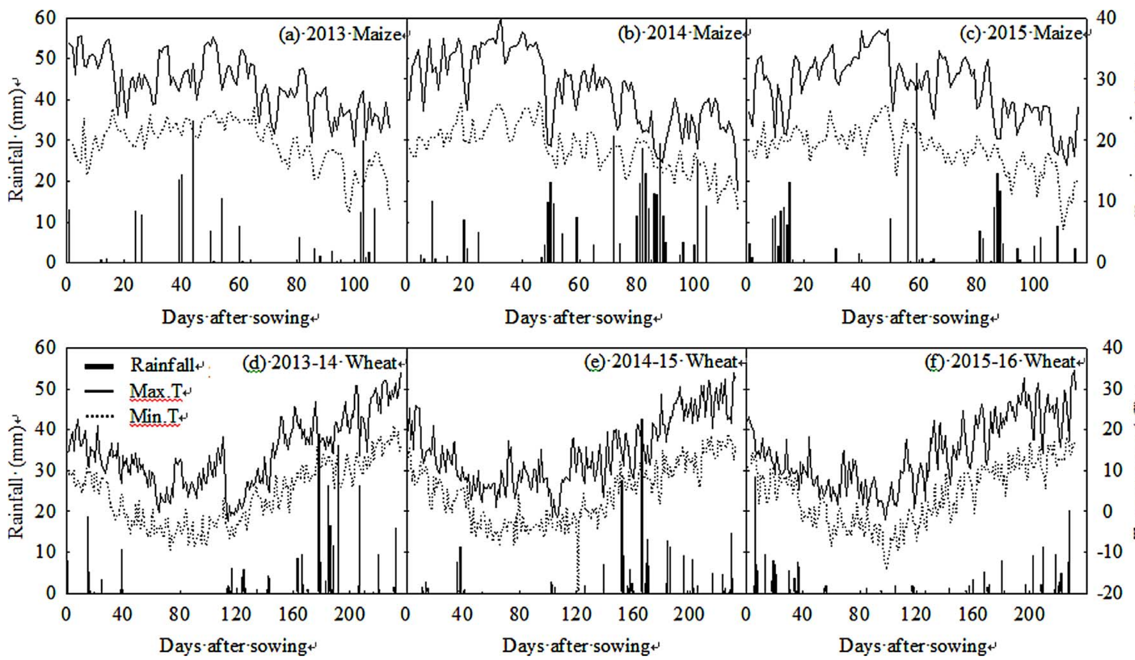

Fig 1. Rainfall distribution, maximum air temperature, and minimum temperature during the three growing seasons for summer maize and winter wheat.

2.3. Soil sampling

2.3.1. Soil water

During each summer maize or winter wheat growing season, soil water content was measured gravimetrically at 20 cm intervals within the 0–100 cm profile in each plot at seeding stage, jointing stage, filling stage, maturity stage, and harvest time. The soil water in the 0–100 cm soil layer in each plot was then calculated as the average soil water content.

In the three experimental seasons, actual crop evapotranspiration (ET_a) was calculated by using the soil water balance equation:

$$ET_a = I + P_e - R - Q - \Delta W \quad (1)$$

where I is the irrigation depth (mm); P_e is effective rainfall (mm); R is runoff loss from ground surface (mm); Q is vertical soil water exchange at the depth of 100 cm, positive downward, negative upward (mm); and ΔW is the difference in soil water storage in the 100 cm soil layer between the two soil water measurements at begin and end seasons (mm). In this experiment, the groundwater table remains at the depth of about 50 m below the surface and irrigation and rainfall amounts were low, so the upward flow and downward flow into the root were negligible. Surface runoff is omitted due to the deep groundwater table and the experimental field being relatively flat.

2.3.2. Soil sample collection and analysis

Soil samples were collected at 0–10 and 10–20 cm soil layer after the maize harvest in October 7, 2015 and the wheat harvest in June 6, 2013 and June 5, 2016. In each plot, five soil cores (each 2.5 cm diameter) were excavated randomly and mixed to form a composite sample. All fresh samples were divided into two parts. One part was air-dried and sieved through a 0.25-mm screen to determine SOC and TN. The other part from 2015 and 2016 growing seasons was immediately transported to the laboratory and stored at 4 °C until the samples were measured for MBC, MBN, DOC, and DON.

SOC was determined by the dichromate oxidation method (Mebius, 1960). TN was analyzed using the Kjeldahl method (Liu et al., 1996). Nitrate nitrogen (NO_3–N) and ammonium nitrogen (NH_4–N) were determined colorimetrically by the salicylate-nitroprusside method on a Flow-Injection Autoanalyzer (FIA, Lachat Instruments, USA). Samples of 5 g fresh homogenized soil without roots were soaked with 50 ml KCl of 2 mol L^{-1} and shook for 1 h, and then analyzed with the FIA (Lachat Instruments, USA) to determine the concentrations of extractable NO_3–N and NH_4–N.

MBC and MBN were determined by the chloroform fumigation extraction method (Wu et al., 1996). Briefly, fresh soil samples equivalent to 20 g air-dried soil were fumigated at 25 °C for 24 h. After removing the $CHCl_3$, C and N were extracted from the fumigated and non-fumigated samples with 0.5 mol L^{-1} K_2SO_4 (soil/solution ratio of 1:4 w/v) for 1 h. The filtered extracts were analyzed using a Multi 3100 N/C TOC analyzer (Analytik Jena, Germany). A k_{EC} value of 0.45 and a k_{EN} value of 0.54 were used to calculate the C and N content of the microbial biomass.

Concentrations of DOC and total dissolved nitrogen (TDN) were determined following Jones' procedures (Jones and Willett, 2006). Specifically, the field-moist soil samples (equivalent to 10 g oven-dried weight) were extracted with 50 ml K_2SO_4 of 0.5 mol L^{-1} (soil to solution ratio of 1:5 w/v) in the polypropylene bottles by shaking for 30 min at a speed of 200 rpm. The supernatant was then filtered through 0.45-μm filters into separate vials for DOC and TDN analysis by using a Shimadzu TOC-TN analyzer (Shimadzu Corp., Kyoto, Japan). DON was calculated as the difference between the TDN concentration and the combined NH_4–N and NO_3–N concentration.

2.4. Yield measurements

Summer maize yield was determined by hand harvesting the two adjacent, center rows (60 cm wide and 500 cm long) in each plot at maturity. The harvest samples were sun-dried for 8–10 days and weighed after threshing. The grain yield of summer maize was calculated when the water content in sun-dried grain was about 12% (measured by oven-drying method). Winter wheat yield was determined by hand harvesting four rows of wheat (100 cm wide and 100 cm long) in each plot at maturity. The harvest samples were sun-dried for 6–8 days and weighed after threshing. The grain yield of winter wheat was calculated considering 12% water content in the sun-dried grain.

Water use efficiency (WUE) can be expressed as:

$$WUE = \frac{Y}{ET_a} \quad (2)$$

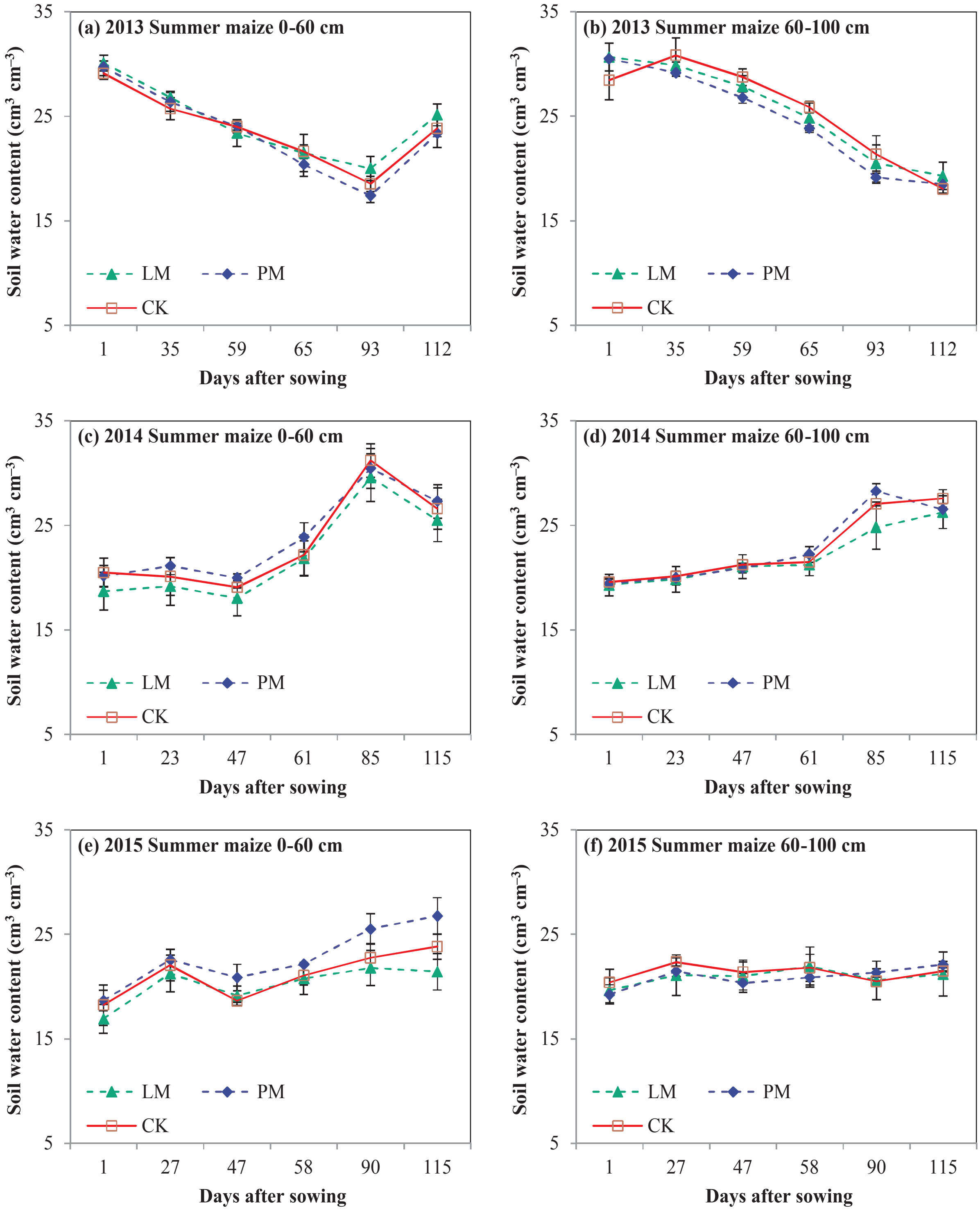

Fig. 2. Soil water content in the 0–60 cm and 60–100 cm layers of experimental plots in thethree growing seasons for summer maize. Abbreviations for treatments: CK = traditional plough with no mulching; PM = traditional plough with plastic film mulching; SM = traditional plough with straw mulching.

where Y is the grain yield, kg ha^{-1}; and ET_a is the corresponding actual crop evapotranspiration (mm).

2.5. Statistical analysis

The data were analyzed using the ANOVA procedure and statistical analyses were performed using the SPSS statistical package. Multiple comparisons of annual mean values were performed using Least significant difference (LSD) method. In all analyses, P-value $<$ 0.05 was considered significant.

3. Results

3.1. Soil water

The dynamics of soil water content in the 0–60 cm and 60–100 cm layers of all experimental plots in 2013–2015 summer maize growing seasons are shown in Fig. 2. Soil water under the PM treatment was higher than that under the SM treatment and mainly changed at the 0–60 cm soil depth. In 2013, the soil water content for three treatments declined until 93 days after the sowing of summer maize (DASM) and increased from 93 to 112 DASM at the 0–60 cm soil depth, which was due to about 55 mm of accumulation precipitation amount between 102 and 107 DASM, and basically declined during the total summer maize growing season at the 60–100 cm soil depth. The soil water content declined with the order of LM, PM, and CK before 60 DASM and increased with the order of PM, CK, and LM after 60 DASM at the 0–60 cm soil depth, and declined with the order of CK, LM, and PM during the total summer maize growing season at the 60–100 cm soil depth (Fig. 2a and b). In 2014, the soil water content for three treatments increased until 85 DASM and declined from 85 to 115 DASM at the 0–60 cm soil depth, which was due to high precipitation amount before 88 DASM and low precipitation amount after 90 DASM, and increased during the total summer maize growing season at the 60–100 cm soil depth. The soil water content declined with the order of PM, CK, and LM at the 0–60 cm and 60–100 cm soil depths during the total summer maize growing season (Fig. 2c and d). In 2015, the soil water content for three treatments increased at the 0–60 cm soil depth. The soil water content declined with the order of PM, CK, and LM at the 0–60 cm soil depth, and basically declined with the order of CK, LM, and PM at the 60–100 cm soil depth during the total summer maize growing season (Fig. 2e and f).

The dynamics of soil water content in the 0–60 cm and 60–100 cm layers of all experimental plots in 2013–2016 winter wheat growing seasons are shown in Fig. 3. In 2013–2014, the soil water content for three treatments basically increased until 194 days after the sowing of winter wheat (DASW) and declined from 194 to 236 DASW at the 0–60 cm soil depth, which was due to three large precipitation events between 170 and 194 DASW, and the similar seasonal trend appeared at the 60–100 cm soil depth. The soil water content declined with the order of LM, PM, and CK before 194 DASW and increased with the order of LM, CK, and PM after 194 DASW at the 0–60 cm and 60–100 cm soil depths (Fig. 3a and b). In 2014–2015, the soil water content for three treatments increased until 161 DASW and declined from 161 to 232 DASW at the 0–60 cm soil depth, which was due to high precipitation amount between 160 and 190 DASW, and decreased during the total growing season at the 60–100 cm soil depth. The soil water content declined with the order of CK, PM, and LM at the 0–60 cm and 60–100 cm soil depths during the total winter wheat growing season (Fig. 3c and d). In 2015–2016, the soil water content for three treatments increased until 75 DASW, declined from 75 to 210 DASW, and increased after 210 DASW at the 0–60 cm soil depth, which was due to high precipitation before 75 DASW and low precipitation after 75 DASW, and the similar seasonal trend appeared at the 60–100 cm soil depth, except for the soil water content after 210 DASW. The soil water content declined before 100 DASW with the order of PM, CK, and LM and after 100 DASW with the order of CK, PM, and LM at the 0–60 cm soil depth (Fig. 3e). The soil water content was basically higher in the CK treatment than in the PM and LM treatments at the 60–100 cm soil depth during the total summer maize growing season (Fig. 3f).

3.2. Soil organic carbon and total nitrogen

SOC at the 0–10 cm soil depth was affected by mulching cultivation with three years (Table 1). SOC was higher at the 0–10 cm soil depth than at the 10–20 cm soil depth. Compared with the CK treatment, SOC under the SM treatment was increased by 16.9% at the 0–10 cm soil depth, whereas the PM treatment had the similar SOC level. At the 10–20 cm soil depth, there was no difference in SOC between the PM and CK treatments after three years of winter wheat-summer maize rotation, which was consistent with Tian et al. (2013). After mulching cultivation with three years, TN was increased by 7.7% at the 0–10 cm soil depth under the SM treatment and increased by 9.0% at the 10–20 cm soil depth under the PM treatment, respectively, compared with the CK treatment (Table 1). From 2013 to 2016, TN at the 0–10 cm soil depth was increased by 11.1% under the CK treatment, by 5.7% under the PM treatment and by 15.2% under the SM treatment. However, the difference of TN at the 10–20 cm soil depth was not significant (Table 1). Compared with the CK treatment, soil C:N ratio was increased by 6.22% ($P < 0.05$) under the SM treatment, but decreased by 5.17% ($P < 0.05$) under the PM treatment after three years.

3.3. Labile SOC fractions under different mulching cultivations

3.3.1. Soil microbial biomass carbon and nitrogen

MBC and MBN concentrations were significantly affected by different mulching practices at the 0–10 cm and 10–20 cm soil depths, respectively, whether in summer maize season or in winter wheat season (Fig. 4). Compared with the CK treatment, MBC concentrations under the PM and SM treatments were significantly increased by 42.0% and 24.1%, respectively, MBN concentration under the PM treatment was significantly increased by 5.6%, and the difference of MBN between the SM treatment and the CK treatment was not significant at the 0–10 cm soil depth after the maize season (Fig. 4a and b). However, MBC and MBN concentrations followed the same changing trend at the 10–20 cm soil depth.

MBC and MBN concentrations under the three treatments after the wheat season followed the same changing trend as that after the maize season (Fig. 4c and d). MBC after the wheat season was significantly increased by 23.8%, 4.8% and 18.2% than after maize season for the CK, PM and SM treatments at 0–10 cm soil depth, respectively. Meanwhile, MBN concentration was higher for three treatments after the wheat season than that after the maize season.

3.3.2. Soil dissolved organic carbon and nitrogen

DOC and DON concentrations under the SM treatment were significantly higher than that under the other treatments at the 0–10 and 10–20 cm soil depths (Fig. 5). Compared with the CK treatment, DOC was significantly increased by 21.0% under the SM treatment and decreased by 13.1% under the PM treatment, whereas DON was significantly increased by 10.5% under the SM treatment and decreased by 4.3% under the PM treatment at the 0–10 cm soil depth after the maize season (Fig. 5a and b). In addition, DOC and DON followed the same changing trend at the 10–20 cm soil depth.

DOC and DON concentrations under the three treatments after the winter wheat season followed the same changing trend as that after the summer maize season (Fig. 5c and d). DOC concentrations under the CK, PM and SM treatments after the winter wheat season were 3.1, 3.2, 2.8 times higher, respectively, than that after the summer maize season. Meanwhile, DON concentration was higher for three treatments after the winter wheat season than that after the summer maize season.

3.4. Relative sensitivity of carbon and nitrogen fractions

Changes in soil organic carbon and nitrogen fractions were differed between the PM and SM treatments and the CK treatment after the summer maize (Fig. 6a and b) and winter wheat seasons (Fig. 6c and d). In general, relative changes of labile soil organic carbon and nitrogen fractions were more sensitive than that of SOC and TN. Compared with a small decline or increase of SOC and TN, the relative decline or increase of labile soil organic carbon and nitrogen fractions was on average almost 13.6% for the mulching treatments. In particular, the average relative increases of the MBC fractions from the PM treatment and the SM treatment were almost 33.1% after the maize season, 19.5% after the wheat season at the 0–10 cm soil depth, respectively. In addition, the relative changes in soil organic carbon and nitrogen fractions followed the same changing trend at the 10–20 cm soil depth.

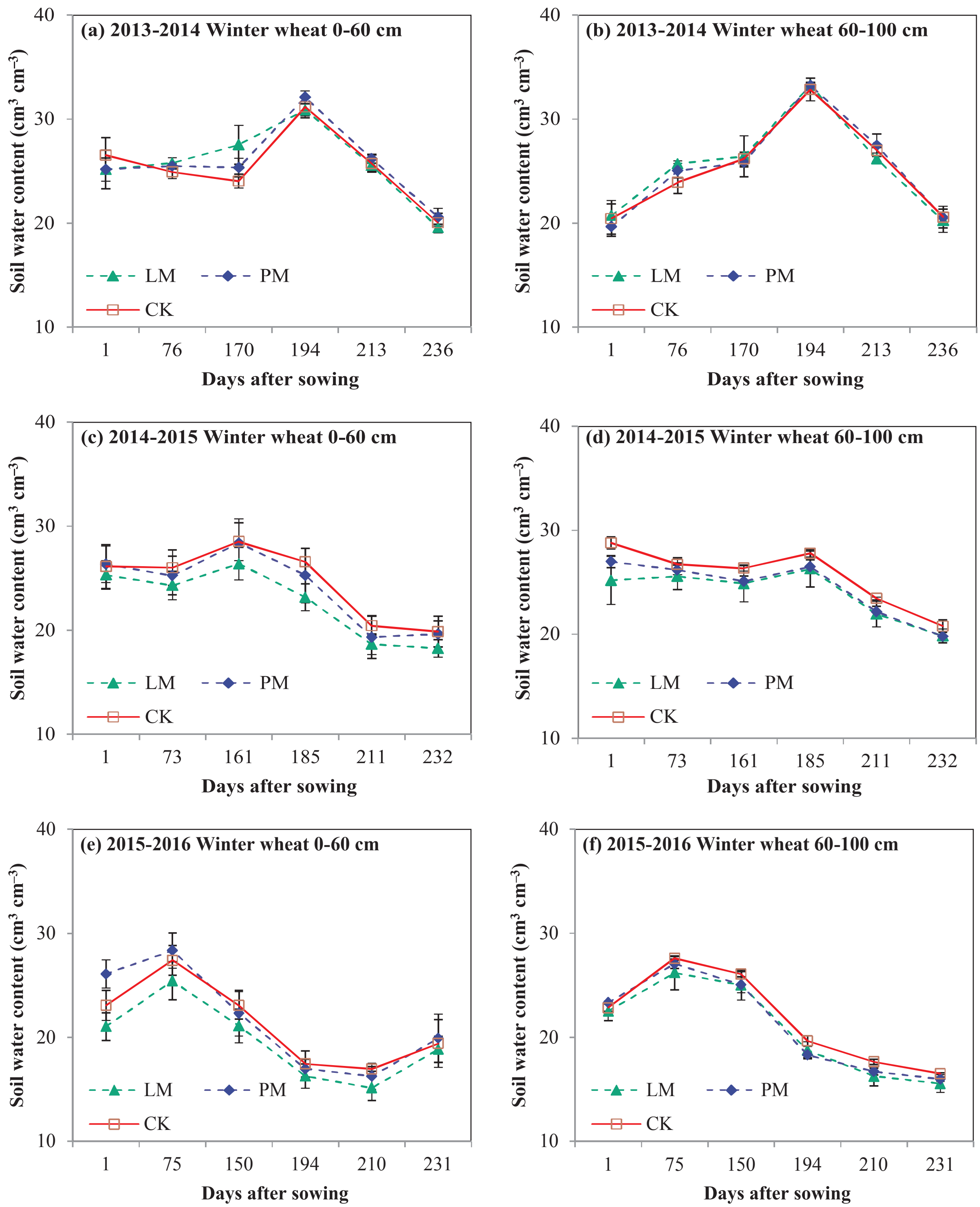

Fig. 3. Soil water content in the 0–60 cm and 60–100 cm layers of experimental plots in the three growing seasons for winter wheat. Abbreviations for treatments: CK = traditional plough with no mulching; PM = traditional plough with plastic film mulching; SM = traditional plough with straw mulching.

3.5. Grain yields and water use efficiency

The grain yields of summer maize and winter wheat were significantly affected by the different mulching treatments over the three years (Table 2). The summer maize yield was highest in 2013 and the lowest in 2014. The three-year mean maize yields for each of the treatments were ranked as follows: PM > SM > CK. Compared with the CK treatment, the mean maize yields with the PM and SM treatments were significantly increased by 26.4% and 9.8%, respectively. Similarly, the three-year mean wheat grain yield with the PM treatment was highest and lowest with the CK treatment. Compared with the CK treatment, the mean wheat yields with the PM and SM treatments were significantly increased by 21.3% and 7.4%, respectively.

The WUE represents the relationship between water consumption and the grain yield. Compared with the CK treatment, the PM and SM treatments significantly increased WUE in three summer maize-winter wheat growing seasons, except for the 2013 and 2014 summer maize growing seasons (Table 1). The average WUE under the PM and SM

Table 1
Soil organic carbon (SOC) and total nitrogen (TN), and the ratio of SOC to TN (C/N) in different soil layers in 2013 and 2016.

Soil depth (cm)	Treatments	SOC ($g\,kg^{-1}$)		TN ($g\,kg^{-1}$)		C/N	
		2013	2016	2013	2016	2013	2016
0–10	CK	9.85a	11.08b	1.11a	1.23b	8.89a	8.99b
	PM	10.14a	10.92b	1.17a	1.24b	8.64a	8.80b
	SM	10.21a	12.96a	1.15a	1.33a	8.86a	9.76a
10–20	CK	7.64a	8.84a	0.89a	0.96b	8.69a	9.19a
	PM	7.94a	8.84a	0.92a	1.05a	8.68a	8.44b
	SM	7.83a	9.04a	0.91a	0.95b	8.64a	9.55a

CK: traditional plough with no mulching; PM: traditional plough with plastic film mulching; SM: traditional plough with straw mulching. Means followed by different lower-case letters are significantly different between the mulching practices at $P \leq 0.05$.

treatments were 24.5%, 8.8% in winter wheat and 22.9%, 6.3% in summer maize higher than that under the CK treatment, respectively. In addition, the PM treatment obtained a higher grain yield using less water.

4. Discussion

4.1. Effect of mulching practices on soil water

With a lack of timely precipitation under arid or semi-arid conditions, surface mulching practices (e.g., straw mulching and plastic film mulching) can reduce unproductive water losses from the soil surface and improve soil water and thermal status, which play an important role in crop management and growth (Kouwenhoven et al., 2002; Zhao et al., 2014). Straw mulching can increase water infiltration into soil, reduce runoff, and increase water in the soil profile (Li et al., 2013a,b). Compared with the CK treatment, the SM treatment consistently increased soil water content in the 0–60 cm soil layer during the summer maize growing season of 2013 and winter wheat growing season of 2013–2014 (Figs. 2a and 3a). This was because that the rate of water vapor flux through mulched straw was generally slow compared with the rate of water loss from a moist soil surface (Li et al., 2013a,b). However, a lower soil water content in the 0–60 cm soil layer was observed for the SM treatment during the summer maize growing season of 2014 and 2015 (Fig. 2c and e), and the winter wheat growing season of 2014–2015 and 2015–2016 (Fig. 3c and e). This was mainly because the mulched straw promoted summer maize and winter wheat development and thus the greater consumption of soil water led to low soil water content (Zhang et al., 2011), and the effectiveness of straw mulching in reducing evaporation weakened with natural decomposition. In addition, there was low rainfall and increased plant growth led to high transpiration rates, further accounting for the reduced soil water content during the winter wheat growing seasons of 2014–2015 and 2015–2016.

Currently, plastic film mulching has been widely used in China for increasing yield (Zhang and Yang, 2001) and water use efficiency (Ma, 1999). In the Loess Plateau with serious water deficit for agricultural production, plastic film mulching has been utilized in cultivating corn, spring and winter wheat (Zhang et al., 2013; Wu et al., 2015). Compared with the CK treatment, the PM treatment resulted in an increase in soil water at the 0–60 cm soil depth during the summer maize growing seasons before 60 DASM in 2013 and of 2014, 2015 (Fig. 2a, c and e), and the winter wheat growing seasons of 2013–2014 (Fig. 3a). This was mainly because that high precipitation appeared in the above

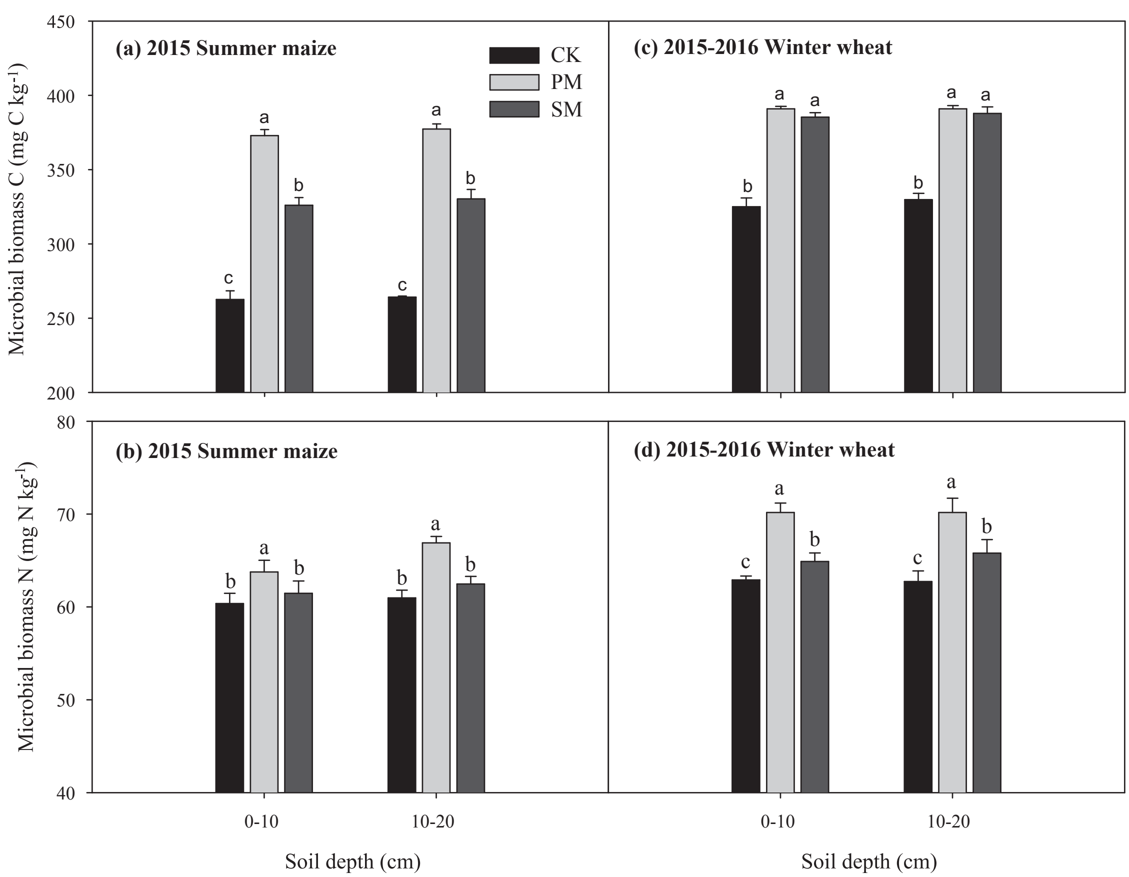

Fig. 4. Effects of mulching on soil microbial biomass carbon and nitrogen at harvest in 2015 maize season (a and b) and in 2015–2016 wheat season (c and d). Error bars represent standard errors of the means (n = 3). Means followed by different letters are significantly ($p < 0.05$) different among treatments within each soil depth. Abbreviations for treatments: CK = traditional plough with no mulching; PM = traditional plough with plastic film mulching; SM = traditional plough with straw mulching.

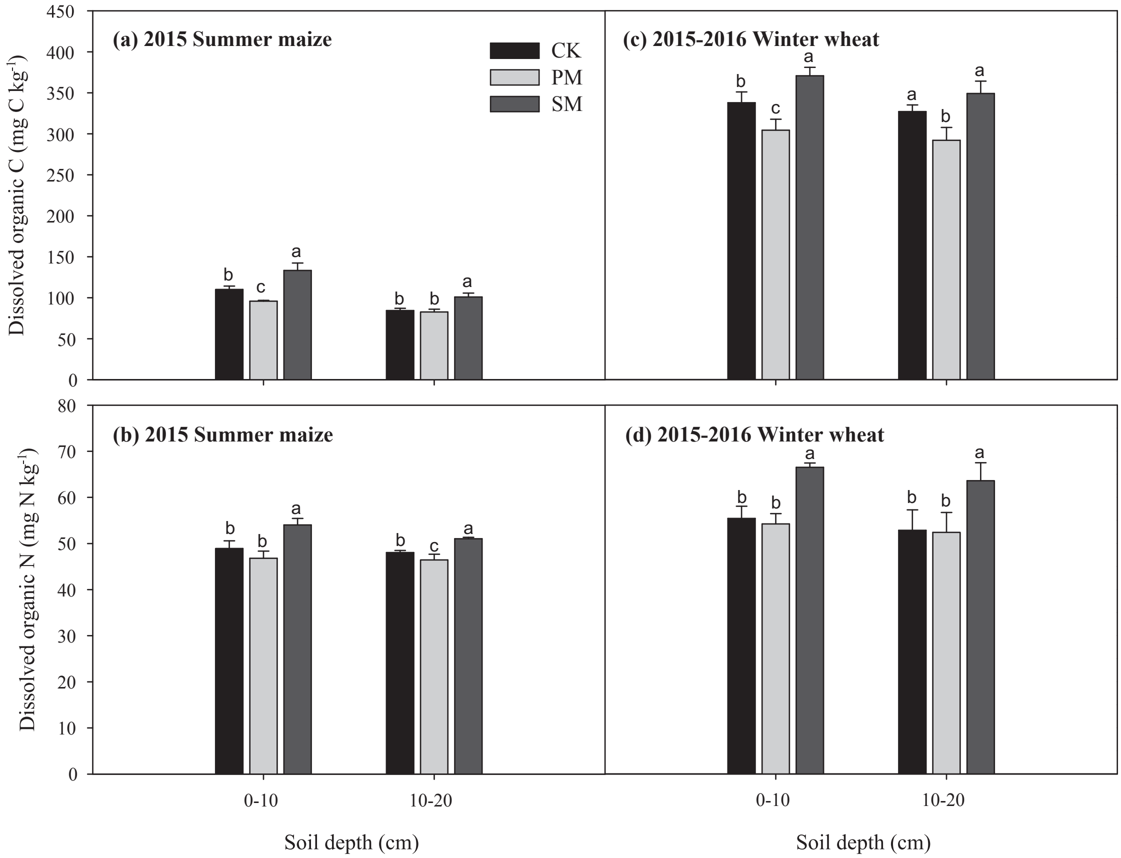

Fig. 5. Effects of mulching on soil dissolved organic C and N at harvest in 2015 maize season (a and b) and in 2015–2016 wheat season (c and d). Error bars represent standard errors of the means (n = 3). Means followed by different letters are significantly ($p < 0.05$) different among treatments within each soil depth. Abbreviations for treatments: CK = traditional plough with no mulching; PM = traditional plough with plastic film mulching; SM = traditional plough with straw mulching.

mentioned growing seasons and mulched plastic film blocked the water vapor movement pathway from the soil surface to the air and greatly reduced evaporation, which could help to solve the low temperature phenomenon induced by straw mulching. However, a lower soil water content in the 0–60 cm soil layer was observed for the PM treatment during the summer maize growing season after 60 DASM in 2013 (Fig. 2a), and the winter wheat growing season of 2014–2015 and 2015–2016 (Fig. 3c and e). This was mainly because that the PM treatment increased crop growth and higher crop transpiration rates during the crop growing seasons led to low soil water content (Li et al., 2013a,b), and reduced soil water by intercepting rainwater and preventing rainwater from penetrating the soil when frequent but small rainfall appeared during the crop growing seasons (Döring et al., 2005). In addition, soil water content at the 0–60 cm soil depth was higher in PM than in SM during the summer maize growing seasons of 2014 and 2015 (Fig. 2c and e), and the winter wheat growing seasons of 2013–2014, 2014–2015 and 2015–2016 (Fig. 3a, c and e). This was similar to the results found by Li et al. (2013a,b) and Zhang et al. (2013) in the same region. The increase in soil water could be attributed to better water retention as PM could reduced more soil evaporation and thus conserve more soil water than SM did, except for the summer maize growing season of 2013, which had the lower rainfall than the other summer maize growing seasons.

4.2. Effect of mulching practices on soil organic matter fractions

Plastic film mulching could lead to a decrease in the SOC and decline in soil quality through increased SOC mineralization and microbial activity (Li et al., 2004; Zhou et al., 2012), indicating that plastic film mulching may not be a long-term solution in managing the soil. In contrast, some other studies reported that plastic film mulching practice contributed to the positive balances of SOC due to the increase in root biomass and root deposition of crops returned back to the soil (Fan et al., 2012; Gao et al., 2014). In our study, compared with the CK treatment, mulching practices leaded to a similar (PM) or increase (SM) SOC concentration at the 0–20 cm soil depths after three years of winter wheat-summer maize rotation (Table 1). Compared with the initial SOC concentration, the SOC concentration under the PM treatment had a comparatively more decrease tendency at the 0–10 cm soil depth, which was inconsistent with Fan et al. (2012). This was probably because the roots for each plot were removed when the crop was harvested in order to facilitate tillage, which decreased the carbon input as crop roots biomass. Compared with the CK treatment, the PM treatment was not conductive to the accumulation of the SOC concentration, despite the insignificant decrease tendency, whereas the SM treatment increased the SOC concentration (relative increase by 16.9%) at the 0–10 cm soil depth after the 3-year of winter maize-summer wheat rotation. TN was an important indicator of soil health. In our study, little changes in TN were found from 2013 to 2016 in three treatments (Table 1). Soil ran short of nitrogen when TN content was less than $2\ g\ kg^{-1}$ (Zhou et al., 2012). In our study, TN in three treatments ranged from 0.89 to $1.33\ g\ kg^{-1}$, which indicated that the soil at the experiment site was very poor in TN. A positive feedback loop between SOC and C/N was observed when the C/N ratio ranged from 5.6 to 11.3 in a similar agro-ecosystem characterized by mulching practices in a typical loess soil (Zhou et al., 2012). The low ration of SOC to TN under the PM treatment (Table 1) could mean an acceleration of soil organic matter decomposition (Jia et al., 2006). A high input of organic matter could increase labile soil organic carbon and nitrogen fractions (Graham et al., 2002). However, the increase in production of high-yield and in soil water and topsoil temperature would result in consistent year-on-year decreases in the SOC concentration.

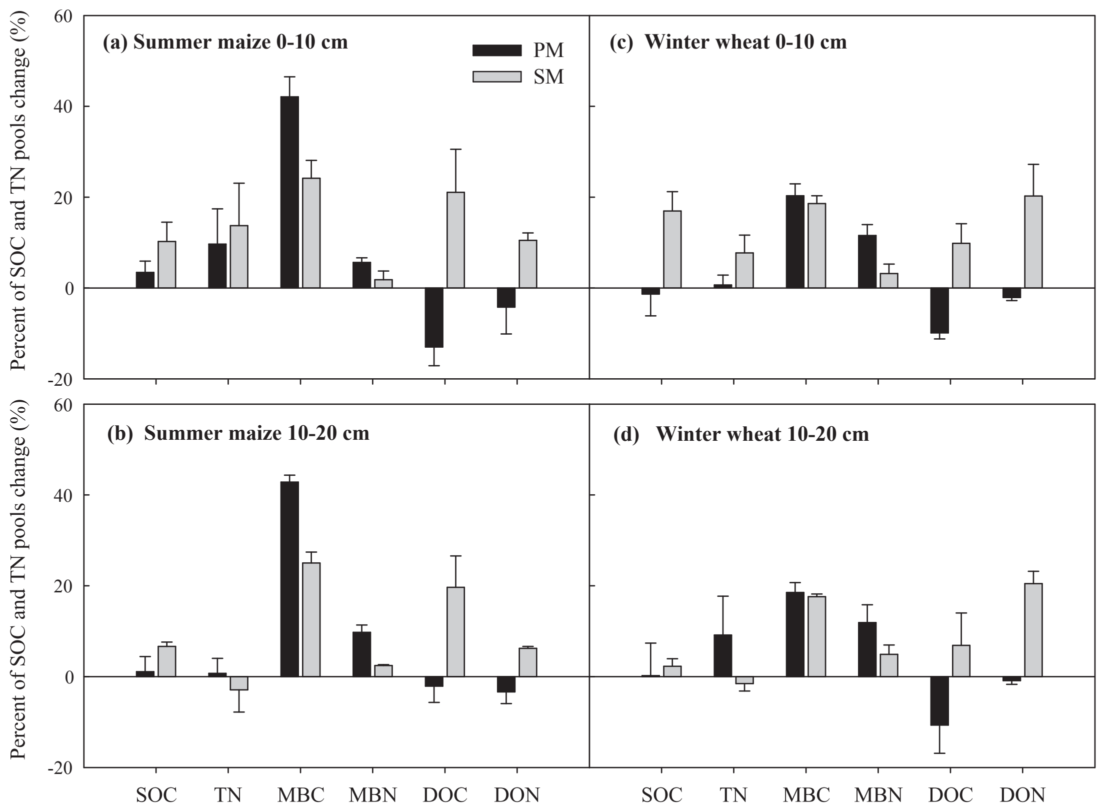

Fig. 6. Changes of soil organic carbon, total nitrogen, and soil organic carbon and nitrogen fractions under PM and SM versus CK at harvest in 2015 maize season (a and b) and in 2015–2016 wheat season (c and d). The changes were presented: (soil fractions under PM or SM—soil fractions under CK) × 100/soil organic fractions under CK. Error bars represent standard errors of the means (n = 3). Abbreviations for treatments: CK = traditional plough with no mulching; PM = traditional plough with plastic film mulching; SM = traditional plough with straw mulching.

MBC and MBN were recognized as important indicators of soil quality that respond rapidly to soil management practices (Chen et al., 2009), although they only had a small proportion of SOC and TN (McLauchlan and Hobbie, 2004; Powlson et al., 1987). The MBC only took about 1–5% of SOC, and the MBN only accounted for 2–6% of TN, but they had an important influence on the rate of nutrient cycling in agricultural ecosystems (Brookes et al., 1985; Powlson et al., 1987). MBN was regarded as the most labile soil organic nitrogen fraction because of the rapid generation rate of soil microbial biomass and represented both a source and sink of mineral nitrogen (Luo et al., 2015). In our study, the significantly higher MBC and MBN concentrations in the mulching practices (PM and SM) versus the CK treatment in the 0–10 and 10–20 cm soil layers were observed (Fig. 4). It supported the previous observation that mulching practices increased MBC and MBN in the topsoil compared with the CK treatment, and the higher topsoil moisture and temperature conditions played an important role in the changes of MBC and MBN in the semiarid area (Li et al., 2004; Liu et al., 2013). Meanwhile, it indicated that mulching practices would improve soil biochemical properties and increase soil microbial activity (Zhou et al., 2012). As reported by Smith et al. (1992) and Li et al. (2004), MBC was significantly improved because of the increased topsoil temperature from plastic film mulching and had a high positive correlation

Table 2
Crop yields, ET_a and water use efficiency at harvest time in 2013–2016 growing seasons.

Time	Treatment	Summer maize			Winter wheat		
		Yield (kg ha^{-1})	ET_a (mm)	WUE (kg ha^{-1} mm^{-1})	Yield (kg ha^{-1})	ET_a (mm)	WUE (kg ha^{-1} mm^{-1})
2013	CK	9565b	377.2	25.4a	–	–	–
	PM	9966a	390.1	25.5a	–	–	–
	SM	9905a	376.3	26.1a	–	–	–
2014	CK	5579b	310.9	17.9b	7545b	384.6	19.6c
	PM	8169a	308.4	26.5a	8910a	382.2	23.3a
	SM	5822b	311.1	18.7b	8271b	381.7	21.7b
2015	CK	7160b	245.4	29.2c	7149b	372.6	19.2c
	PM	8615a	233.2	36.9a	8610a	368.3	23.4a
	SM	8111a	249.9	32.5b	7580b	368.5	20.6b
2016	CK	–	–	–	4801b	249.1	19.3c
	PM	–	–	–	6729a	269.8	24.9a
	SM	–	–	–	5028b	245.7	20.5b

CK: traditional plough with no mulching, PM: traditional plough with plastic film mulching, SM: traditional plough with straw mulching. ET_a: actual crop evapotranspiration, WUE: water use efficiency.

with soil moisture. In our study, MBC and MBN were higher under the PM treatment than that under the CK treatment, which was largely due to the increase of soil water availability and temperature during the crop growing seasons as reported by our team previously (Chen et al., 2017).

DOC represented the main source of energy-rich carbon substrate for microorganisms and microbial metabolites constituted an important proportion of DOC (Montano et al., 2007; Kamble et al., 2014). DON represented a labile nitrogen source for soil microorganisms (Jones and Kielland, 2002). In contrast to MBC and MBN, the PM treatment showed a lower DOC and DON concentration after both summer maize and winter wheat growing seasons compared with the CK treatment. This probably reflected a lower microbial use and microbial production of DOC and DON. The increases in soil water and temperature due to plastic film mulching could change the biological characteristics (Song et al., 2002), which could stimulate microbial activity and increases DOC and DON consumption (Neff and Asner, 2001), thereby decreasing the DOC concentration (Fig. 5a and c). This indicated that the PM treatment can be an effective practice in soils with adequate N, low soil water and temperature. The SM treatment showed a higher DOC and DON concentration after both summer maize and winter wheat growing seasons compared with the CK treatment. This was mainly because that crop straw decomposition could release a substantial amount of DOC, increased labile organic C and N, and alleviated nutrient limitation of the microbes (Chan et al., 2002; Chen et al., 2009; Li et al., 2016; Xie et al., 2017). This indicated that the SM treatment can be applied in soils with low quality. In addition, soil microorganisms consumed SOC for energy (Loveland and Webb, 2003), therefore, SOC was much important for maintaining the pool of soil nutrients and improving nutrient availability (Zhao et al., 2009). In our study, MBC, MBN, DOC and DON were higher under the SM treatment than under the CK treatment in the 0–10 and 10–20 cm soil layer (Fig. 6), this was mainly because that straw mulching increased SOC concentration, thereby stimulating microorganisms and producing more MBC, MBN, DOC and DON, which was consistent with Li et al. (2016).

4.3. Effect of mulching practices on grain yields

The effects of mulching practices on crop yields depend on the climate condition, crop type, and soil texture (Pituello et al., 2016). In our study, compared with the CK treatment, the mean maize and wheat grain yields under the SM treatment were increased by 9.8% and 7.4%, respectively, and the mean maize and wheat yields under the PM treatment were increased by 26.4% and 21.3%, respectively (Table 2). This was because that the SM and PM treatments reduced soil evaporation, increased the proportion of plant transpiration, and provided the higher soil MBC and MBN than the CK treatment did. Correlation analysis revealed that maize and wheat grain yields were significantly correlated with soil MBC, MBN, DOC, and DON concentrations under the SM treatment ($P < 0.05$), and with soil MBC and MBN under the PM treatment ($P < 0.05$). These results suggested that adequate available C and N should be supplied to achieve high crop yields in soils. N was the most yield-limiting and difficult to manage nutrient in crop systems, and N dynamics became more complex in the presence of straw mulching and plastic film mulching (Eagle et al., 2000; Xie et al., 2017). The performance in grain production of both summer maize and winter wheat was better under the PM treatment than under the SM treatment, this suggested that the PM treatment was more efficient than the SM treatment in alleviating C and N and hydrothermal limitations to maize and wheat growth, which was consistent with Luo et al. (2015) and Chen et al. (2017).

5. Conclusion

Our study showed that soil water was higher under the PM treatment than under the SM treatment and mainly changed in the upper 60 cm soil layer. Soil organic carbon and nitrogen fractions were significantly affected in topsoil by the PM and SM treatments. Compared with the CK treatment, the PM treatment decreased DOC and DON concentrations, but significantly increased MBC and MBN concentrations, and the SM treatment significantly increased SOC, TN, MBC, DOC, and DON concentrations. In addition, the average grain yields under the PM and SM treatments were 26.4%, 9.8% in summer maize and 21.3%, 7.4% in winter wheat higher than that under the CK treatment, respectively. The average WUE under the PM and SM treatments were 24.5%, 8.8% in winter wheat and 22.9%, 6.3% in summer maize higher than that under the CK treatment, respectively. Thus it can be concluded that the SM treatment can be an effective practice for improving SOC, TN, MBC, DOC, and DON concentrations in the short term, but the PM treatment, which can improve soil MBC and MBN concentrations, is recommended with the objective of the highest crop yield and water use efficiency in the Loess Plateau, China.

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