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Response of labile organic C and N pools to plastic film removal from semiarid farmland soil

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Abstract

To examine the effects of plastic film removal on grain yield and soil organic matter (SOM), a spring maize (*Zea may* L.) field experiment was conducted for 5 yr at Changwu Agricultural and Ecological Experimental Station of Northwest China. Compared with traditional plastic film mulching during entire growing stages (FM), plastic film removal at the silking stage (RM) resulted in a 6.3% higher average maize yield. Under the RM treatment, soil organic carbon and total nitrogen significantly increased after the 5-yr cultivation in the 0- to 20-cm layer. Significant increases in extractable organic C (EOC), $KMnO_4$-oxidizable C ($KMnO_4$-C) and C management index (CMI) in the 0- to 20-cm layer, and light fraction organic C and EOC in the 20- to 40-cm layer were observed in response to plastic film removal after the 1-yr treatment; the responses were more significant after 5 yr. Under the RM treatment, significant increases in microbial biomass C, light fraction organic N, extractable organic N, $KMnO_4$-C and CMI were also observed after five years in the 20- to 40-cm layer. Moreover, $KMnO_4$-C and EOC were much more sensitive than other labile SOM fractions to the application of RM, even after only 1 yr of cultivation. Therefore, compared with mulching for the whole growing season, plastic film removal at the maize silking stage is an effective option for increasing yields and enhancing SOM concentration and soil sustainability in the regions with semiarid monsoon climates that have sufficient rainfall during maize reproductive stages.

Keywords: Plastic film mulching, plastic film removal, labile soil organic matter, C management index, spring maize

Introduction

The Loess Plateau has a typical semiarid monsoon climate, in which maize (*Zea mays* L.) is one of the most common grain crops; however, cool air temperatures and drought during the early crop growth stage in the spring often result in poor crop yields (Liu *et al*., 2009). Plastic film mulching, which has been widely used in China's semiarid region (Dong *et al*., 2009), may greatly improve crop yields by increasing soil moisture and topsoil temperatures (Bu *et al*., 2013). Although the plastic film mulching technique generally affords greater grain yields and economic benefits than conventional cultivation (Zhou *et al*., 2009; Fan *et al*., 2012), in some conditions (e.g. high air temperatures), the technique when used throughout the growing season is detrimental to crop yield improvement (Wang *et al*., 2009), most likely because it accelerates plant senescence during the later part of the growing season. On the Loess plateau, the rainy season occurs from July to September and coincides with the spring maize reproductive stages (RS) (Liu *et al*., 2010). Compared with mulching for the entire growing season, removing plastic film at the maize silking stage decreased the leaf and root senescence rate, decreased the soil temperature and slightly increased the final grain yield (Liu *et al*., 2014a). Although there are some reports on effects of different mulching times during crop growing season on yields (Wang *et al*., 2009; Liu *et al*., 2014a), little is known about the effects of removing plastic film at the silking stage relative to retaining them throughout the whole maize growing season on SOC, total nitrogen (TN), labile SOM pools and C management index (CMI).

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Labile SOM fractions such as microbial biomass C (MBC) and N (MBN), light fraction organic C (LFOC) and N

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(LFON), water-soluble organic C (WSOC) and N (WSON), extractable organic C (EOC) and N (EON) and $KMnO_4$-oxidizable C ($KMnO_4$-C) are all characterized by their rapid turnover and are considered to be early indicators of the effects of management practices on soil quality (Haynes, 2005; Gong *et al.*, 2009). Crop residues are generally incorporated into agricultural soils as coarse fragments. The breakdown of crop residues is mediated by soil microbes, which derive their energy and other nutrients from the residues (St. Luce *et al.*, 2014). Decomposition of crop residues results in the formation of light fraction organic matter (LFOM), which are subsequently further degraded by microorganisms and generate soluble organic matter as a by-product (Murphy *et al.*, 2000). The LFOM includes partially decomposed plant residues together with microbial by-products and is a major source of N for microbes (Gregorich *et al.*, 2006). In 1995, the CMI was first derived by combining labile and non-labile C fractions (Blair *et al.*, 1995). CMI provides an integrated measure of quantity and quality of SOC. Compared to a single measure such as the total SOC concentration, CMI can be used as a more sensitive indicator of the rate of change of SOC in response to soil management changes and was suggested to be a useful technique for describing soil fertility (Whitbread *et al.*, 1998). Subsequently, the CMI has been widely used as a sensitive indicator of SOC variation rates in response to soil management changes (Gong *et al.*, 2009). Accordingly, understanding the labile SOM pools, along with SOC, TN and CMI, is essential to identify changes in SOM quality and environmental sustainability.

As part of our evaluation of plastic film mulching cultivation, this study was designed to (1) reveal the impacts of removing plastic film during the maize RS on SOC, TN, CMI and especially the labile SOM fractions under both one- and 5-yr experimental durations, and to (2) evaluate the sensitivity of labile SOM fractions and CMI as early indicators for SOM change.

Materials and methods

Site description

The study was conducted from 2009 to 2013 at Changwu Agricultural and Ecological Experimental Station (35.28°N, 107.88°E, 1200 m altitude), which is located in semiarid area on the Loess Plateau of China. The annual mean air temperature was 9.7 °C, and the average annual precipitation from 1957 to 2008 was 582 mm with 73% of this falling during the maize growing season. The annual mean air temperature and precipitation amount averaged 10.1 °C (range 9.4–11.0 °C) and 555 mm (range 481–644 mm) from 2009 to 2013, respectively. The years 2010, 2011 and 2013 were wet years and the years 2009 and 2012 were dry years. The soil at the study site was developed from loess and had a silt loam texture according to the USDA texture classification system. The soil properties at the top 20 cm were as follows: bulk density 1.3 g/cm^3, pH 8.4, organic C 8.2 g/kg, total N 1.05 g/kg, available phosphorus (Olsen P) 20.7 mg/kg, available potassium (NH_4OAc-K) 133.1 mg/kg and mineral N 28.8 mg/kg in April 2009, prior to the start of the experiment.

Experimental design and field management

We applied two treatments, including plastic film mulching during all growth stages (FM) and plastic film removal at the silking stage (RM), to maize plots. The treatments were applied to 56-m^2 (8 m × 7 m) plots arranged in a randomly block design with three replicates. After ridging the treatment plots, chemical fertilizers and organic manure were broadcast over the soil at rates of 90 kg N/ha in the form of urea (containing 46% N), 40 kg P/ha in the form of calcium super phosphate (12% P_2O_5), 80 kg K/ha in the form of potassium sulphate (45% K_2O) and 30 t/ha cattle manure (total organic C 5.6%, total N 0.28%); the soil was then ploughed to mixed the fertilizer into the subsoil. The treatments involved an alternating wide and narrow row spacing of 60 cm and 40 cm. Plastic film (0.005 mm thick, 1.2 m wide) was used to cover the soil in two treatments. The maize was planted 5 cm deep at a density of 85,000 plants/ha using a hole-sowing machine. These holes allowed rainwater to collect and be channelled from the ridges to enter the soil. All of the plots were top-dressed twice with 67.5 kg N/ha (urea) during the jointing and silking stages, using the same handheld device as used for sowing.

Sampling and measurements

At maturity, the crop biomass and grain yield were measured for all plants selected from a 10-m^2 area in each plot, and all samples were dried to a constant weight in a fan oven at 75 °C. Soil was sampled after harvesting at the end of September in 2009 and 2013. At each plot, soil cores were drilling randomly using a 4-cm-diameter auger with five replications and then mixed together to form one composite sample for every soil depth (0–20 cm and 20–40 cm). The fresh subsamples were refrigerated (0–4 °C) until the samples were measured for MBC and N, WSOC and N, and EOC and N. The other subsamples were air-dried and sieved through a 2-mm sieve and then analysed for LFOC and N. Subsamples of <2-mm soils were then grounded to pass 0.15-mm sieve for determination of soil TN, SOC and $KMnO_4$-C. Soil organic C was analysed by the dichromate oxidation method (Mebius, 1960) and total N by the Kjeldahl method (Bremmer & Mulvaney, 1982).

Light fraction organic C and N used the density fractionation scheme as described by Gregorich & Ellert (1993). The amounts of soil organic C and N in the light fraction were determined using a CHN elemental analyzer (Fisons Instruments, Germany). Microbial biomass C and N were measured using a modified chloroform fumigation-extraction method (Brookes *et al*., 1985; Vance *et al*., 1987). Water-soluble organic C and N were extracted using a method described by Liang *et al*. (1998). Extractable organic C and N were measured using a method described by Jones & Willett (2006). Total organic C concentration in the filtrate was measured using an automated total organic C analyzer (TOC-Vcph, Shimadzu, Japan). The filtrates were later defrosted at room temperature and analysed for NH_4^+-N and NO_3^--N with a continuous flow analyzer (FLOWSYS, Italy), and total soluble N by dual-wavelength ultraviolet spectrophotometry after alkaline persulphate oxidation (Norman *et al*., 1985; Cabrera & Beare, 1993). Total organic N concentrations in the filtrates were calculated by taking the difference between total soluble N and total mineral N. MBC and MBN were calculated by taking the difference between total organic C and soluble N of the fumigated and non-fumigated soils, respectively. A K_C value of 0.45 (Vance *et al*., 1987) and a K_N value of 0.54 (Brookes *et al*., 1985) were used to calculate the C and N content of the microbial biomass. $KMnO_4$-oxidizable C was determined following the method of Blair *et al*. (1995) and Vieira *et al*. (2007).

Calculations and statistical analysis

CMI was calculated for each treatment using a reference sample value for the calculation according to the method of Blair *et al*. (1995). Based on changes in SOC between the reference site and sample site, a carbon pool index (CPI) was calculated as follows: CPI = (sample SOC)/(SOC of reference soil). Based on changes in C lability (L = $KMnO_4$-C/(SOC − $KMnO_4$-C)), lability index (LI) was determined as follows: LI = (sample L)/(L of reference soil). These two indices were used to calculate CMI as follows: CMI = CPI × LI × 100. The soil under FM was used as a reference soil in this study. The effects of plastic film removal on the measured parameters were evaluated using one-way ANOVA. When F-values were significant, the least significant difference (LSD) test was used to compare means. In all cases, differences were deemed to be significant if $P < 0.05$ using SPSS version 20.0.

Results

Grain yield and biomass

Compared with the FM treatment, the RM treatment resulted in a 6.3% higher average grain yield and significantly increased the grain yield in 2009 and 2013, but no significant yield increase was observed in 2010, 2011 and 2012 (Figure 1). There was no significant difference between the FM and RM treatments in biomass from 2009 to 2013 (Figure 1).

Soil organic C and total N

There was no significant difference between the FM and RM treatments in SOC, TN and the C/N ratio after 1 yr, with the exception of the C/N ratio in the 0- to 20-cm layer (Table 1). After 5 yr, compared with the FM treatment, the SOC and TN contents under RM increased significantly by 7.1% and 14.5%, respectively, in the 0- to 20-cm layer (Table 1). No significant difference in SOC, TN and the C/N ratio was found between two treatments in the 20- to 40-cm

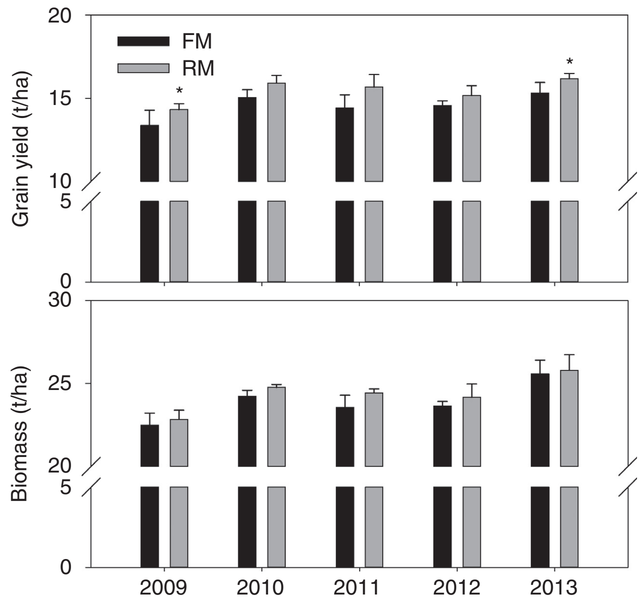

Figure 1 Effects of plastic film removal on grain yield and biomass. Error bars represent standard errors of the means (n = 3). Asterisk (*) is significantly (P < 0.05) different between cultivation systems. FM, plastic film mulched; RM, plastic film removal.

Table 1 Effects of plastic film removal on soil organic C, total N and the C/N ratio

Soil depth (cm)	Duration (yr)	SOC(g/kg)		Total N(g/kg)		C/N ratio	
		FM	RM	FM	RM	FM	RM
0–20	1	8.57a	8.39a	1.06a	1.08a	8.11a	7.75b
	5	10.75b	11.51a	1.10b	1.26a	9.75a	9.13b
20–40	1	6.62a	6.91a	0.76a	0.80a	8.70a	8.64a
	5	7.04a	7.13a	0.82a	0.80a	8.58a	8.79a

FM, plastic film mulched; RM, plastic film removal; SOC, soil organic C. Means (n = 3) followed by different lower-case letters are significantly different between the mulching practices at P < 0.05.

layer after 5 yr. Compared with the FM treatment, the C/N ratio under RM significantly decreased by 4.5% and 6.4% after the 1- and 5-yr treatments, respectively, in the 0- to 20-cm layer.

Labile soil organic C fractions

Plastic film removal during the maize reproductive stages significantly affected labile SOC fractions in two layers (Figure 2). After 1 yr, compared with the FM treatment, the LFOC, MBC and EOC contents under RM increased significantly in the 0- to 20-cm layer, and the RM treatment led to increase in WSOC, despite the insignificant increase tendency; the LFOC and EOC contents under RM significantly increased in the 20- to 40-cm layer, whereas the RM treatment led to decrease in WSOC significantly. No significant difference in MBC and WSOC was found between two treatments in the 0- to 20-cm layer after the 5-yr treatment. After 5 yr, the LFOC content under RM significantly decreased in the 0- to 20-cm layer, whereas the RM treatment led to increase in EOC, compared with the FM treatment. In the 20- to 40-cm layer, compared with the FM treatment, the LFOC, MBC and EOC contents under RM increased significantly, and the RM treatment led to a small increase in WSOC.

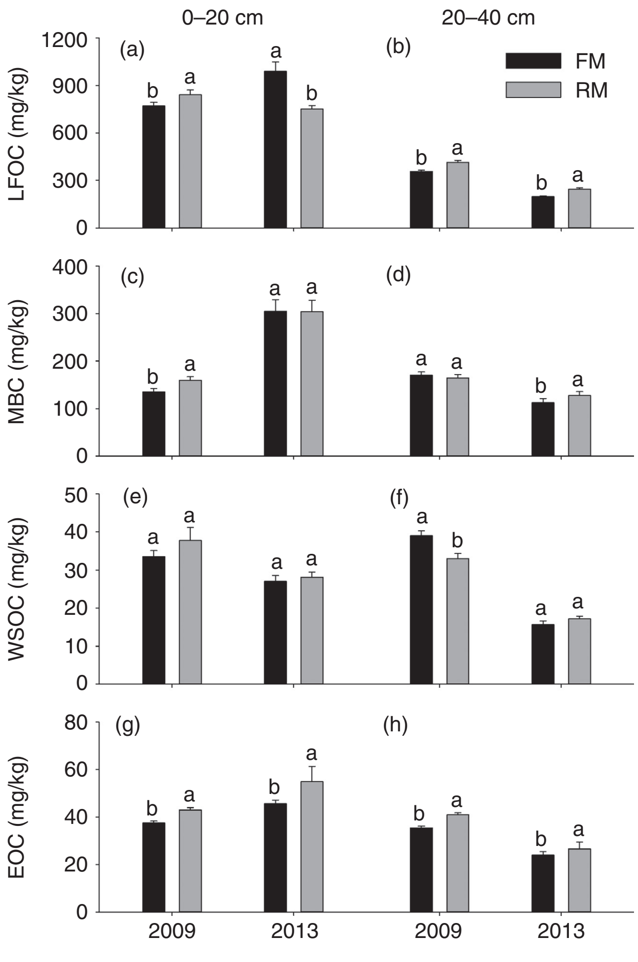

Figure 2 Effects of plastic film removal on light fraction organic C, microbial biomass C, water-soluble organic C and extractable organic C after the 1- and 5-yr experimental durations (in 2009 and 2013) in the 0- to 20-cm- and 20- to 40-cm layers. Error bars represent standard errors of the means ($n = 3$). Means followed by different letters are significantly ($P < 0.05$) different between cultivation systems within each soil depth. FM, plastic film mulched; RM, plastic film removal; LFOC, light fraction organic C; MBC, microbial biomass C; WSOC, water-soluble organic C; EOC, extractable organic C.

Labile soil organic N fractions

Plastic film removal during the maize reproductive stages also significantly affected labile soil organic N fractions in two layers (Figure 3). There was no significant difference between the FM and RM treatments in LFON, MBN, WSON and EON contents after 1 yr, with the exception of the EON in the 0- to 20-cm layer. Compared with the FM treatment, the EON content under RM significantly decreased by 16.6% in the 0- to 20-cm layer after 1 yr. After 5 yr, the LFON and MBN contents under RM significantly decreased in the 0- to 20-cm layer, whereas the RM treatment led to a significant increase in EON. In the 20- to 40-cm layer, compared with the FM treatment, the LFON and EON contents under RM increased significantly, and the RM treatment led to a small increase in WSON.

$KMnO_4$-oxidizable C and CMI

The effects of plastic film removal on $KMnO_4$-C and CMI are shown in Table 2. After 1 yr, compared with the FM treatment, the RM treatment significantly increased $KMnO_4$-C and CMI by 27.0% and 30.4%, respectively, in the 0- to 20-cm layer. No significant difference in $KMnO_4$-C and CMI was found between two treatments in the 20- to 40-cm layer after 1 yr. After 5 yr, compared with the FM treatment, the RM treatment significantly increased $KMnO_4$-C and CMI by 56.7% and 64.9% in the 0- to 20-cm layer, respectively, and led to a significant increase in $KMnO_4$-C and CMI by 13.9% and 15.7% in the 20- to 40-cm layer.

Discussion

Plastic film removal effects on the grain yield and biomass

At this study site, during the maize growing season (May to September), the mean air temperature was 19.0 °C, and the precipitation amount was 426 mm from 1957 to 2008. The mean air temperature and precipitation amount averaged 18.9 °C (range 18.2–19.7 °C) and 427 mm (range 363–496 mm) from 2009 to 2013, respectively, which are close to

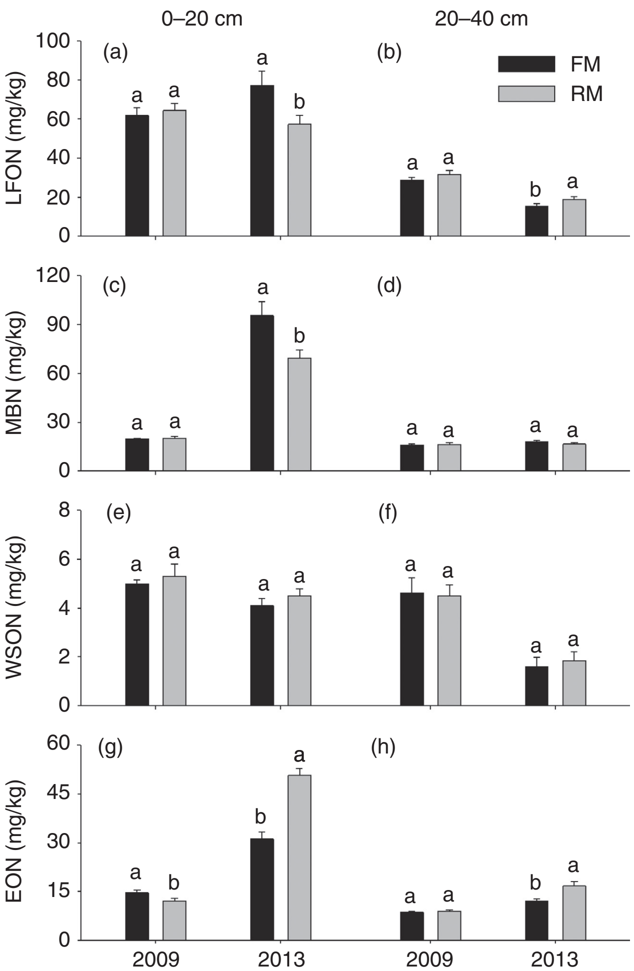

Figure 3 Effects of plastic film removal on light fraction organic N, microbial biomass N, water-soluble organic N and extractable organic N after the 1- and 5-yr experimental durations (in 2009 and 2013) in the 0- to 20-cm- and 20- to 40-cm layers. Error bars represent standard errors of the means (n = 3). Means followed by different letters are significantly ($P < 0.05$) different between cultivation systems within each soil depth. FM, plastic film mulched; RM, plastic film removal; LFON, light fraction organic N; MBN, microbial biomass N; WSON, water-soluble organic N; EON, extractable organic N.

the 52-yr (1957–2008) mean. The maize yields in this study are better than the mean 5-yr (2008–2012) maize yields of 3.8 t/ha when not mulched and 7.7 t/ha under full mulch (i.e. FM) in a study site with similar weather condition and soil texture on the Loess Plateau (Liu *et al*., 2014b). The mean air temperature ranged from 16.5 to 17.1 °C during the 5-yr maize growing season (2008–2012), and precipitation amount ranged from 215 to 336 mm (Liu *et al*., 2014b), which was less than that observed in this study. Relative to the FM treatment, the RM treatment may decrease the cumulative soil temperature and plant senescence rate during the maize RS, thereby increasing the grain yield and biomass (Liu *et al*., 2014a). The RM treatment was therefore more efficient than FM in enhancing crop yield.

Plastic film removal effects on soil organic C and total N

Rhizodeposition (mainly root exudates and residues) and organic manure provided the main C and N input sources for the FM and RM treatments. In this study, after 5 yr, the FM and RM treatments significantly increased SOC, TN and the C/N ratio in the 0- to 20-cm layer and SOC in the 20- to 40-cm layer relative to the 1-yr treatment ($P < 0.05$). Organic manure may be primarily responsible for the increases in SOC and TN. There was no significant difference between the FM and RM treatments in SOC and TN after 1 yr of cultivation, whereas the RM treatment displayed greater effects on increasing SOC and TN in the 0- to 20-cm layer after 5 yr of cultivation. Relative to the FM treatment, the RM treatment may decrease root senescence (Liu *et al*., 2014a). Greater rhizodeposition may lead to increases in SOC and TN. In this study, compared with the FM treatment, the C/N ratio under RM significantly decreased by 4.5% and 6.4% after the one- and 5-yr treatments, respectively, in the 0- to 20-cm layer. Soil C/N ratio can indicate the substrate quality and microbial transformation processes. Larger C/N ratios indicate poorly degradable litter and a slow transformation and recycling of organic matter (Kindler *et al*., 2011). To further enhance SOC and TN, it may therefore be desirable to replace conventional film mulching with the RM treatment in regions with semiarid monsoon climates that have sufficient rainfall during the maize RS.

Plastic film removal effects on labile soil organic C and N pools

The light fraction organic matter (LFOM) consists mainly of plant residues, small animals and microorganisms that remain undecomposed for a short period of time (Mueller *et al*., 1998). Previous studies have reported that LFOM was higher in the plastic film mulching treatment than in non-mulched treatment at harvest time (Zhou *et al*., 2012). In this study, relative to the FM treatment, the RM treatment significantly decreased LFOC and LFON by 24.0% and 25.9% after the 5-yr cultivation in the 0- to 20-cm layer, while there is no significant difference between the two treatments in microbial biomass (with reference to MBC). Thus, the difference in LFOM concentration might depend mainly on plant residue decomposition over a short period. The higher topsoil moisture and temperature might increase the decay of plant roots (Liu *et al*., 2014a), which could lead to increased LFOM formation in the topsoil under the FM treatment. In this study, compared with the FM treatment, the LFOC and LFON under RM were increased by 16.1% and 9.4% after only 1 yr, and the responses were more

Table 2 Effects of plastic film removal on $KMnO_4$-oxidizable C, carbon pool index, lability, lability index and carbon management index

Soil depth (cm)	Duration (yr)	Treatment	$KMnO_4$-C (g/kg)	CPI	L	LI	CMI (%)
0–20	1	FM	0.71b	1.00a	0.09b	1.00b	100.0b
		RM	0.90a	0.98a	0.12a	1.33a	130.4a
	5	FM	1.04b	1.00b	0.11b	1.00b	100.0b
		RM	1.63a	1.07a	0.17a	1.54a	164.8a
20–40	1	FM	0.63a	1.00a	0.11a	1.00a	100.0a
		RM	0.64a	1.04a	0.10a	0.97a	100.6a
	5	FM	0.76b	1.00a	0.12b	1.00a	100.0b
		RM	0.86a	1.01a	0.14a	1.14a	115.7a

FM, plastic film mulched; RM, plastic film removal; $KMnO_4$-C, $KMnO_4$-oxidizable C, CPI, C pool index; L, lability; LI, lability index; CMI, C management index. Means (n = 3) followed by different lower-case letters are significantly different between the mulching practices at $P < 0.05$.

significant after 5 yr by 24.1% and 21.8% in the 20- to 40-cm layer. Thus, the RM treatment was more efficient than FM in maintaining LFOM in the 20- to 40-cm layer. Soil processes are closely related to root activity, with C and N transformations being stimulated by inputs of root exudates and other root-borne substances (Kuzyakov *et al.*, 2007). The lower topsoil moisture and temperature might decrease the decay of plant roots (Liu *et al.*, 2014a), which could lead to increased input of root biomass and rhizodeposits under RM, compared with the FM treatment, and would be expected to increase the microbial community. The breakdown of crop residues is mediated by soil microbes, which derive their energy and other nutrients from the residues (St. Luce *et al.*, 2014) and generate soluble organic matter as a by-product (Murphy *et al.*, 2000). In this study, relative to the FM treatment, the RM treatment significantly increased MBC in the 20- to 40-cm layer and EOC in two layers after 5 yr. Relative to the FM treatment, the EOC under RM was increased by 14.5% and 15.4% after only 1 yr in the 0- to 20-cm- and 20- to 40-cm layers, respectively, and increased by 20.3% and 10.8% after 5 yr. The significant increases in EOC under RM may be attributed to the more microbial metabolites and demonstrated the greater carbon availability to soil microorganisms. In addition, increased soil temperatures are known to directly increase the size of the microbial community (Belay-Tedla *et al.*, 2009). In this study, compared with the RM treatment, the MBN under FM significantly increased the microbial biomass in the 0- to 20-cm layer after 5 yr. Greater topsoil moisture and temperature might increase plant root decay, providing more substrates for promoting microbial biomass activity, which could lead to greater microbial biomass. Soluble organic N or extractable organic N is extracted from field moist or dried soils by shaking with water or a salt solution at a high soil/solution ratio for short periods of time, followed by centrifugation or filtering to separate the solution phase from the solid phase (Jones & Willett, 2006). Compared with the FM treatment, the RM treatment demonstrated some tendency to increase the WSON content in two layers after five years; the EON under RM was increased by 62.7% and 37.7% after 5 yr in the 0- to 20-cm- and 20- to 40-cm layers, respectively. In general, salt solution (0.5 mol/L K_2SO_4) tended to extract more soil organic N than water. Salt extraction may disturb adsorption equilibria on soil surfaces and organic N measured in these extracts may include N originally adsorbed on the surface of soil mineral and organic clays (Murphy *et al.*, 2000). The significant increases in EON under the RM treatment may be attributed to the more microbial metabolites and the more extracted N originally adsorbed on the surface of soil mineral and organic clay-sized particles.

Plastic film removal effects on carbon management index

CMI allows the evaluation of soil quality gain or loss processes since higher values mean higher soil quality and vice versa. In this study, the CPI did not change significantly under RM after 1 yr relative to the FM treatment, but increased significantly under RM in the 0- to 20-cm layer after 5 yr (Table 2). Similarly, the lability (L) of SOC and LI were significantly enhanced under RM after 1 yr and further increased after 5 yr in the 0- to 20-cm layer (Table 2). Thus, the CMI under RM was significantly larger (1.30 times) than FM after 1 yr and the effect was more significant (1.65 times) after 5 yr in the 0- to 20-cm layer (Table 2). Meanwhile, in the 20- to 40-cm layer, there was no significant difference between the FM and RM treatments in CMI after 1 yr; however, the CMI under RM was 1.16 times greater than FM after 5 yr, mainly as a consequence of changes in LI. The RM treatment could enhance the soil quality and fertility in contrast to the FM treatment. These results indicated the suitability of using $KMnO_4$-C for calculating CMI, the reliability of CMI as an index for assessing SOC change and the great sensitivity of the CMI to plastic film removal during the maize RS. These findings also indicate that removing plastic film during the maize RS would decrease SOM mineralization, thereby increasing soil quality and environmental sustainability.

Conclusions

Our study has demonstrated that early removal of plastic film from maize crops can contribute to increases in topsoil SOC and TN. Early film removal was also associated with increases in the CMI index and soil labile SOM fractions particularly after longer periods (5 yr) of cultivation. Therefore, compared with mulching for the whole growing season, early plastic film removal at the maize silking stage is an effective option for increasing yields and enhancing SOM concentration and soil sustainability in the regions with semiarid monsoon climates that have sufficient rainfall during the maize reproductive stages.

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