Mulching Effects on Labile Soil Organic Nitrogen Pools under a Spring Maize Cropping System in Semiarid Farmland

Shasha Luo, Lin Zhu, Jianliang Liu, Lingduo Bu, Shanchao Yue, Yufang Shen, and Shiqing Li*

ABSTRACT

Understanding the response of labile soil organic nitrogen (SON) pools to soil surface mulching is essential in identifying changes in soil N availability. Three treatments included non-mulched (CK), gravel-mulched (GM), and plastic film-mulched (FM), based on a 5-yr spring maize (Zea mays L.) field experiment in northwestern China. Compared with the CK, the GM and FM treatments significantly increased the grain yield and aboveground biomass, while had no effect on the soil organic carbon (SOC) and total nitrogen (TN) contents after 5 yr of this study. Compared with the CK, the GM and FM treatments significantly decreased light fraction organic N by 12.2 and 6.5 mg kg⁻¹, respectively, and extractable organic N by 7.7 and 9.3 mg kg⁻¹ in the 0- to 20-cm layer; while significantly increased water soluble organic N by 1.6 and 1.5 mg kg⁻¹ in the 0- to 20-cm layer, respectively, and by 1.3 and 1.2 mg kg⁻¹ in the 20- to 40-cm layer after 4 yr of this study. Meanwhile, the FM treatment significantly increased the microbial biomass N by 19.5 mg kg⁻¹ in the 0- to 20-cm layer compared with the CK after 4 yr of this study. In general, the GM and FM treatments increased maize productivity without detriment to the SOC and TN balance compared with the CK. The FM treatment displayed greater effects on enhancing crop yield and increasing labile SON pools than GM. It is suitable to choose plastic film mulching over gravel mulching to have increases in crop yields and improvements in soil N availability in semiarid farmland.

Soil N availability largely regulates both biomass production and species composition in terrestrial ecosystems. More than 80% of N in soil is present in organic form (Schulten and Schnitzer, 1997) and is unavailable to plants. A number of techniques, including physical, biological, and chemical fractionations, have been developed to fractionate soil organic nitrogen (SON) into labile and stable parts. Because labile SON pools are accessible to soil microorganisms, they can function as an important short-term reservoir of nutrients for microbes and plants (Schimel et al., 2007). Therefore, labile SON pools play an important role in maintaining soil nutrient cycling in terrestrial ecosystems (Chen et al., 2005).

Rainfed agriculture constitutes a major part of global agriculture, plays a crucial role in achieving food security (Wani et al., 2009), and occupies about 50% of total farmland in China (Deng et al., 2006). The Loess Plateau has a typical semiarid monsoon climate (Li et al., 2004b), in which maize (Zea mays L.) is one of the most common grain crops; however, low air temperatures and drought during the early crop growth stage in the spring often result in poor crop yield (Liu et al., 2009). Limited precipitation coupled with drought and heat stress during the cropping season, threatens agricultural sustainability in dryland environments (Turner, 2004; Siddique et al., 2012). To tackle the problem, new technologies have been developed to increase the precipitation use efficiency in rainfed farming systems. Gravel mulching is a traditional technique (Gale et al., 1993; Doolittle, 1998; Li, 2003) that is still practiced in the dryland farming area of northern China (Wang et al., 2011; Ma and Li, 2011; Fan et al., 2014). Gravel mulching is effective in reducing evaporation and runoff, improving infiltration, and increasing soil temperature (Nachtergaele et al., 1998; Xie et al., 2010). Gravel mulching is usually implemented in fields where a local source of gravel is available. Historically, gravel-covered fields have been used for producing fruit and vegetables, and this technique has been used in field crops recently. Gravel is applied to the soil surface, and crops are usually planted beneath the gravel layer or by making a shallow furrow and seeding the crop in the furrow (Gan et al., 2013). In this practice, the labor cost increased significantly, because the gravel has to be removed away when annual crops are planted regularly (Fan et al., 2014). With modern devices invented, such as the gritting machine and earth-rock separator, this technique has liberated labor and reduced cost. In addition,

Abbreviations: CK, non-mulched; EON, extractable organic nitrogen; FM, plastic film-mulched; GM, gravel-mulched; LFON, light fraction organic nitrogen; MBN, microbial biomass nitrogen; SOC, soil organic carbon; SON, soil organic nitrogen; TN, total nitrogen; WSON, water soluble organic nitrogen.
plastic film mulching has been widely adopted for dryland agriculture in arid and semiarid areas (Anikwe et al., 2007; Sharma et al., 2011; Gao et al., 2014). Many studies (Li et al., 2004c; Zhou et al., 2012; Liu et al., 2014) have shown that plastic film mulching is an efficient technology and can be applied easily due to its low investment cost. Most plastic films are not readily degradable and have to be removed and destroyed at the end of the cropping season, but new biodegradable plastics are being developed and trialed (Gan et al., 2013; Li et al., 2014). Gravel and plastic film mulching may greatly improve crop yields due to increases in soil moisture and top soil temperatures (Li et al., 2004a; Bu et al., 2013). Alleviating the hydrothermal limitations to growth by mulching, however, risks reducing soil quality through increased soil organic matter mineralization and microbial activity (Zhou et al., 2012). Increases in both soil moisture and temperature may disturb the original balance between abiotic and biotic factors in agroecosystems and may negatively impact productivity and sustainability (Li et al., 2004c). Little is known whether the increased grain yield was a consequence of mining the soil or causing soil nutrient imbalance. Until now, limited information is available about the effects of soil surface mulching on SON pools in semiarid environments, especially in a spring maize cropping system of northwestern China. Accordingly, measuring labile SON pools is essential in identifying changes in soil N availability and environmental sustainability. Labile SON pools such as light fraction organic nitrogen (LFON), microbial biomass nitrogen (MBN), water soluble organic nitrogen (WSON) and extractable organic nitrogen (EON) are especially important because they control ecosystem productivity and are sensitive indicators of changes in N cycling and availability due to management practices (Zhou et al., 2011).

This study was designed to: (i) reveal the impacts of mulching on labile SON pools and (ii) evaluate the correlations among TN, SOC, and labile SON pools. This information will be useful for understanding labile SON dynamics and soil N availability in a spring maize cropping system in the semiarid Loess Plateau.

### Experimental Design and Field Management

In this experiment, we applied three treatments, including non-mulched (CK), gravel-mulched (GM), and plastic film-mulched (FM), to maize plots. The treatments were applied to 56 m² (8 by 7 m) plots arranged in a randomly block design with three replicates. After ridging the treatment plots, chemical fertilizers were broadcast over the soil rates of 90 kg N ha⁻¹ and 30 kg P ha⁻¹, the form of calcium super phosphate (12% P₂O₅), and 40 kg P ha⁻¹ in the form of urea (containing 46% N), 4 kg P ha⁻¹ in the form of calcium super phosphate (12% P₂O₅), and 80 kg K ha⁻¹ in the form of potassium sulfate (45% K₂O); the soil was then plowed to mix the fertilizer into the subsurface.

### Materials and Methods

#### Site Description

This study was conducted from 2010 to 2014 at the Changwu Agricultural and Ecological Experimental Station (35.28° N, 107.88° E, 1200 m altitude), which is located in a semiarid area on the Loess Plateau, China. The annual mean air temperature is 9.7°C, and the average annual precipitation is 580 mm from 1957 to 2009. In contrast, the average annual evaporation from a free water surface is 1565 mm, with a ratio of free evaporation to precipitation of 2.7. The water table is at a depth of more than 60 m and thus, ground water is unavailable for plant growth. The mean air temperature was 19.0°C, and the precipitation amount was 425 mm during the maize growing season from 1957 to 2009 (Table 1). The mean air temperature and precipitation amount averaged 18.9°C (range 18.2–19.7°C) and 429 mm (range 363–496 mm) from 2010 to 2014 during the maize growing season, respectively, which are close to the 53-yr mean (1957–2009). The years 2010 and 2011 were wet years and the years 2012 and 2014 were dry years, while the rainfall in 2013 fell in the normal range during the maize growing season. The soil at the study site is developed from loess and has a silt loam texture according to the USDA texture classification system. The soil properties at the top 20 cm were: bulk density 1.3 g cm⁻³, pH 8.4, available phosphorus (Olsen-P) 20.7 mg kg⁻¹, available potassium (NH₄OAc-K) 133.1 mg kg⁻¹, and mineral N 28.8 mg kg⁻¹ in April 2010, before the start of the experiment.

| Years  | Precipitation mm | Mean air temperature °C | Grain yield† (kg ha⁻¹) | Biomass (kg ha⁻¹) |
|--------|------------------|--------------------------|------------------------|------------------|
| 1957–2009 | 425              | 19.0                     | CK: 17.5c, 19.4b, 21.2a | GM: 15.5c, 20.2b, 21.8a |
| 2010    | 496              | 19.2                     | GM: 17.8c, 19.4b, 22.1a | GM: 15.5c, 20.2b, 21.8a |
| 2011    | 487              | 18.2                     | GM: 15.5c, 20.2b, 21.8a | GM: 15.5c, 20.2b, 21.8a |
| 2012    | 363              | 18.7                     | GM: 15.5c, 20.2b, 21.8a | GM: 15.5c, 20.2b, 21.8a |
| 2013    | 421              | 19.7                     | GM: 15.5c, 20.2b, 21.8a | GM: 15.5c, 20.2b, 21.8a |
| 2014    | 376              | 18.9                     | GM: 15.5c, 20.2b, 21.8a | GM: 15.5c, 20.2b, 21.8a |
| 2010–2014 | 429             | 18.9                     | GM: 15.5c, 20.2b, 21.8a | GM: 15.5c, 20.2b, 21.8a |

*** Significantly different at P < 0.001.
† CK, non-mulched; GM, gravel-mulched; FM, plastic film-mulched.
‡ Means followed by different lower-case letters are significantly different between the mulching practices at P < 0.05.

Summary of ANOVA

- Mulch treatment ***
- Year ***
- Mulch × year ***
Three treatments involved an alternating wide and narrow row spacing of 60 and 40 cm. Gravel (2–4 cm in diameter, 5–6 cm in final thickness) and plastic film (0.005 mm thick, 1.2 m wide, and transparent) were used to cover the soil in the GM and FM treatments, respectively, after the base fertilizer application and before sowing. In each plot, the maize was planted 5-cm deep at a density of 65,000 plants ha$^{-1}$ using a hole-sowing machine. These holes allowed rainwater to collect and be channeled from the ridges to enter the soil. All of the plots were top-dressed twice with 67.5 kg N ha$^{-1}$ (urea, 46% N) during the 10th leaf stage (V10) and silking stage (R1) recorded according to the standardized maize development stage system (Ritchie et al., 1992), using the same handheld device as used for sowing. In 2011 to 2014, each plot was at the same site as in 2010; the gravel and plastic film were both replaced in the latter 4 yr. Manual weeding was undertaken as required during the maize growing season.

**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. The biomass and grain yield were determined based on the average of three plot replicates, and all samples were dried to a constant weight in a fan oven at 75°C. Soil was sampled before sowing (PT) and after harvesting at physiological maturity stage (R6) recorded according to the standardized maize development stage system (Ritchie et al., 1992) from 2010 to 2014. At each plot, soil cores were drilled randomly using a 4 cm diam. auger with five replications and then mixed together to form one composite sample for every soil depth (0–20 cm and 20–40 cm). Soil water content of each sample was measured after removing visible plant residues and gravel, and then soil sample passed through a sieve. The fresh subsamples were refrigerated (0–4°C) until the samples were measured for MBN, WSON, and EON. The other subsamples were air-dried and sieved through a 2-mm sieve and then analyzed for LFON. Subsamples of <2 mm soil were then grounded to pass a 0.15-mm sieve to determine TN and SOC.

Soil organic C was analyzed by the dichromate oxidation method (Mebius, 1960) and total N was analyzed by the Kjeldahl method (Bremmer and Mulvaney, 1982). Light fraction organic N amount was determined using a CHN elemental analyzer (Fisons Instruments, Mainz, Germany). Microbial biomass N was measured using a modified chloroform fumigation-extraction method (Brookes et al., 1985). Total soluble N in the filtrate was followed by alkaline persulfate oxidation and measured by dual-wavelength ultraviolet spectrophotometry (Norman et al., 1985; Cabrera and Beare, 1993). The MBN was calculated by taking the difference between soluble N of the fumigated and non-fumigated soils. A K$_{\text{N}}$ value of 0.54 (Brookes et al., 1985) was used to calculate the N content of the microbial biomass. Water soluble organic N was measured according to Liang et al. (1997). Extractable organic N was measured according to Jones and Willett (2006). The filtrate was analyzed for NH$_4^+$-N and NO$_3^-$-N with a continuous flow analyzer (FLOWSYS, Roma, Italy), and total soluble N by dual-wavelength ultraviolet spectrophotometry after alkaline persulfate oxidation (Cabrera and Beare, 1993; Norman et al., 1985). The WSON and EON concentrations in the filtrate were calculated by taking the difference between total soluble N and total mineral N.

**Statistical Analysis**

Two-way ANOVA was conducted to test the effects of mulch and cropping year on maize grain yield and aboveground biomass, with mulch and cropping year as two fixed factors. Two-way ANOVA was also used to test the effects of mulch and sampling time on the measured parameters, with mulch and cropping year as two fixed factors. Significant differences among means were detected using the least significant difference (LSD) test at $P < 0.05$. All statistical procedures were performed in SPSS version 20.0.

**RESULTS**

**Grain Yield and Biomass**

Mulch and cropping year significantly affected the grain yield (at 15.5% moisture content) and total dry biomass ($P < 0.001$) (Table 1). Averaging across years from 2010 to 2014, the grain yield under CK was 8.9 t ha$^{-1}$ and increased by 23.6% under GM and by 56.2% under FM. The aboveground biomass also increased by 12.7% under GM and by 40.5% under FM, while the aboveground biomass was 15.8 t ha$^{-1}$ under CK.

**Soil Organic Carbon and Total Nitrogen**

The contents of SOC ($P < 0.001$) and TN ($P < 0.05$) were influenced by mulch and sampling time (Table 2). However, no significant interaction between mulch and sampling time was observed for SOC and TN, except for TN in the 20- to 40-cm layer ($P < 0.05$). The response of TN to sampling time was greater than mulch in the 0- to 20-cm layer. The SOC was significantly higher at harvest in 2012 than at sowing in 2010 or harvest in 2010, 2013, and 2014 ($P < 0.05$), while SOC averaged across sampling time followed the trend CK > GM > FM in the 0- to 20-cm layer and CK > FM > GM in the 20- to 40-cm layer ($P < 0.05$). The TN was significantly higher at harvest in 2013 than at harvest in 2012 and 2014 ($P < 0.05$), while TN averaged across sampling time followed the trend CK > GM > FM ($P < 0.05$). After the 5-yr of this study, no significant difference in SOC and TN contents were found among three treatments in two layers ($P > 0.05$). Compared to the initial SOC content, the SOC significantly increased in the 0- to 20-cm layer across three treatments after the 5 yr of this study ($P < 0.05$), which is mainly contributed by the FM treatment (68.3%).

**Light Fraction Organic Nitrogen**

Mulch, sampling time, and their interaction had significant effects on the LFON content and LFON/TN ($P < 0.001$). The LFON fluctuated within a large range from 11.6 to 59.5 mg kg$^{-1}$, and accounted for 1.7 to 6.1% of TN in two layers (Fig. 1). After 4 yr of this study, compared with the CK, the LFON under GM and FM decreased significantly in the 0- to 20-cm layer, and no significant difference in LFON was found among three treatments in the 20- to 40-cm layer. Compared with the initial LFON content, the CK, GM, and FM treatments decreased the LFON content by 12.6, 26.7 and 10.2 mg kg$^{-1}$ in the 0- to 20-cm layer, respectively, and decreased by 17.4, 4.3 and 12.8 mg kg$^{-1}$ in the 20- to 40-cm layer. The increase in LFON was found among three treatments in the 20- to 40-cm layer ($P < 0.001$).
layer after the 4 yr of this study. As a whole, the decrease of LFON over time indicates potential soil mining of total N. The LFON content and LFON/TN significantly decreased under GM in the 0- to 20-cm layer, whereas the decreases in LFON and LFON/TN were less under GM than under CK and FM in the 20- to 40-cm layer. Compared with the initial LFON content, the decrease of LFON was less under FM than under CK by 4.6 mg kg\(^{-1}\) in the 20- to 40-cm layer (\(P < 0.05\)). The FM displayed a greater effect on maintaining the LFON content than GM.

### Microbial Biomass Nitrogen

Mulch, sampling time, and their interaction had significant effects on the MBN content and MBN/TN (\(P < 0.05\)). MBN fluctuated within a large range from 11.7 to 50.0 mg kg\(^{-1}\), and accounted for 1.4 to 4.9% of TN in two layers (Fig. 2). After 4 yr of this study, compared with the CK, the MBN under FM significantly increased in the 0- to 20-cm layer, whereas decreased in the 20- to 40-cm layer. Compared with the initial MBN content, the MBN under GM and FM treatments increased by 1.9, 13.2 and 32.8 mg kg\(^{-1}\) in the 0- to 20-cm layer, respectively, and decreased by 4.3, 5.9 and 5.5 mg kg\(^{-1}\) in the 20- to 40-cm layer after the 4 yr of this study. Briefly, compared with the CK, the GM and FM treatments significantly increased MBN/TN in the 0- to 20-cm layer after the 4 yr of this study. The FM led a greater increase in MBN content than GM in the 0- to 20-cm layer.

#### Table 2. Effects of mulching and sampling time on soil organic carbon (SOC) and total nitrogen (TN) in the 0- to 20-cm and 20- to 40-cm layers.

| Soil depth | Sampling time | SOC† | TN |
|------------|---------------|------|-----|
| cm         |               | CK   | GM | FM | CK | GM | FM |
| 0–20       | 2010 PT‡      | 8.16a§ | 8.03a | 7.83a | 0.98a | 0.97a | 0.98a |
|            | 2010 R6       | 8.40a | 8.14ab | 7.84b | 0.99a | 0.97a | 0.97a |
|            | 2011 R6       | 8.63a | 8.32a | 8.26a | 0.98a | 0.92b | 0.89a |
|            | 2012 R6       | 8.97a | 8.65a | 8.59a | 0.95a | 0.91a | 0.94a |
|            | 2013 R6       | 8.32a | 8.29a | 8.07a | 1.01a | 0.95a | 0.99a |
|            | 2014 R6       | 8.17a | 8.21a | 8.24a | 0.94a | 0.93a | 0.94a |
| 20–40      | 2010 PT       | 6.66a | 6.21a | 6.12a | 0.78a | 0.79a | 0.77a |
|            | 2010 R6       | 7.18a | 6.33b | 6.42b | 0.79a | 0.79a | 0.83a |
|            | 2011 R6       | 7.06a | 6.41a | 7.03a | 0.77b | 0.74b | 0.82a |
|            | 2012 R6       | 7.22a | 6.74b | 7.30a | 0.80a | 0.72b | 0.76ab |
|            | 2013 R6       | 6.67a | 6.00b | 6.59a | 0.81a | 0.76a | 0.79a |
|            | 2014 R6       | 6.53a | 6.27a | 6.49a | 0.77a | 0.75a | 0.76a |

**Summary of ANOVA**

| Mulch treatment (M) | 0–20 cm | 20–40 cm | 0–20 cm | 20–40 cm |
|---------------------|---------|-----------|---------|----------|
|                      | ***     | ***       | **      | **       |
| Sampling time (T)    | ***     | #ns       | ns      | #ns      |
| M × T ns#            | #ns     | ns        | ns      | #ns      |

* Significant at \(P < 0.05\).
* * Significant at \(P < 0.01\).
* * * Significant at \(P < 0.001\).
† CK, non-mulched; GM, gravel-mulched; FM, plastic film-mulched.
‡ PT, before sowing; R6, after harvesting.
§ Means followed by different lower-case letters are significantly different between the mulching practices at \(P < 0.05\).
# ns, not significant.

Fig. 1. Mulching effects on soil light fraction organic nitrogen (LFON) and the proportion of LFON accounting for soil total nitrogen (TN) in the 0- to 20-cm and 20- to 40-cm layers from 2010 to 2013. Error bars represent standard errors of the means (n = 3). Different letters indicate a significant difference among treatments at \(P < 0.05\).

CK, non-mulched; GM, gravel-mulched; FM, plastic film-mulched; PT, before sowing; R6, after harvesting. Bars represent the LFON contents; Scatters represent the LFON/TN ratios.
Water Soluble Organic Nitrogen

Mulch, sampling time, and their interaction had significant effects on the WSON content and WSON/TN ($P < 0.05$). A similar trend of WSON and WSON/TN changes were observed between different soil depths (Fig. 3). The WSON fluctuated within a large range from 0.7 to 5.9 mg kg$^{-1}$, and accounted for 0.1 to 0.6% of TN in two layers. After the 4 yr of this study, compared with the CK, the WSON under GM and FM increased significantly in two layers. Compared with the initial WSON content, the WSON under CK, GM, and FM decreased by 32.6 and 17.8%, whereas under GM increased by 8.9% in the 0- to 20-cm layer; the WSON under CK, GM, and FM decreased by 67.6, 18.1, and 45.7% in the 20- to 40-cm layer. As a whole, compared with the CK, the GM and FM treatments restrained the increase in the WSON content and increased the WSON/TN in two layers. No significant difference in WSON and WSON/TN were found between GM and FM after the 4 yr of this study.

Extractable Organic Nitrogen

Mulch, sampling time, and their interaction had significant effects on the EON content and EON/TN ($P < 0.01$). A similar trend of EON and EON/TN changes were observed between two layers (Fig. 4). The EON fluctuated within a large range from 6.8 to 23.6 mg kg$^{-1}$, and accounted for 0.8 to 2.3% of TN in two layers. After the 4 yr of this study, compared with the CK, the EON and EON/TN under GM and FM significantly decreased in the 0- to 20-cm layer, and the EON under GM decreased significantly in the 20- to 40-cm layer. Compared with the initial EON content, the CK, GM, and FM treatments increased EON content by 10.0, 3.0, and 0.1 mg kg$^{-1}$ in the 0- to 20-cm layer, respectively. However, the EON content only changed slightly in the 20- to 40-cm layer after the 4 yr of this study. Overall, compared with the CK, the GM and FM treatments restrained the increase in the EON content.

Relative Changes of Labile Soil Organic Nitrogen Pools

The relative changes of labile SON fractions differed after the 4 yr of this study between mulching practices (GM and FM) and...
CK (Fig. 5). In general, the relative changes of labile SON fractions were more sensitive than SOC and TN changes. Compared with a small decline or increase of SOC and TN (<7.7% for SOC and <10.4% for TN), after the 4 yr of this study, the absolute value of decline or increase was almost 40.9% on average among labile SON fractions. In particular, the increase of the MBN fraction averaged 85.4% across three treatments in the 0- to 20-cm layer. Compared to the CK, the absolute value of decline or increase was almost 38.2% on average for the mulching practices among labile SON fractions. In particular, compared to the CK, the relative increase of the MBN fraction was almost 118.4%, and the relative decrease of the EON fraction was 61.4% on average for the mulching practices in the 0- to 20-cm layer.

DISCUSSION

This study showed that mulching significantly increased the maize yield and biomass in the temperature- and rainfall-limited region of China. The dry grain yield ranged from 6.0 to 9.0 t ha⁻¹ under CK, but increased to 7.5 to 10.6 t ha⁻¹ under GM and 11.3 to 12.4 t ha⁻¹ under FM. The better performance in grain and biomass production under FM than under GM suggests that FM was more efficient than GM in alleviating hydrothermal limitations to maize growth. The maize yields in this study are better than the mean 5-yr (2008–2012) maize yields of 3.8 when not mulched (i.e., CK) and 7.7 t ha⁻¹ under full mulch (i.e., FM). It was conducted in a study site with the similar weather condition and soil texture on the Loess Plateau (Liu et al., 2014). 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., 2014), which are less than that demonstrated in this study.

Bu et al. (2013) found that plastic film and gravel mulching could significantly improve soil water and temperature and improve the amounts of accumulated dry matter, which would lead to a greater final biomass and grain yield. However, increases in soil moisture and topsoil temperature would risk depleting the SOC and reducing soil quality through increased SOC mineralization and microbial activity (Li et al., 2004c; Zhou et al., 2012). A previous study has reported that plastic film mulching can lead to a short-term decrease in total SOC of the topsoil, while little change in soil TN from sowing to harvest and no differences between mulched and unmulched treatments in a 2-yr study on maize (Zhou et al., 2012). In this study, the GM and FM treatments had no effect on the SOC and TN contents after the 5 yr of this study compared with the CK. The amount of SOC depends on the rate of organic matter decomposition and the amount of crop residue returned to the soil (Liang et al., 2010). Improvements in soil water and temperature may promote the growth of crop roots and root distribution across the soil profile. Plastic film mulching improved the rooting systems and mainly increased root biomass in the 0- to 40-cm layer (Gao et al., 2014), which may eventually increase the quantity of SOC. The increased production of high-yield and high-biomass maize would result in consistent year-on-year increases in the SOC content.

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 (including N) 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 WSON as a by-product (Murphy et al., 2000). The LFON includes partially decomposed plant residues together with microbial by-products and is a major source of N for microbes (Gregorich et al., 2006). In this study, compared with the CK, the FM treatment substantially remitted the decrease in LFON content in two layers. Root biomass of crops is known to be closely related to aboveground productivity (Johnson et al., 2006). Thereby, higher root biomass under FM could increase the input of LFOM into the soil. Thus, FM could maintain and even increase the LFON content, and its content could be recovered gradually over the years.

The MBN only accounts for approximately 2 to 6% of soil total N, but it is believed to have a key influence on the rate of nutrient cycling in agroecosystems (Brookes et al., 1985). Due to the rapid generation time of soil microbial biomass, MBN is thought to be the most labile SON fraction. It represents both a source and sink of mineral N (Brookes 2001). The higher topsoil moisture and temperature may increase the growth of plant roots, providing more substrates for microbial biomass, also may have promoted microbial activity, leading to higher microbial biomass (Yao et al., 2011). A
previous study has reported that plastic film mulching enhanced soil microbial biomass (Zhou et al., 2012). A similar result was observed in this study, where FM showed greater MBN and MBN/TN in the 0- to 20-cm layer when compared with the CK. In addition, FM had a greater effect on increasing MBN and MBN/TN than GM in the 0- to 20-cm layer.

Soluble organic N or extractable organic N is soil N that is extracted from the soil using water, KCl, electro ultrafiltration (EUF), K$_2$SO$_4$, CaCl$_2$, or any other extractant (Murphy et al., 2000). Dissolved organic nitrogen (DON) is composed of amino acids and other light organic molecules, and may represent a labile N source for soil microorganisms (Jones and Kielland 2002). The WSON is widely used as a surrogate for DON in soil solutions and includes the DON present in macropores and some smaller pores (Chantigny et al., 2008). It is derived from microbial degradation of fresh and partially decomposed organic residues, including autochthonous SON (Murphy et al., 2000). In general, the salt solution (0.5 mol L$^{-1}$ K$_2$SO$_4$) extracted more SON than water. A salt extraction may disturb the adsorption equilibrium 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). In this study, after the 4-yr duration, GM and FM showed greater WSON concentrations and WSON/TN ratios, which can be attributed to the greater release of soluble organic N that occurs after microbial degradation of the crop residues. On the other hand, GM and FM showed a decrease in EON concentrations and EON/TN ratios, which may be due to the less amounts of extracted N that are originally adsorbed on the surface of soil mineral and organic clays and/or the greater amounts of extracted N that are reused by soil microbes.

In this study, after the 4-yr duration, TN was highly correlated with SOC, LFON, MBN, and EON ($R = 0.905^{**}$, 0.832**, 0.784**, and 0.778*, respectively), SOC was highly correlated with MBN, EON, LFON, and WSON ($R = 0.822^{**}$, 0.813**, 0.811**, and 0.581*, respectively). The significant correlations observed among TN, SOC, and labile SON fractions may suggest that the labile SON pools may provide an indication of soil N availability and soil fertility. Significant positive correlations were found between WSON and MBN, between MBN and LFON and between LFON and EON ($R = 0.724^{**}$, 0.692** and 0.926**, respectively). The significant correlations among the labile SON pools measured by different fractionation techniques indicate that they partly represent similar N pools in soil. In general, the labile SON fractions were more sensitive than SOC and TN in the relative changes. The MBN and EON demonstrated the opposite trends in the 0- to 20-cm layer in comparison of relative changes of labile SON fractions. Much more increase in MBN and decrease in EON under FM suggest that the greater amounts of extracted N are reused by soil microbes. As a whole, all the labile SON fractions that were analyzed in this study were sensitive to soil surface mulching with the trend as follows: LFON > MBN > EON > WSON.

**CONCLUSION**

Gravel and plastic film mulching resulted in higher maize yields and biomass than that of the control, while had no effect on the SOC and TN contents after 5 yr of this study in semiarid farmland. Compared with the CK, the GM and FM treatments significantly decreased LFON and EON in the 0- to 20-cm layer, whereas increased WSON in two layers; meanwhile, the MBN under FM significantly increased in the 0- to 20-cm layer after 4 yr of this study. Briefly, FM displayed greater effects on enhancing crop yield and maintaining or improving soil labile N pools than GM. In conclusion, plastic film mulching is an excellent option for enhancing crop productivity, maintaining soil quality and improving soil N availability in the semiarid regions of the Loess Plateau, China.

**ACKNOWLEDGMENTS**

This research was financially supported by the National Natural Science Foundation of China (31270553, 51277197), the Ministry of Science and Technology of China (2015CB150402) and the Special Fund for Agricultural Profession (201103003).

**REFERENCES**

Anikwe, M.A.N., C.N. Mbahe, P.I. Ezekwu, and V.N. Onyia. 2007. Tillage and plastic mulch effects on soil properties and growth and yield of cocoyam (Colocasia esculenta) on an ultisol in southeastern Nigeria. Soil Tillage Res. 93:264–272. doi:10.1016/j.still.2006.04.007

Bremner, J.M., and C.S. Mulvaney. 1982. Nitrogen-total. In: A.L. Page, R.H. Miller, and D.R. Keeney, editors, Methods of soil analysis. Part 2. Chemical and microbiological properties. ASA and SSA, Madison, WI. p. 595–624.

Brookes, P.C. 2001. The soil microbial biomass: Concept, measurement and applications in soil ecosystem research. Microbes Environ. 16:131–140. doi:10.1264/jume2.2001.131

Brookes, P.C., A. Landman, G. Pruden, and D.S. Jenkinson. 1985. Chloroform fumigation and the release of soil-nitrogen—A rapid direct extraction method to measure microbial biomass nitrogen in soil. Soil Biol. Biochem. 17:837–842. doi:10.1016/0038-0717(85)90144-0

Bu, L.D., J.L. Liu, L. Zhu, S.S. Luo, X.P. Chen, S.Q. Li, R.L. Hill, and Y. Zhao. 2013. The effects of mulching on maize growth, yield and water use in a semi-arid region. Agric. Water Manage. 123:71–78. doi:10.1016/j.agwat.2013.03.015

Cabrera, M.L., and M.H. Beare. 1993. Alkaline persulfate oxidation for determining total nitrogen in microbial biomass extracts. Soil Sci. Soc. Am. J. 57:1007–1012. doi:10.2136/soja1993.03615995005700040021x

Chantigny, M.H., D.A. Angers, K. Kaiser, and K. Kalbitz. 2008. Extraction and characterization of dissolved organic matter. In: M.R. Carter and E.G. Gregorich, editors, Soil sampling and methods of analysis. 2nd ed. Canadian Soc. of Soil Sci., CRC Press, Boca Raton, FL. p. 617–635.

Chen, C.R., Z.H. Xu, S.L. Zhang, and P. Keay. 2005. Soluble organic nitrogen pools in forest soils of subtropical Australia. Plant Soil 277:285–297. doi:10.1007/s11104-005-7530-4

Deng, X.P., L. Shan, H. Zhang, and N.C. Turner. 2006. Improving agricultural water use efficiency in arid and semiarid areas of China. Agric. Water Manage. 80:23–40. doi:10.1016/j.agwat.2005.07.021

Doolittle, W.E. 1998. Innovation and diffusion of sand and gravel-mulch agriculture in the American Southwest: A product of the eruption of Sunset Crater. Quaternaire. 9:61–69. doi:10.3406/quate.1998.2107

Fan J., Y. Gao, Q.J. Wang, S.S. Malhi, and Y.Y. Li. 2014. Mulching effects on maize growth, yield and water use in rainfed environments. Adv. Agron. 118:429–476. doi:10.1016/B978-0-12-405924-9.00007-4
Gao, Y.H., Y.P. Xie, H.Y. Jiang, B. Wu, and J.Y. Niu. 2014. Soil water status and root distribution across the rooting zone in maize with plastic film mulching. Field Crops Res. 156:40–47. doi:10.1016/j.fcr.2013.10.016

Gregorich, E.G., M.H. Beare, U.F. McKim, and J.O. Skjemstad. 2006. Chemical and biological characteristics of physically uncomplexed organic matter. Soil Sci. Soc. Am. J. 70:975–985. doi:10.2136/sssaj2005.0116

Gregorich, E.G., and B.H. Ellert. 1993. Light fraction and macro organic matter in mineral soils. In: M.R. Carter, editor, Soil sampling and methods of analysis. Canadian Soc. of Soil Sci., Lewis Publ., Div. of CRC Press, Boca Raton, FL. p. 397–407.

Johnson, J.M.-F., R.R. Allmaras, and D.C. Reicosky. 2006. Estimating source carbon from crop residues, roots and rhizodeposits using the national grain-yield database. Agron. J. 98:622–636. doi:10.2134/agronj2005.0179

Jones, D.L., and V.B. Willett. 2006. Experimental methods of orders to quantify dissolved organic nitrogen (DON) and dissolved organic carbon (DOC) in soil. Soil Biol. Biochem. 38:991–999. doi:10.1016/j.soilbio.2005.08.012

Li, X.Y. 2003. Gravel-sand mulch for soil and water conservation in the semiarid loess region of northwest China. Catena 52:105–127. doi:10.1016/S0341-8162(02)00181-9

Li, C.H., J. Moore-Kucera, C. Miles, K. Leonas, J. Lee, A. Corbin, and D. Inglis. 2014. Degradation of potentially biodegradable plastic mulch films at three diverse US locations. Agrocol. Sust. Food 38:861–889. doi:10.1080/21683565.2014.884535

Li, F.M., Q.H. Song, J.H. Hao, P.K. Jjemba, and Y.C. Shi. 2004c. Dynamics of soil microbial biomass C and soil fertility in cropland mulched with plastic film in a semiarid agro-ecosystem. Soil Biol. Biochem. 36:1893–1902. doi:10.1016/j.soilbio.2004.04.040

Li, F.M., P. Wang, J. Wang, and J.Z. Xu. 2004b. Effects of irrigation before sowing and plastic film mulching on yield and water uptake of spring wheat in semiarid Loess Plateau of China. Agric. Water Manage. 67:77–88. doi:10.1016/j.agwat.2004.02.001

Li, F.M., J. Wang, J.Z. Xu, and H.L. Xu. 2004a. Productivity and soil response to plastic film mulching durations for spring wheat on eiseidos in the semiarid Loess Plateau of China. Soil Tillage Res. 78:9–20. doi:10.1016/j.still.2003.12.009

Liang, B.C., A.F. Mackenzie, and M. Schnitzer. 1997. Management-induced change in labile soil organic matter under continuous corn in eastern Canadian soils. Biol. Fertil. Soils 26:88–94. doi:10.1007/s003740050348

Liang, Y.C., Y.G. Zhu, F.A. Smith, and H. Lambers. 2010. Soil–plant interactions and sustainability of eco-agriculture in arid region: A crucially important topic to address. Plant Soil 326:1–2. doi:10.1007/s11104-009-0208-6

Liu, C.A., S.L. Jin, L.M. Zhou, Y. Jia, F.M. Li, Y.C. Xiong, and X.G. Li. 2009.

Liu, Z., Y.Z. Xue, S.S. Malihi, C.L. Verma, P.B. Zhuang, and Z.H. Guo. 2011. Effects of gravel-sand mulch, plastic mulch and ridge and furrow rainfall harvesting system combinations on water use efficiency, soil temperature and watermelon yield in a semi-arid Loess Plateau of northwestern China. Agric. Water Manage. 101:88–92. doi:10.1016/j.agwat.2011.09.006

Liu, C.A., S.L. Jin, L.M. Zhou, Y. Jia, F.M. Li, Y.C. Xiong, and X.G. Li. 2009.

Ma, Y.J., and X.Y. Li. 2011. Water accumulation in soil by gravel and sand mulches: Influence of textural composition and thickness of mulch layers. J. Arid Environ. 75:432–437. doi:10.1016/j.jare.2010.12.017

Meibus, L.J. 1960. A rapid method for the determination of organic carbon in soil. Anal. Chim. Acta 22:120–124. doi:10.1016/S0003-986X(00)90012-2

Murphy, D.V., A.J. Macdonald, E.A. Stockdale, K.W.T. Goulding, S. Fortune, J.L. Gaunt et al. 2000. Soluble organic nitrogen in agricultural soil. Biol. Fertil. Soils 30:374–387. doi:10.1007/s003740050018

Nachtergaele, J., J. Poesen, and B.V. Wesemael. 1998. Gravel mulching in vineyards of southern Switzerland. Soil Tillage Res. 46:51–59. doi:10.1016/S0167-6167(97)00078-0

Norman, R.J.C. Edberg, and J.W. Stucki. 1985. Determination of nitrate in soil extracts by dual-wavelength ultraviolet spectrophotometry. Soil Sci. Soc. Am. J. 49:1182–1185. doi:10.2136/sssaj1985.0365559500490005002X

Ritchie, S.W., J.J. Hanway, and G.O. Benson. 1992. How a corn plant develops. Spec. Rep. 48. Iowa State Univ., Coop. Ext. Serv., Ames. http://maize.agron.iastate.edu/corngrows.html (accessed 20 Apr. 2006).

Schimel, J., T.C. Balser, and M. Wallenstein. 2007. Microbial stress-response physiology and its implications for ecosystem function. Ecology 88:1386–1394. doi:10.1890/06-0219

Schulen, H.R., and M. Schnitzer. 1997. The chemistry of soil organic nitrogen: A review. Biol. Fertil. Soils 26:1–15. doi:10.1007/s003740050335

Sharma, P., V. Abrol, and R.K. Sharma. 2011. Impact of tillage and mulch management on economics, energy requirement and crop performance in maize-wheat rotation in rainfed subhumid inceptisols, India. Eur. J. Agron. 34:46–51. doi:10.1016/j.eja.2010.10.003

Siddique, K.H.M., C. Johansen, N.C. Turner, M.H. Jeuffroy, A. Hashem, D. Sakar et al. 2012. Innovations in agronomy for food legumes—A review. Agron. Sustain. Dev. 32:45–64. doi:10.1007/s11368-011-0353-4

Turner, N.C. 2004. Sustainable production of crops and pastures under drought in a Mediterranean environment. Ann. Appl. Biol. 144:139–174. doi:10.1111/j.1744-7348.2004.tb00327.x

Wang, Y.J., Z.K. Xue, S.S. Malihi, C.L. Verma, Y.B. Zhuang, and Z.H. Guo. 2011. Effects of gravel-sand mulch, plastic mulch and ridge and furrow rainfall harvesting system combinations on water use efficiency, soil temperature and watermelon yield in a semi-arid Loess Plateau of northwestern China. Agric. Water Manage. 101:88–92. doi:10.1016/j.agwat.2011.09.006

Wani, S.P., T.K. Streevedy, J. Rockstrom, and Y.S. Ramakrishna. 2009. Rainfed agriculture: Past trends and future prospects. In: S.P. Wani et al., editors, Rainfed agriculture: Unlocking the potential. CAB Int, Oxford, UK. p. 1–35

Xie, Z.K., Y.J. Wang, G.D. Cheng, S.S. Malihi, C.L. Verma, Z.H. Guo, and Y.B. Zhang. 2010. Particle-size effects on soil temperature, evaporation, water use efficiency and watermelon yield in fields mulched with gravel and sand in semi-arid Loess Plateau of northwest China. Agric. Water Manage. 97:917–923. doi:10.1016/j.agwat.2010.01.023

Yao, H.Y., D. Bowman, and W. Shi. 2011. Seasonal variations of soil microbial biomass and activity in warm-and cool-season turfgrass systems. Soil Biol. Biochem. 43:1536–1543. doi:10.1016/j.soilbio.2011.03.031

Zhou, L.M., S.L. Jin, C.A. Liu, Y.C. Xiong, J.T. Si, X.G. Li, Y.T. Gan, and F.M. Li. 2012. Ridge-furrow and plastic mulching tillage enhances maize–soil interactions: Opportunities and challenges in a semiarid agroecosystem. Field Crops Res. 126:181–188. doi:10.1016/j.fcr.2011.10.010

Zhou, X.Q., X. Liu, Y.C. Rui, C.R. Chen, H.W. Wu, and Z.H. Xu. 2011. Symbiotic nitrogen fixation and soil N availability under legume crops in an arid environment. J. Soils Sediments 11:762–770. doi:10.1007/s11368-011-0533-4