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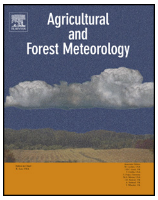

Multi-site assessment of the effects of plastic-film mulch on the soil organic carbon balance in semiarid areas of China

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ABSTRACT

Plastic-film mulch is widely used to increase soil temperature and reduce water evaporation in vegetable production. In China, it is also extensively used for growing grain crops, especially in temperature and rainfall limited areas. However, it remains unclear whether the technology is sustainable in terms of maintenance of soil organic carbon (SOC) balance. We assessed the effects of plastic-film mulch on the SOC balance in maize (*Zea mays* L.) production in a range of cold semiarid environments. We imposed four treatments: (i) no plastic-film mulch or straw incorporation, (ii) plastic-film mulch, (iii) straw incorporation in soil without mulch, and (v) straw incorporation plus mulch, in ridge–furrow prepared fields at five sites along a hydrothermal gradient for up to six years. Maize root biomass across sites increased by 23–38% in mulched plots associated with the increase in aboveground biomass, indicating an increased SOC input, compared to that in non-mulched plots. The plastic-film mulch increased SOC mineralization, indicated by the stimulated decomposition of buried maize straw, and a 4–5% reduction in the concentration of light-fraction SOC ($<1.8\,\mathrm{g\,cm^{-3}}$), but the total SOC concentration and stock in the 0–0.15 m soil layer did not change relative to no mulch after six years of continuous cropping. Plastic-film mulch did not affect the total non-cellulosic sugar content; however, it significantly increased the contribution of microbial-synthesized sugars to the total non-cellulosic sugars, indicating an intensified microbial action on the SOC pool compared to no mulch. Straw incorporation increased the root biomass, light and total SOC concentrations and non-cellulosic sugars, and changed the non-cellulosic sugar composition. We conclude that the increase in soil temperature and moisture by use of plastic-film mulch enhances productivity, but importantly maintains the SOC level in temperature- and rainfall-limited semiarid regions by balancing the increased SOC mineralization with increased root-derived C input.

1. Introduction

Plastic-film mulch is a technology used worldwide for vegetable production (Clarkson, 1960; Lamont, 1993; Díaz-Pérez et al., 2004; Anikwe et al., 2007; Berger et al., 2013). In China, plastic-film mulch is not only used for vegetable production, but also in maize (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), potato (*Solanum tuberosum* L.), wheat (*Triticum aestivum* L.) and rice (*Oryza sativa* L.) production, particularly to enable earlier planting in regions with cold and long winter. In 2014, the total production of plastic-film in China was 1.42 million t and about 19% (25 million ha) of total arable land (130 million ha) in China was cultivated under plastic-film mulch (http://www.ampcn.com/news/content.asp?newsid=103593). The large scale use of plastic-film mulch in China originates from its severe shortages of arable land and water resources for agriculture (Zhang et al., 2013); only 0.1 ha of cropland is available for each of China's 1.3 billion people, less than 1/6 of the per capita cropland area in the USA (0.64 ha in 2000; Lal, 2002). Therefore, meeting the demand for increased grain production requires improved productivity of existing cropping systems (Godfray et al., 2010; Tilman et al., 2011; Zhang et al., 2013), but not at the expense of long-term degradation of the soil resources. Improved productivity without environmental degradation is termed sustainable intensification (Garnett et al., 2013).

Insufficient precipitation and shortages of irrigation water are major constraints to increasing crop productivity in semiarid areas while low air temperatures in spring are limitations in high altitude and/or high latitude regions. Plastic-film mulch provides a

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way of reducing these soil and water limitations by simultaneously increasing soil temperatures and decreasing soil water evaporation (Li et al., 2007; Gan et al., 2013; Chai et al., 2014; Liu et al., 2014a,b). On the Loess Plateau in northwest China, plastic-film mulch increases the upper (0–0.15 or 0.20 m) soil temperatures by 2–7 °C in the early growth of maize or wheat (Li et al., 2004, 2013a; Liu et al., 2014a,b; Wang et al., 2015, 2016). By blocking soil water evaporation, plastic-film mulch significantly increases soil moisture (Li et al., 2007, 2013b; Liu et al., 2014b; Wang et al., 2016). Crops grown under plastic-film mulch typically have increased yields of 50–100% in drought years or cold sites, 30–90% in an average-rainfall year or warmer sites, and 10–40% in a wetter-than-normal year and milder temperatures, compared non-mulched crops (Gan et al., 2013; Wang et al., 2016). In maize, the increased yields in mulched-systems are typically a combination of increases in various yield components, such as more fertile cobs per plant, increased 1000-seed weight, and more seeds per head (Li et al., 1999; Niu et al., 2004; Ren et al., 2009).

Any increase in crop productivity must not be at the expense of soil quality, as measured by soil organic carbon (SOC) and must not exacerbate greenhouse gas emissions in the face of rapid global change (Godfray et al., 2010; Cui et al., 2013). While the impacts of commonly-employed practices such as treatment of straw and stubble residues, application of mineral fertilizers, improvement of cultivars, species and tillage on food production and global climate change have been extensively studied (Ciais et al., 2011), the impact of plastic-film mulch on the carbon balance is less known. The basic principal of using plastic-film mulch in crop production is to simultaneously increase soil temperature and moisture (Liu et al., 2010; Gan et al., 2013; Chai et al., 2014), which is well known to stimulate mineralization and loss of SOC (Yin et al., 2013; Hadden and Grelle, 2016). The SOC level not only determines the productivity and sustainability of a cropping system, but also affects the CO_2 fluxes between the soil and atmosphere (Lal, 2004; Luo et al., 2011; Liu et al., 2015). The change in the SOC level in the soil is the result of inputs from plant-derived organic sources and losses by microbial decomposition (Lal, 2004; Liu et al., 2015). Sporadic data has shown that plastic-film mulch increases soil microbial biomass (Li et al., 2004; Wang et al., 2014; Hai et al., 2015), soil enzymatic activity (Wang et al., 2014; Liu et al., 2014a), nitrogen mineralization and availability (Chen and Katan, 1980; Zhang et al., 2012; Hai et al., 2015), and decreases labile SOC pools after one growing season (Wang et al., 2014). This implies that by increasing soil temperature and moisture plastic-film mulch may increase SOC mineralization and thus negatively affect the SOC balance if the increased mineralization is not balanced by increased inputs. However, despite plastic-film mulch being widely adopted, its effect on the SOC balance has not been rigorously assessed. It remains unclear if the plastic-film mulch is a technology of sustainable intensification, in terms of the SOC balance.

Previously we showed that the continuous use of plastic-film mulch along a hydrothermal gradient significantly increased the grain yield and aboveground biomass of maize compared with non-mulched plots at five semiarid sites varying in temperature and precipitation (Wang et al., 2016). Additionally, we showed that straw incorporation increased the yield and aboveground biomass of maize by 7–12% and 8–12%, respectively (Wang et al., 2016). The objective of the present study was to examine the effect of the plastic-film mulch and straw incorporation on SOC balance under maize at the same five sites. We hypothesized that: (i) the plastic-film mulch and straw incorporation would increase the input of SOC from increased belowground biomass associated with the increased aboveground biomass; (ii) the plastic-film mulch would increase the microbial mineralization of SOC; and (iii) the increase in belowground biomass with the use of plastic-film mulch would counterbalance the loss of SOC from the increased mineralization. To test our first hypothesis, we measured the root biomass production of maize in plastic-film mulched and non-mulched plots and with and without straw incorporation. There should be more roots in the mulched treatments because of the increased water content in the top soil. To test our second hypothesis, we measured the decomposition of maize straw buried in soil to indicate SOC mineralization as affected by plastic-film mulch, because the direct measurement of SOC mineralization is difficult due to the low SOC content of the local soils. Finally, we measured the changes in total and light-fraction SOC pools and non-cellulosic carbohydrates in different treatments to assess the effect of plastic-film mulch and straw incorporation on SOC levels and composition. The light-fraction SOC and carbohydrates are readily-available carbon and energy sources for microorganisms and are sensitive to changes in soil management practices (Gregorich et al., 1994; Haynes, 2005). In addition, the analysis of the respective contribution of hexoses, pentoses, and desoxy-hexoses to the neutral sugar pool allows an assessment of changes in the polysaccharide sources (microbial versus plant-derived polysaccharides) when subjected to the different treatments (Murayama, 1984; Oades, 1984; Schmidt et al., 2015).

2. Materials and methods

2.1. Site and experimental design

The study was conducted at five sites in Gansu Province, China, varying in altitude, temperature and precipitation: Ningxian, Chongxin, Tongwei, Huining and Yuzhong (Table 1). The five sites increased in altitude from Ningxian through Chongxin, Tongwei and Huining to Yuzhong, while mean annual rainfall and mean temperature (1982–2012) decreased from Ningxian through Chongxin, Tongwei, and Huining to Yuzhong (Table 1). At each site, the experiments were conducted on a flat field that had been cropped for many years. The soils across all five sites are classified as Mollisols at Ningxian and Chongxin, and Entisols at Tongwei, Huining and Yuzhong, developed from wind-blown loess that has a deposition thickness of more than 100 m above the bedrock. They have a silt loam texture (2–0.05 mm 3.5–6.7%; 0.05–0.002 mm 71.1–74.8%; <0.002 mm 21.6–22.0%), a bulk density ranging from 1.00 to 1.14 g cm^{-3} and pH values (water:soil = 2.5:1) from 8.0 to 8.2 in the upper 0.15-m soil profile. At the start of the experiment in October 2008, the total SOC varied from 9.1 to 12.2 g kg^{-1}, total soil nitrogen (N) varied from 1.02 to 1.23 g kg^{-1}, mineral N varied from 23 to 128 mg kg^{-1}, and Olsen phosphorus varied from 7 to 56 mg kg^{-1} across the five sites (Wang et al., 2016).

A detailed description of the experimental sites and experimental design are given in Wang et al. (2016). At each site, four treatments with three replicates were imposed in October in a ridge-furrow field: (1) control (no plastic-film mulch and no straw incorporation), (2) plastic-film mulch over ridges and furrows (without straw incorporation), (3) straw incorporation (without plastic-film mulch), and (4) plastic-film mulch with straw incorporation. The experiment was conducted continuously in the same field at each site for three years (2009–2011) at Ningxian, four years (2009–2012) at Chongxin and six years (2009–2014) at Tongwei, Huining and Yuzhong. At each site, maize straw (stems and leaves, <0.06 m in length) was applied in late October on the straw-incorporation plots. The amount of maize straw incorporated was between 5 and 7.5 t ha^{-1} (constant mass at 60 °C) per year (2.4–3.6 t C ha^{-1} y^{-1}) at Ningxian, Tongwei, Huining and Yuzhong, and between 4 and 6 t ha^{-1} y^{-1} (1.9–2.9 t C ha^{-1} y^{-1}) at Chongxin. Urea at 276 kg N ha^{-1} and superphosphate at 37 kg soluble phosphorus ha^{-1} were broadcast on each plot before plowing to a depth of 0.15 m with a spade. Afterwards, alternate narrow

Table 1
Geographic coordinates, altitude, mean annual rainfall and mean annual air temperature (1982–2013) and the aboveground biomass (ABM, t ha^{-1}) and grain yield (GY, t ha^{-1}) averaged over cropping years of maize given four treatments (Control: no plastic-film mulch plus no straw incorporation; M: plastic-film mulch; S: straw incorporation; S + M: straw incorporation plus plastic-film mulch) at five sites, Ningxian, Chongxin, Tongwei, Huining and Yuzhong, Data of ABM and GY adapted from Wang et al. (2016).

Location	Geographic coordinates	Altitude (m)	Mean annual rainfall (mm)	Mean air temperature (°C)	Control		M		S		S + M	
					ABM	GY	ABM	GY	ABM	GY	ABM	GY
Ningxian	35°29′N; 107°45′E	1264	565	8.7	13.08	6.28	18.13	8.40	14.37	7.20	19.23	9.06
Chongxin	33°21′N; 106°35′E	1407	501	9.7	11.47	5.19	15.95	8.28	12.65	5.95	17.47	9.10
Tongwei	35°05N′; 105°15′E	1750	450	7.2	10.99	4.46	18.07	8.75	12.49	5.28	19.57	9.20
Huining	35°32′N; 105°04′E′	1810	410	7.1	10.97	4.79	18.98	10.18	12.15	5.30	20.16	10.73
Yuzhong	35°54′N; 104°05′E	2013	388	6.7	11.17	4.65	17.77	9.03	12.53	5.18	19.77	9.99

(0.15 m high × 0.40 m wide) and wide (0.10 m high × 0.70 m wide) ridges were established in all treatments. For the plastic-film mulch treatments, the entire soil surface was covered with colorless, transparent 0.008 mm thick polyethylene film. After covering the soil with the plastic film, holes 15 mm in diameter and 0.20 m apart were punched through the film in the furrows. These holes and those made at sowing allowed rainwater from the ridges to enter the soil in the furrows (Liu et al., 2014b; Jiang and Li, 2015). Preparing the plastic-film mulched ridge–furrow system before winter, rather than in spring, has been shown to conserve more rainwater in the soil by blocking soil water evaporation over the winter (Liu et al., 2009) and is widely practiced in areas. The following late-April of each year, 12 rows of maize were hand sown in each plot at all sites after punching new holes in the furrows 0.35 m apart. The sowing density was 52,500 plants ha^{-1}. The maize cultivars used at each site were those commonly grown locally and are listed in Wang et al. (2016). Each of the 12 plots (4 treatments × 3 replicates) was 38.4 m^2 at Ningxian, 44.0 m^2 at Chongxin, 37.4 m^2 at Tongwei, 41.8 m^2 at Huining and 39.6 m^2 at Yuzhong. The space between plots was >0.4 m.

2.2. Sampling and measurements

At each site, the maize was harvested in late September/early October. After the grain yield and aboveground biomass (Table 1) had been harvested (Wang et al., 2016), roots in the top 0.20 m were taken from five random soil columns (the area of each column was considered that shared by a maize plant) in each of two selected maize rows. The roots were carefully washed free of soil and were then oven dried at 60 °C to constant weight. Leaves and stems were removed from all plots, chopped with a hay chopper and then used for the next-season's straw incorporation treatment. Each year after harvest, the ridges and furrows were re-established and the plastic-film replaced.

When the plastic-film mulched ridge–furrow system was installed in October 2008, four nylon-mesh (aperture 1.5 mm) bags, each containing 60 g of air-dried maize straw (length <30 mm) were separately buried under the top 0.10-m soil layer of randomly-selected narrow ridges on each of the six straw-incorporated plots (three non-mulched and three plastic-film mulched). The maize straw had 439 g C and 6.7 g N kg^{-1} (C/N = 65.5). Half of the nylon-mesh bags in the non-mulched and mulched treatments were sampled at the 2009 harvest and the other half at the 2010 harvest. The contents were air-dried in the laboratory. The carbon content of the initial and buried maize straw (ground to fine powders) was analyzed using a Multi C/N 3100 (Analytik Jena, Jena, Germany) analyzer. C loss percentage of the buried maize straw was calculated as the difference in the amount of C in each nylon-mesh bag between October 2008 and harvest in 2009 or 2010 divided by the C amount in October 2008.

At sowing in 2009 and at harvest each year, the soil at all sites was randomly sampled on narrow ridges from the surface to 0.15 m depth using an auger. Subsamples within each plot were pooled to form one composite soil sample. Each air-dried composite soil sample was passed through a 2 mm sieve and plant residues >2 mm on the sieve were discarded. The air-dried and sieved composite soil samples were stored in the laboratory. The light-fraction SOC (density <1.8 g cm^{-3}) was separated from the soil (<2 mm) according to Marriott and Wander (2006) using NaI solution as a density agent. Organic C in the soil samples and in the light fractions (all ground to <0.15 mm) were determined by the Walkley and Black dichromate oxidation method and a factor of 1.3 was applied to adjust the organic C recovery (Nelson and Sommers, 1982). The total and light-fraction SOC in all samples at all the five sites were measured in 2014. At Tongwei, Huining and Yuzhong, the bulk density in the upper 0.15 m of the soil at harvest in 2013 was measured in each plot using a cutting ring (volume 100 cm^3, inner diameter 5.05 mm). Using this measurement, we converted the total and light-fraction SOC concentrations determined at sowing in 2009 and harvest in 2014 to the carbon stock in the 0–0.15 m soil layer at the three sites of Tongwei, Huining and Yuzhong.

On the soil samples taken at harvest in 2013 (five years after continuous implementation of the experiment) at Tongwei, Huining and Yuzhong, we analyzed neutral sugar contents with adonitol as an internal standard, following the procedure described by Li et al. (2013c). Hydrolysis of noncellulosic carbohydrates in the soil (air-dried samples ground to <0.15 mm; containing about 4 mg organic C) was conducted in 4 M trifluoroacetic acid (Guggenberger and Zech, 1994) with purification according to Zhang et al. (2007). Measurements of sugar monomers were performed using a gas chromatograph equipped with an FID detector (BEIFEN SP-3420A, Beijing Beifen-Ruili Analytical Instrument Group, Beijing, China). Separation of the sugar monomers was achieved with an AT SE-30 fused silica capillary column (30 m × 0.25 mm × 0.25 μm; Lanzhou Institute of Chemical Physics, Chinese Academy of Science). The split ratio was 30:1, and N_2 was used as the carrier gas with a flow rate of 0.02 mL s^{-1}. The gas chromatography temperature program was set at 175 °C for 240 s, 225 °C for 270 s, 270 °C for 120 s, and 300 °C for 120 s, with increasing rates at 0.07 °C s^{-1} from 175 °C to 225 °C and 0.5 °C s^{-1} from 225 °C to 300 °C. Altogether, eight sugar monomers (rhamnose, fucose, ribose, arabinose, xylose, mannose, galactose, and glucose) were analyzed, with the sugar amounts in soil samples expressed as mg sugar per g of total SOC. In the analysis, mixtures of the eight standard sugar monomers were included as external standards. The mass ratios of galactose plus mannose to arabinose plus xylose (GM/AX) and rhamnose plus fucose to arabinose plus xylose (RF/AX) were used to indicate the proportion of microbial-synthesized sugars in the total non-cellulosic carbohydrates (Murayama, 1984; Oades, 1984).

2.3. Statistical analyses

2.3.1. Experimental data were assessed using two different analyses of variance (ANOVA):

ANOVA 1: Within each site, repeated measures ANOVA, using experimental years as the repeated factor and film mulch and straw incorporation as two fixed factors, was conducted to assess treatment effects on total and light-fraction SOC pools and maize root biomass (Quinn and Keough, 2002). Repeated measures ANOVA, using experimental years as the repeated factor and film mulch as a fixed factor, was conducted to test treatment effects on C loss percentage of the buried maize straw (Quinn and Keough, 2002). The Greenhouse-Geisser adjustment was used when the assumption of sphericity was not met, and the corrected mean square error and associated degrees of freedom were then used to calculate least significant difference (LSD) values.

ANOVA 2: Within each site, two-way ANOVA using plastic-film mulch and straw incorporation as two fixed factors was conducted on total non-cellulosic sugar content and compositions (GM/AX and RF/AX).

The Kolmogorov-Smirnov test indicated that all data pools followed a normal distribution. The significance of the differences between means in all ANOVAs was identified using LSD at $P \leq 0.05$.

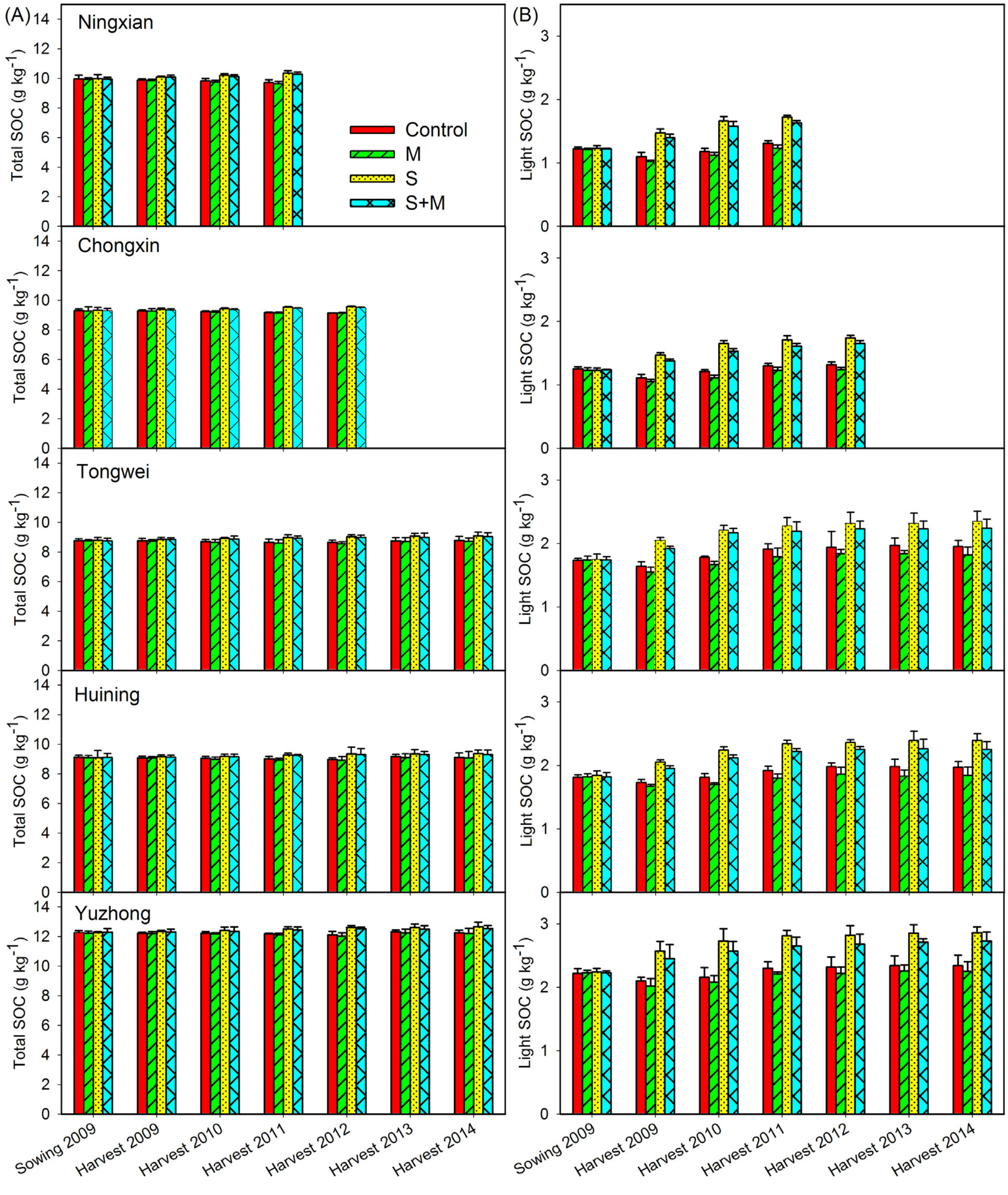

Fig 1. Total and light-fraction soil organic carbon (SOC) concentrations in the top 0.15-m soil when maize was sown in April 2009 and at harvest in October each year with (i) no straw incorporation plus no plastic-film mulch (control), (ii) plastic-film mulch (M), (iii) straw incorporation (S), and (iv) straw incorporation plus plastic-film mulch (S + M) for 2009–2011 at Ningxian, 2009–2012 at Chongxin, and 2009–2014 at Tongwei, Huining, and Yuzhong. Column (A): total SOC; column (B): light-fraction SOC. Bars are + one standard error of the mean ($n = 3$).

The significance of linear correlations between parameters was expressed as the Pearson's product moment correlation coefficient. All statistical analyses were performed by GenStat 17.0 (VSN International Ltd., Rothamsted, England).

3. Results

3.1. Soil organic carbon pools and non-cellulosic sugars

Total SOC concentration was not affected by plastic-film mulch or cropping year at any site; however, averaging across mulch treatments and cropping years, straw incorporation marginally increased total SOC concentration by 2–3% across the five sites (Fig. 1A; Table 2).

Averaging across straw incorporation treatments and cropping years, the plastic-film mulch decreased the light-fraction SOC concentration by 4–5% across the five sites, relative to no mulch (Fig. 1B; Table 2). The concentration of light-fraction SOC averaged over straw incorporations and cropping years was 1.30 g kg^{-1} under plastic-film mulch compared to 1.36 g kg^{-1} under no mulch at Ningxian, 1.33 g kg^{-1} compared to 1.40 g kg^{-1} at Chongxin, 1.92 g kg^{-1} compared to 2.01 g kg^{-1} at Tongwei, 1.96 g kg^{-1} compared to 2.06 g kg^{-1} at Huining, and 2.38 g kg^{-1} compared to 2.48 g kg^{-1} at Yuzhong (Fig. 1B). However, the reduction in the light SOC concentration in mulched relative to non-mulched soils did not vary with year of cropping (non-significant interaction between plastic-film mulch and year on light-fraction SOC at all five sites) (Fig. 1B; Table 2). Across the five sites, averaging mulch treatments and cropping years, straw incorporation increased the light-fraction SOC concentration by 18–27% compared with no straw incorporation (Fig. 1B; Table 2). With increasing years of incorporation of straw, the light-fraction SOC significantly increased, but the increase after one or two years was small (Fig. 1B; Table 2).

At sowing in 2009 and harvest in 2014, the total SOC stock in the upper 0.15 m of soil was similar in all treatments at Ningxian, Chongxin and Huining; six years of maize cropping did not change the total SOC stock (Table 3). At sowing in 2009, the light SOC stock was similar between mulched and non-mulched, and between straw-incorporated and non-straw-incorporated treatments; however, at harvest in 2014, it was 15–18% higher in the straw-incorporated treatment compared to the non-straw-incorporated treatment across the three sites, while there was no change from the application of plastic-film mulch at any sites (Table 3). The light SOC stock averaged over all the treatments at sowing in 2009 was 2.98 t ha^{-1} at Tongwei, 3.12 t ha^{-1} at Huining and 3.63 t ha^{-1} at Yuzhong, which increased to 3.57 (by 20%), 3.60 (15%) and 4.14 t ha^{-1} (14%) at the three sites, respectively, by the harvest in 2014.

At harvest in 2013 (five years after continuous treatment implementations), the total non-cellulosic sugar concentration of the total SOC did not differ between mulched and non-mulched treatments at Tongwei, Huining or Yuzhong; however, straw incor-

Table 2
Results of repeated measure analysis of variance on total and light-fraction soil organic carbon (SOC) concentrations and maize root biomass using cropping year as the repeated factor and plastic mulch (M) and straw incorporation (S) as two fixed factors within each of the five sites (ANOVA 1).

Site	Source	Total SOC			Light SOC			Maize root biomass		
		df	F value	P value	df	F value	P value	df	F value	P value
Ningxian	Year	3	0.034	0.991	3	21.8	<0.001	2	48.1	<0.001
	M	1	0.709	0.424	1	14.8	0.005	1	290	<0.001
	S	1	22.9	0.001	1	412	<0.001	1	24.7	0.001
	Year × M	3	0.027	0.994	3	0.463	0.711	2	4.02	0.039
	Year × S	3	2.68	0.069	3	16.5	<0.001	2	2.20	0.143
	M × S	1	0.014	0.909	1	1.67	1.00	1	13.9	0.006
	Year × M × S	3	0.003	1.00	3	0.024	0.995	2	5.76	0.013
	Error	24			24			16		
Chongxin	Year	4	0.050	0.995	4	40.0	<0.001	3	192	<0.001
	M	1	0.342	0.575	1	9.42	0.015	1	124	<0.001
	S	1	7.55	0.025	1	175	<0.001	1	51.2	<0.001
	Year × M	4	0.006	1.00	4	1.20	0.328	3	17.1	<0.001
	Year × S	4	1.22	0.323	4	24.9	<0.001	3	12.9	<0.001
	M × S	1	0.026	0.875	1	0.094	0.767	1	1.07	0.332
	Year × M × S	4	0.014	1.00	4	0.094	0.984	3	0.350	0.789
	Error	32			32			24		
Tongwei	Year	6	0.297	0.359	6	7.11	<0.001	5	189	<0.001
	M	1	0.826	0.390	1	5.94	0.041	1	261	<0.001
	S	1	17.5	0.003	1	84.9	<0.001	1	30.3	0.001
	Year × M	6	0.007	1.00	6	0.143	0.990	5	8.62	<0.001
	Year × S	6	0.555	0.764	6	1.80	0.120	5	2.53	0.044
	M × S	1	0.003	0.956	1	0.015	0.906	1	0.004	0.952
	Year × M × S	6	0.006	1.00	6	0.016	1.00	5	0.214	0.954
	Error	48			48			40		
Huining	Year	3.25	0.222	0.893	2.82	10.3	<0.001	5	326	<0.001
	M	1	0.150	0.709	1	12.9	0.007	1	619	<0.001
	S	1	3.33	0.105	1	154	<0.001	1	46.9	<0.001
	Year × M	3.25	0.008	0.999	2.82	0.363	0.769	5	7.77	<0.001
	Year × S	3.25	0.292	0.845	2.82	3.55	0.033	5	1.35	0.264
	M × S	1	0.001	0.976	1	0.030	0.867	1	2.27	0.170
	Year × M × S	3.25	0.003	1.00	2.82	0.015	0.997	5	1.06	0.399
	Error	26			22.6			40		
Yuzhong	Year	6	0.450	0.842	6	4.13	0.002	5	417	<0.001
	M	1	0.294	0.602	1	4.63	0.064	1	259	<0.001
	S	1	5.96	0.040	1	84.5	<0.001	1	16.8	0.003
	Year × M	6	0.024	1.00	6	0.116	0.994	5	17.2	<0.001
	Year × S	6	0.646	0.693	6	2.07	0.075	5	1.12	0.368
	M × S	1	0.009	0.929	1	0.314	0.591	1	0.045	0.837
	Year × M × S	6	0.008	1.00	6	0.008	1.00	5	0.242	0.941
	Error	48			48			40		

Table 3
The effect of the four treatments (Control: no straw incorporation plus no plastic-film mulch; M: plastic-film mulch; S: straw incorporation; S + M: straw incorporation plus plastic-film mulch) and cropping year on the total and light-fraction soil organic carbon (SOC) stocks in the top 0.15-m soil layer at Tongwei, Huining, and Yuzhong.

Treatments	Total SOC (t ha^{-1})		Light SOC(t ha^{-1})	
	At sowing 2009	At harvest 2014	At sowing 2009	At harvest 2014
Tongwei				
Control[a]	15.7(0.1)	15.7(0.5)	3.1(0.1)	3.5(0.2)
M[a]	15.1(0.5)	15.0(0.9)	3.0(0.0)	3.1(0.2)
S[a]	14.6(0.2)	15.1(0.5)	2.9(0.1)	3.9(0.3)
S + M[a]	14.7(0.2)	15.1(0.3)	2.9(0.1)	3.9(0.2)
Treatment effect (*P* values) (ANOVA 1)				
Year	0.354		0.001	
Mulch	0.509		0.273	
Straw	0.239		0.157	
Year × mulch	0.944		0.388	
Year × straw	0.339		0.021	
Mulch × straw	0.396		0.499	
Year × mulch × straw	0.970		0.762	
Huining				
Control[a]	16.3(0.2)	16.3(0.6)	3.2(0.1)	3.5(0.2)
M[a]	16.1(0.2)	16.1(1.0)	3.2(0.1)	3.3(0.3)
S[a]	14.3(0.7)	14.7(0.2)	2.9(0.1)	3.8(0.2)
S + M[a]	15.7(0.4)	16.0(0.6)	3.1(0.1)	3.9(0.2)
Treatment effect (*P* values) (ANOVA 1)				
Year	0.548		0.001	
Mulch	0.238		0.814	
Straw	0.066		0.477	
Year × mulch	0.948		0.351	
Year × straw	0.524		0.013	
Mulch × straw	0.147		0.316	
Year × mulch × straw	0.924		0.783	
Yuzhong				
Control[a]	20.1(0.1)	20.1(0.5)	3.6(0.1)	3.8(0.3)
M[a]	20.6(0.2)	20.6(0.2)	3.8(0.1)	3.8(0.3)
S[a]	19.2(0.6)	19.8(0.5)	3.5(0.1)	4.5(0.2)
S + M[a]	20.0(0.3)	20.4(0.7)	3.6(0.1)	4.5(0.2)
Treatment effect (*P* values) (ANOVA 1)				
Year	0.396		0.002	
Mulch	0.180		0.765	
Straw	0.280		0.145	
Year × mulch	0.866		0.518	
Year × straw	0.396		0.009	
Mulch × straw	0.762		0.947	
Year × mulch × straw	0.898		0.969	

[a] Values are means ± one standard errors ($n = 3$) in parentheses.

Table 4
Treatments (Control: no straw incorporation plus no plastic-film mulch; M: plastic-film mulch; S: straw incorporation; S + M: straw incorporation plus plastic-film mulch) effects on total non-cellulosic sugar content along with mass ratios (GM/AX: galactose plus mannose to arobinose plus xylose; RF/AX: rhamnose plus fucose to arobinose plus xylose) in the top 0.15 m soil at harvest in October 2013 (5 years after the start of the experiment) at Tongwei, Huining, and Yuzhong.

Treatment	Tongwei			Huining			Yuzhong		
	Total sugars (mg g^{-1} SOC)[a]	GM/AX	FR/AX	Total sugars (mg g^{-1} SOC)[a]	GM/AX	FR/AX	Total sugars (mg g^{-1} SOC)[a]	GM/AX	FR/AX
Control[b]	73(2)	1.36(0.01)	0.29(0.01)	70(1)	1.26(0.02)	0.26(0.00)	65(1)	1.31(0.02)	0.19(0.01)
M[b]	71(3)	1.57(0.02)	0.32(0.02)	71(2)	1.81(0.02)	0.32(0.00)	65(1)	1.73(0.03)	0.26(0.01)
S[b]	84(2)	1.04(0.02)	0.30(0.00)	88(3)	1.17(0.02)	0.30(0.00)	81(2)	1.03(0.02)	0.23(0.00)
S + M[b]	83(2)	1.31(0.03)	0.31(0.01)	84(1)	1.26(0.02)	0.31(0.00)	83(2)	1.34(0.03)	0.23(0.01)
Treatment effect (*P* values) (ANOVA 2)									
Mulch	0.661	<0.001	0.024	0.266	<0.001	<0.001	0.438	<0.001	<0.001
Straw	0.001	<0.001	0.513	<0.001	<0.001	0.012	<0.001	<0.001	0.124
Mulch × straw	0.883	0.249	0.121	0.205	<0.001	<0.001	0.438	0.053	<0.001

[a] Abbreviation: SOC, total soil organic carbon.
[b] Numbers are means with ± one standard errors (n = 3) in parentheses.

poration increased SOC-normalized total non-cellulosic sugars by 17–26% across the three sites compared with no straw incorporation (Table 4). Plastic-film mulch increased the mass ratio of GM/AX by 20–31% relative to no mulch, whereas straw incorporation decreased the ratio by 19–22% across the three sites relative to no straw incorporation (Table 4). The mass ratio of FR/AX in mulched soils was 10, 23 and 37% higher at Tongwei, Huining and Yuzhong, respectively, than in non-mulched soils, generally when no straw was incorporated (Table 4). Compared to no straw incorporation, straw incorporation increased the mass ratio of FR/AX by 15–21% at Huining and Yuzhong only when no mulch was applied to the soil surface (Table 4).

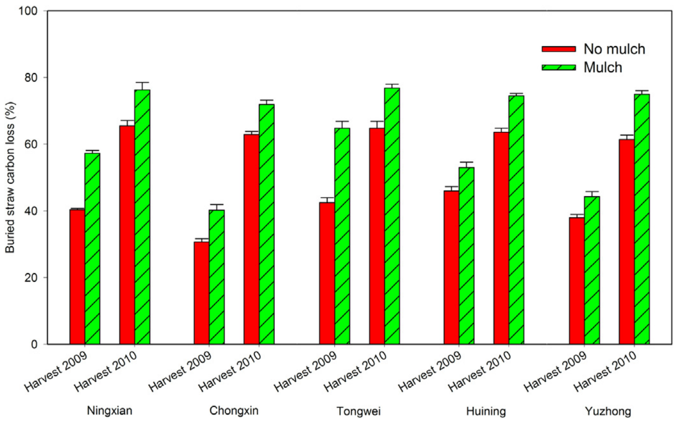

Fig. 2. Percent carbon loss by harvest in October 2009 and 2010 from maize straw buried 0.10 m depth in the soil in October 2008 at Ningxian, Chongxin, Tongwei, Huining, and Yuzhong. Differences in values between non-mulched and plastic-film mulched treatments in both 2009 and 2010 were significant at $P \leq 0.001$ at each of the five sites. Bars are + one standard error of the mean ($n = 3$).

3.2. *Carbon loss of maize straw buried in soil*

At the 2009 harvest (1 year after burial), the percentage C loss from the buried maize straw in the non-mulched plots was 40, 31, 43, 46 and 38%; however, the percentage C loss in the mulched plots increased to 57, 40, 54, 53 and 44% at Ningxian, Chongxin, Tongwei, Huining and Yuzhong, respectively (Fig. 2; $P < 0.001$ at all five sites). By the harvest in 2010 (2 years after burial), the percentage cumulative C loss from the buried maize straw in non-mulched plots was 65, 63, 65, 64 and 61%, while it increased to 76, 72, 77, 75 and 75% in the mulched plots at Ningxian, Chongxin, Tongwei, Huining and Yuzhong, respectively (Fig. 2; $P < 0.001$ at all five sites).

3.3. *Maize root biomass production*

As reported previously, compared with no mulch, plastic film mulch increased the aboveground biomass and the grain yield of the maize by 37–69% and by 30–107%, respectively, depending on site and season (Wang et al., 2016). Averaging straw incorporation treatments and years, the plastic-film mulch increased root biomass by 33% at Ningxian (1.04 t ha^{-1} under mulch vs. 0.78 t ha^{-1} t ha^{-1} under no mulch), 23% at Chongxin (0.97 t ha^{-1} vs. 0.79 t ha^{-1}), 24% at Tongwei (0.93 t ha^{-1} vs. 0.75 t ha^{-1}), 35% at Huining (1.01 t ha^{-1} vs. 0.75 t ha^{-1}), and 38% at Yuzhong (1.24 t ha^{-1} vs. 0.90 t ha^{-1}) (Fig. 3A; Table 2). At each site, cropping year significantly affected root biomass while the increase in root biomass in mulched compared with non-mulched treatments changed with cropping years (Fig. 3A; Table 2). At Ningxian, plastic mulch increased root biomass by 29–30% in 2009 and 2011 and increased it by 39% in 2010, relative to no mulch (Fig. 3A; Table 2). At Chongxin, plastic mulch increased root biomass by 6% in 2009, 39% in 2010, 25% in 2011 and 16% in 2012 compared to no mulch (Fig. 3A; Table 2). At Tongwei, plastic mulch did not affect root biomass in 2009; however, it increased root biomass by 35–40% in 2010, 2011, 2013 and 2014 and by 15% in 2012, compared to no mulch (Fig. 3A; Table 2). At Huining, plastic mulch increased root biomass by 35–54% in 2009, 2013 and 2014, by 15–21% in 2010 and 2012 and by 86% in 2011, compared to no mulch (Fig. 3A; Table 2). At Yuzhong, plastic mulch increased root biomass by 43% in both 2009 and 2010, 81% in 2011 and 20–30% in 2012–2014 cropping years, compared to no mulch (Fig. 3A; Table 2). Averaging mulch treatments and cropping years, straw incorporation increased root biomass by 7–13% across all the 5 sites, compared with no straw incorporation (Fig. 3A; Table 2). The root biomass was significantly correlated ($P < 0.01$) with the aboveground biomass over cropping years at each site except Chongxin, such that the root biomass reflected the variation in aboveground biomass among treatments and cropping years at each site (Fig. 3B). The root biomass in the upper 0.2 m of the soil varied on average across treatments and seasons from 5.4% of the aboveground biomass at Tongwei to 7.0% at Yuzhong (Fig. 3B).

4. Discussion

The continuous use of plastic-film mulch for up to six years significantly increased the productivity of maize (Wang et al., 2016), but the total SOC remained remarkably constant at all sites, despite a small (4–5%) decrease in the light-fraction SOC concentration relative to no plastic mulch. The observed warming of the soil, principally shortly after sowing in the spring, and the increased soil water content under the plastic-film mulch (Wang et al., 2016) increased the mineralization of SOC, but this was counterbalanced by an increase in the C input from roots due to the improved crop growth in the plastic-mulched treatments relative to the non-mulched treatments. Straw incorporation, as expected, significantly increased the light-fraction SOC across sites and seasons, but had only a small effect on the total SOC.

The improved soil hydrothermal conditions in the plastic-film mulched plots (Wang et al., 2016) facilitated both the aboveground and belowground growth of maize. It has been shown that increases in soil temperature and moisture positively affect root biomasses of maize (Barber et al., 1988) and other plants (Flanagan et al., 2013; Yin et al., 2013), but the present study showed that the aboveground biomass contributed above 90% of the total biomass at maturity as root biomass in the top 0.2 m of the soil profile was only 5–7% of the aboveground biomass. The small proportion of total biomass in the roots may be a result of limiting the sampling to the upper 0.2 m of the soil profile while roots may have grown to greater depths, and by using measurements at final harvest. The root biomass of maize is greatest at flowering and silking (Amos and Walters, 2006). Thus, root biomass was probably underestimated in all treatments in this study. In addition, as maize develops faster and matures earlier under plastic-film mulch relative to no mulch (Gan et al., 2013; Liu et al., 2014a; Wang et al., 2014), more fine roots would have decayed before harvest under the mulch. Nevertheless, the root biomass averaged over years and straw incorporated plots varied in the non-mulched plots from 0.75 to 0.90 t ha^{-1} and increased to 0.93–1.24 t ha^{-1} in the mulched plots, an increase of 23–38% from the use of plastic-film mulch. The higher root biomass in the plastic-film mulched treatments may also suggest that rhizodeposits potentially increased in rhizosphere (Kuzyakov and Domanski, 2000; Yin et al., 2013), compared with non-mulched treatments. As maize rhizodeposits in one growing season are assumed equivalent to root biomass (Bolinder et al., 1999; Flessa et al., 2000), assuming a C to dry weight ratio of 0.475 (Mangnussen and Reed, 2004), annually the mulched plots added 0.44–0.59 t C ha^{-1} while the non-mulched plots added 0.36–0.43 t C ha^{-1} in root biomass or rhizodeposits to the SOC stocks. Using ^{13}C pulse-labeling, An et al. (2015) showed that C flux from photosynthesis in maize plants to soil (including root biomass C and rhizodeposition) under plastic-film mulch increased during seedling growth compared with that under no mulch.

However, as the SOC stocks in the 0–0.15 m depth did not vary significantly between the mulched and non-mulched plots at Tongwei (15.2 t C ha^{-1}), Huining (15.8 t C ha^{-1}), and Yuzhong (20.2 t C ha^{-1}); this suggests that the increased net root-derived below-ground C production in mulched compared with non-mulched treatments was equivalent to the increased SOC

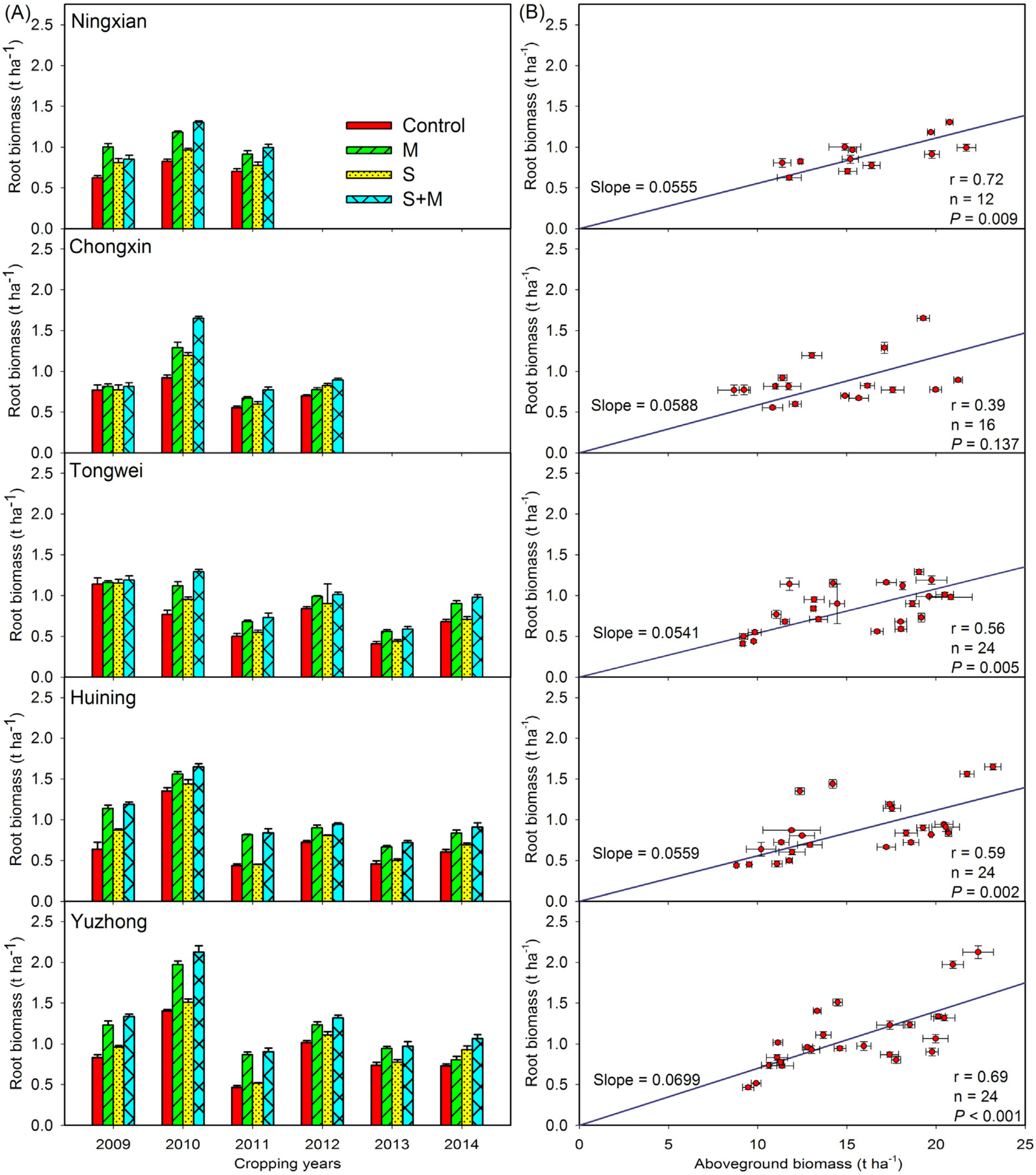

Fig. 3. Maize root biomass in the upper 0.2 m of the soil profile and its correlation with aboveground biomass from 2009 to 2011 at Ningxian, 2009–2012 at Chongxin, and 2009–2014 at Tongwei, Huining, and Yuzhong. Column (A): root biomass with (i) no straw incorporation plus no plastic-film mulch (control), (ii) plastic-film mulch (M), (iii) straw incorporation (S), and (iv) straw incorporation plus plastic-film mulch (S + M). Bars are + 1 standard error of the mean ($n = 3$). Column (B): Correlations of root biomass with maize aboveground biomass over cropping years (2-tailed). Bars are ± 1 standard error of the mean for both maize root and aboveground biomass ($n = 3$). Regression lines were all forced to pass through origin; data of aboveground biomass were derived from Wang et al. (2016).

mineralization and C loss to the atmosphere in mulched relative to non-mulched treatments. Indeed, the increased decomposition of maize straw buried in plastic-film mulched soils relative to non-mulched soils showed that plastic-film mulch increased SOC mineralization and C losses to the atmosphere compared with no plastic-film mulch. Clearly, this is caused mainly by the increased soil temperature and moisture. Plastic-film mulch has reportedly been shown to substantially increase soil N mineralization (Zhang et al., 2012; Hai et al., 2015), such that soil N availability is increased compared to that under no mulch (Wang et al., 2005, 2014, 2015; Gao et al., 2009). Nutrient mineralization is generally considered to be coupled to SOC mineralization (Jonasson et al., 1999; Manzoni et al., 2010). The increased SOC mineralization under plastic-film mulch can be attributed to stimulated soil microbial biomass and enzymatic activity as a result of improved soil hydrothermal conditions (Li et al., 2004; Liu et al., 2014a; Wang et al., 2014; Hai et al., 2015). The increased SOC mineralization in a warm soil can also result from a shift in composition of the microbial population (Richards et al., 1985; Carreiro and Koske, 1992; Zogg et al., 1997; Rinnan et al., 2007).

Changes in composition of the soil non-cellulosic sugars in mulched treatments indicate an intensification of microbial action on the SOC pool compared with no plastic-film mulch. Plant tissues contain large proportions of pentose sugars (mainly xylose and arabinose), whereas the soil microbial organisms, predominantly synthesize galactose, glucose, mannose and desoxy-hexoses, but little if any, arabinose and xylose (Oades, 1984). Thus the compositions of non-cellulosic sugar pools (i.e., mass ratios of GM/AX and RF/AX) can be used as biomarkers to indicate the contribution of microbial assimilates to SOC pool (Murayama, 1984; Oades, 1984; Schmidt et al., 2015). That the concentration of total non-cellulosic sugars in the total SOC between plastic mulched and non-mulched soils was similar suggests that a potentially-stimulated mineralization of soil non-cellulosic sugars in the mulched treatments was offset by the increased input derived from the plant tissues compared with non-mulched treatments. The increased non-cellulosic sugar concentration in the soils with straw incorporated relative to non-incorporated was expected because hemicelluloses in plants contain large proportions of xylose, arabinose and glucose (Kögel-Knabner, 2002). The greater mass ratio of GM/AX and RF/AX in soils under plastic-film mulch suggests a greater contribution of microbially-derived monosaccharides to the total non-cellulosic sugar pool and thus a more pronounced contribution of microbial re-synthesis to SOC (Murayama, 1984; Oades, 1984; Schmidt et al., 2015) compared with soils under no plastic-film mulch. As discussed above, plastic-film mulch increased soil microbial biomass and activity (Li et al., 2004; Wang et al., 2014; Hai et al., 2015) and thus stimulated the turnover of organic input and microbial growth and necromass accumulation in soil compared with no mulch. Schmidt et al. (2015) showed that non-cellulosic sugar levels correlate positively with microbial biomass. The microbial degradation of plant-derived non-cellulosic carbohydrates is known to take priority over that of microbially-derived ones (Spielvogel et al., 2007). The decreased mass ratio of GM/AX in soils with straw incorporation suggests a dilution of microbially-synthesized galactose and mannose monomers with plant-derived arabinose and xylose compared with soils without straw incorporation. In the absence of plastic-film mulch, the increased mass ratio of FR/AX in straw-incorporated relative to non-straw-incorporated soils indicates that the addition of straw also increased microbial synthesis of rhamnose and fucose relative to no straw addition. However, in the presence of plastic-film mulch, the similar mass ratio of FR/AX in straw-incorporated and non-straw-incorporated soils indicates that the increased microbial synthesis was offset by potentially stimulated microbial mineralization of rhamnose and fucose in straw-incorporated soils.

Plastic-film mulch did not affect total SOC concentration and stock; however, the light SOC concentration did decrease by 4–5% in the mulched compared with the non-mulched plots. We suggest that the marginal reduction in the light-fraction SOC concentration in plastic-mulched treatments further confirmed the stimulated mineralization compared with that in non-mulched treatments. This is because the decreasing magnitude of the light SOC concentration in mulched relative to non-mulched treatments did not expand with cropping year. By the time the soil was sampled at harvest each year, macro root residues produced during the season had not yet been incorporated into the light SOC pool to compensate for the loss of the stimulated mineralization. The light SOC pool is sensitive to decomposition (Gregorich et al., 1994; Haynes, 2005). In the present study, the increases in the light SOC stock in all the treatments with cropping year indicate that the introduction of high-yielding crops such as maize as a result of simultaneous improvement in hydrothermal soil conditions has helped sequestrate SOC in croplands along with augmenting the biomass production of arable land in cold semiarid regions.

5. Conclusions

Because of warmer and moister conditions in soil under plastic-film mulch, particularly in spring, SOC mineralization in the cold semiarid area of this study increased compared with no plastic-film mulch, as indicated by the increased decomposition of maize straw buried in soil. Meanwhile, the plastic-film mulch also induced an increase in root biomass and hence an increase in SOC input to the soil compared to no mulch. Therefore after six years of continuous growth of maize under plastic-film mulch, the total SOC stocks in the upper 0.15 m of soil were similar in mulched and non-mulched soils. The data show that the SOC mineralization stimulated by the increased soil temperature and moisture in the mulched treatments was balanced by an increase in belowground carbon input to the soil, relative to the non-mulched treatments. The findings suggest that in the hydrothermally-improved soil environment the SOC turnover rate has been accelerated and microbial action on the SOC has been intensified, compared with that in the ambient soil environment. Combining results published previously (Wang et al., 2016), we conclude that plastic-film mulch induces a simultaneous increase in soil temperature and moisture that enhances crop productivity, but importantly maintains the SOC level in the temperature- and rainfall-limited semiarid regions. Thus, the plastic-film mulch technology applied to maize production maintains SOC balance in the medium term. However, longer term effects of plastic-film mulch on SOC dynamics need to be further investigated.

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