Front. Agr. Sci. Eng. 2017, **4**(2): 146–154
DOI: 10.15302/J-FASE-2017136
Available online at http://engineering.cae.cn

RESEARCH ARTICLE

Effects of mulching for water conservation on soil carbon, nitrogen and biological properties

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Abstract The effect of mulching with straw, white plastic film and black plastic film for improving soil water storage and on the soil properties was examined in a wheat-maize rotation system on Loess soil in northwestern China. All the mulches improved the water storage to some extent and led to warmer soils. However, the organic C and total N contents of the soils declined significantly under the mulches, particularly the plastic film mulches, and this could have long-term detrimental effects on soil quality and the sustainability of the some mulching practices.

Keywords biomass, carbon, mulch, nitrogen, plastic films, soil, straw, water storage

1 Introduction

By 2050, global grain demand is projected to double from that at the beginning of the century[1], yet there will be limited or no increase in cropping area or water for irrigation and there may even be reductions in both. The situation is serious in China where only 0.1 hm^2 of cropland is available per person[2]. Growing population and consumption in China drive agricultural innovation to improve food production and sustainable development of agriculture. Meeting the demand for increased grain production requires improved productivity in existing cropping systems[2,3]. *In situ* soil and water management is a feasible way of improving dryland agricultural productivity[4]. An example being cultivation with surface-mulching (i.e., covering the soil surface between the crop plants with a permeable or impermeable material), such as straw[5,6,7,8] or plastic-film[9,10]. Mulching with straw significantly improves water use efficiency by reducing water evaporation from the soil surface, and also affects soil temperatures and crop yields[6,11–13]. Mulching with plastic film also improves water use efficiency but also directly changes soil biological characteristics and fertility because, unlike straw mulching, it is impermeable and does not add any organic matter or nutrients[14,15]. Research aimed understanding the processes that affect crop productivity as a result of mulching is needed, because most of the biogeochemical processes are not yet sufficiently understood and short term benefits should not be traded against longer-term soil degradation[16,17].

In this research, the aim were to (1) investigate the effects of different mulching materials on soil temperature, water content and storage; (2) compare soil fertility parameters especially soil organic carbon and nitrogen under different mulching materials; and (3) suggest optimum mulching approaches for wheat-maize rotational cultivation on Eum-Orthric Anthrosols (Lou soil) in the semi-arid Loess Plateau of China.

Received September 21, 2016; accepted December 6, 2016

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2 Materials and methods

2.1 Experimental site

An experiment was established at the Irrigation Experimental Station of the Key Laboratory of Agricultural Soil and Water Conservation Engineering in Arid Areas (Ministry of Education), at the Northwest A&F University near Yangling in Shaanxi Province in the northwestern China (108°24′ E, 34°20′ N). The site is at 521 m above sea level with the typical Eum-Orthric Anthrosols soils of the Loess Plateau. The site has a semi-arid climate with 12.9°C mean annual temperature. There is 660–680 mm per annum rainfall, most of which falls in the late summer (July to September) with dry conditions during the winter (December and January). The soil at the site has silt loamy texture, soil organic C of 8.26±0.25 $g \cdot kg^{-1}$ soil, total N of 0.95±0.03 $mg \cdot kg^{-1}$ soil and pH 8.02±0.04 in the surface (0–20 cm) horizons. A two phase rotation of winter wheat, sown in October and harvested in May, followed by summer maize, sown in June and harvested in September, is typical for the region (Table 1). Weather data for the site was obtained from a recording station located within 50 m of the experimental plots.

2.2 Experimental design

The design comprised the following treatments:

(1) Control;

(2) Mulching with wheat straw (4 $t \cdot hm^{-2}$) after sowing in both phases of the rotation;

(3) Mulching with white polythene film (0.008 mm thickness) between the rows of plants in both phases of the rotation;

(4) Mulching with black polythene film (0.008 mm thickness) between the rows of plants in both phases of the rotation.

Thus, in the control, rain water infiltrated the soil and could evaporate from the soil surface without a mulch barrier. In the straw mulch treatment, rain water could penetrate the mulch, which also impeded evaporation from the soil surface. By contrast, in the plastic film treatments, rain water ran off the surface of the film and entered the soil along the planted rows at the edges of the film, and evaporation from the soil surface was restricted to a narrow region along the rows. Between each phase of the rotation, the straw mulch and polythene covers were removed at harvest time and the soil was cultivated at the start of each phase of the rotation. The timing of the phases of the rotation used for this experiment and the soil sampling dates are shown in Table 1. The four treatments (control, straw mulch, white film and black film) were established on plots 5 by 2 m replicated three times and laid out in a randomized block design. The sowing density was 30 cm row spacing for the wheat, and 30 cm plant space and 60 cm row spacing for the maize. For winter wheat, fertilizer N and P at 120 kg N per hectare and 100 kg P_2O_5 per hectare as urea and single superphosphate were applied at sowing and 30 kg N per hectare applied by top dressing soon after emergence. For summer maize, fertilizer N and P were applied at 225 kg N per hectare and 90 kg P_2O_5 per hectare. Soil temperatures were measured continuously at 1 h intervals in one plot per treatment with 5TE probes and data loggers (Degacon Em50, Degacon Devices, Pullman, WA, USA) installed at a depth of 30 cm[18].

2.3 Soil sampling and analyses

In the first week of October 2014, immediately after the summer maize had been harvested, soil samples were collected. A soil sampling pit 2 m deep was excavated in each plot and volume-specific soil samples were collect from each at 20-cm increments down to 200 cm. A subsample of soil from each depth was dried at 105°C in a fan-assisted oven for 24 h and the water content estimated gravimetrically. The soil bulk density was determined from the mass of dry soil per unit volume, which was then used for estimates of area-based or volumetric soil water content.

The soil organic C and total N contents were determined on air-dried and ground subsamples of soil from the 0–20 cm depth using the potassium dichromate volumetric[19] and Kjeldahl[20] methods. The soil NO_3^--N was extracted from the soil by shaking samples in 1 $mol \cdot L^{-1}$ KCl (1:5 (w/w) soil:KCl solution) for 1 h and then filtered. The filtrate was analyzed for NO_3^--N with a Chemlab Auto-Analyzer[21].

Microbial biomass C and N contents was determined by the chloroform-fumigation extraction method[22]. Fresh soil equivalent to 10 g oven-dried soil was fumigated for 24 h with ethanol-free chloroform and then extracted with 0.5 $mol \cdot L^{-1}$ K_2SO_4. The same amount of soil was extracted without fumigation. The dissolved organic contents of the soil extracts were measured using TOC-V_{CPH} (Shimadzu, Japan), and the total N contents of the extracts were analyzed using peroxide potassium sulfate-ultraviolet spectrophotometry[23].

2.4 Statistical analyses

All the results were shown as means of three replicates with standard error. The data were subjected to an ANOVA and Duncan's multiple range tests for evaluation of the mulching effects. Significant differences were reported at $P < 0.05$ level. All of these data were analyzed with SPSS 16.0 (IBM Analytics, Armonk, NY, USA).

Table 1 Dates of rotations and soil sampling

Rotation phase	Crop	Start date (DD-MM-YY)	End date (DD-MM-YY)	Soil sampling period (DD-MM-YY)
1	Winter wheat	01-10-13	31-05-14	
2	Summer maize	01-06-14	30-09-14	01-10-14 to 07-10-14

3 Results

3.1 Soil temperature

In the control treatment, the mean annual soil temperature was 15.8°C, which was higher than the annual air temperature, and over the year the soil ranged from 2.0 to 33.4°C (Table 2). The mulching treatments had no effect on the mean annual soil temperature, but did affect the minimums and maximums. The straw mulch reduced the temperature by slightly decreasing the maximum soil temperature and slightly increasing the minimum soil temperature compared to the control. Both the white and black film treatments led to increases in the maximum soil temperatures and either no or only minor effects on the minimum soil temperature compared to the control. Over the year, the total thermal time values ranged between 5017 and 5429 °C·d for the different treatments and the variation between treatments was no more than 8%. The straw mulch led to a lower thermal time value than the control and the white film had a higher thermal time than the control, while the black film was only slightly lower than the control. Although the overall effects of the mulching treatments on temperature were relatively small, the mulching treatments affected the rates at which the soil temperature changed (Fig. 1). The straw mulch treatment warmed and cooled at similar rates to the control, while the white and black film treatments warmed and cooled more rapidly than the control (Table 3).

3.2 Rainfall

The rainfall during the experiment (October 2013 to September 2014) was 686 mm, of which 288 mm fell during the 8-month winter wheat phase and 397 fell during the 4-month summer maize phase (Table 4). There was no rainfall during the two mid-winter months of December and January.

Table 2 Temperature conditions in soil for the control and mulching treatments

Phase in rotation	Control	Straw	White film	Black film
Mean annual temperature/°C	15.8	15.9	16.2	15.7
Annual maximum/°C	33.4	32.0	38.5	36.0
Annual minimum/°C	2.0	2.8	2.0	1.7
Thermal time/(°C·d)	5314	5017	5429	5257

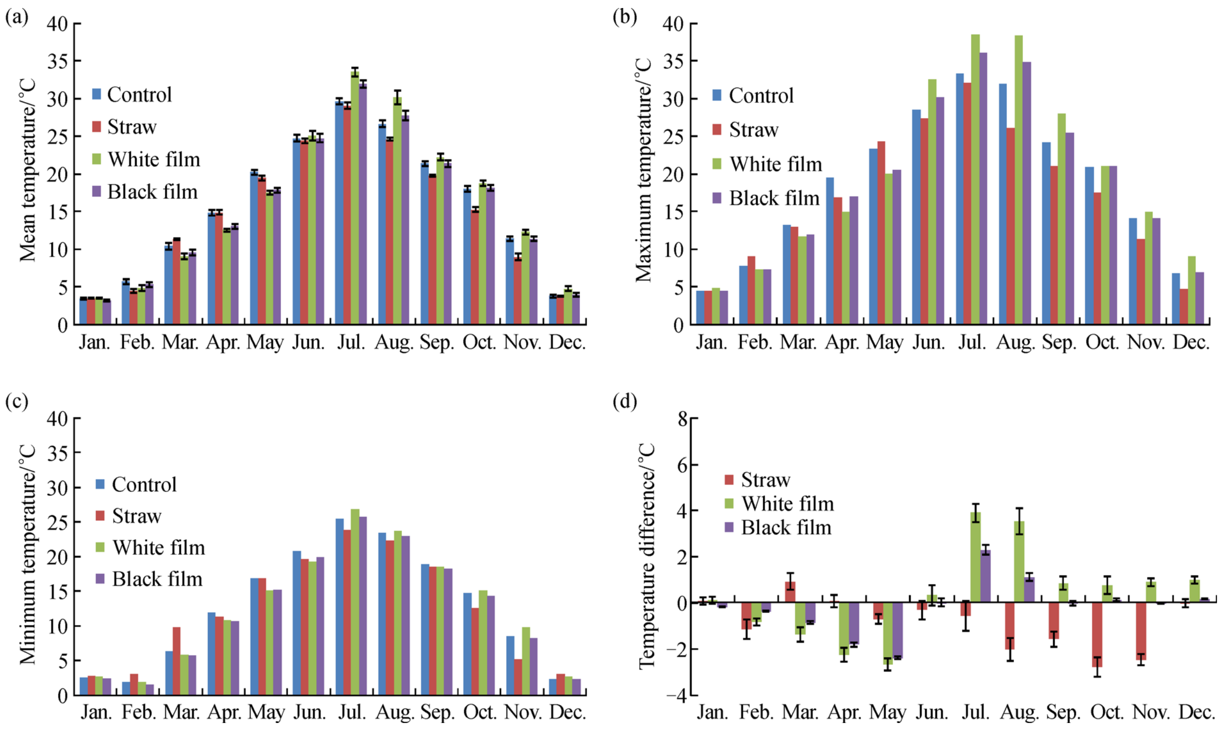

Fig. 1 Summary of soil temperatures during the experiment for the control and the different mulching treatments. (a) Mean temperature; (b) maximum temperature; (c) minimum temperature; (d) temperature difference relative to control.

Table 3 Rates of change of soil temperatures for the control and mulching treatments

Item	Increase rate during January to July/(°C·d^{-1})				R^2				n
	Control	Straw	White film	Black film	Control	Straw	White film	Black film	
Monthly mean	0.163	0.161	0.187	0.176	0.99	0.99	0.95	0.97	7
Monthly maximum	0.177	0.168	0.217	0.195	1.00	0.99	0.94	0.97	7
Monthly minimum	0.154	0.135	0.156	0.154	0.97	0.98	0.95	0.96	7
Item	Decrease rate during July to December /(°C·d^{-1})				R^2				n
	Control	Straw	White film	Black film	Control	Straw	White film	Black film	
Monthly mean	– 0.187	– 0.183	– 0.208	– 0.199	0.98	1.00	0.99	0.99	6
Monthly maximum	– 0.199	– 0.190	– 0.236	– 0.221	0.97	0.99	0.97	0.98	6
Monthly minimum	– 0.173	– 0.170	– 0.172	– 0.171	0.98	0.96	0.98	0.99	6

Table 4 Distribution of rainfall during the experiment

Phase	Date (DD-MM)	Rainfall/mm	Rain days
Winter wheat	13-10	35.7	4
	13-11	16.0	6
	13-12	0.0	0
	14-01	0.0	0
	14-02	28.0	16
	14-03	28.7	6
	14-04	142.0	13
	14-05	38.4	6
	Sub total	288.8	51
Summer maize	14-06	51.3	11
	14-07	22.9	4
	14-08	108.6	11
	14-09	215.1	16
	Sub total	397.9	42
	Total at soil sampling	686.7	93

3.3 Soil water storage

At the end of the experiment, the pattern of soil water distribution in the soil increased with depth (Fig. 2). The effect of all the mulching treatments was to increase the soil water storage significantly compared to the control, with the white and black film treatments having a significantly greater effect than the straw mulch (Fig. 2a). The soil volumetric water content ranged between 0.15 and 0.24 g·cm^{-3}, and was greatest toward the top and the base of the profile, and least in middle of the profile (Fig. 2b).

3.4 Soil organic carbon and total nitrogen contents

The three mulching treatments significantly reduced soil organic C relative to the control (Fig. 3). The reduction of organic C ranged between 2.1 and 2.8 g·kg^{-1} soil or between 20% and 26% of the control value, but there were no significant differences between the mulching treatments (Fig. 3). The effects of the mulching treatment on soil total N were also significant reductions, but the differences were smaller than those observed for soil organic C (Fig. 3). The differences of total N ranged from 55 to 110 mg·kg^{-1}, and the negative effect of the white and black film mulches on soil N was significantly greater than for the straw mulch (Fig. 3).

3.5 Soil microbial biomass carbon and nitrogen contents

The three mulching treatments significantly reduced microbial biomass relative to the control (Fig. 4). The reduction of biomass C ranged between 95 and 230 mg·kg^{-1} soil and that of biomass N ranged between 15 and 22 mg·kg^{-1} soil. For biomass C, the differences were smallest for the straw mulch and greater for the white and the black films, with the effect of the black film being

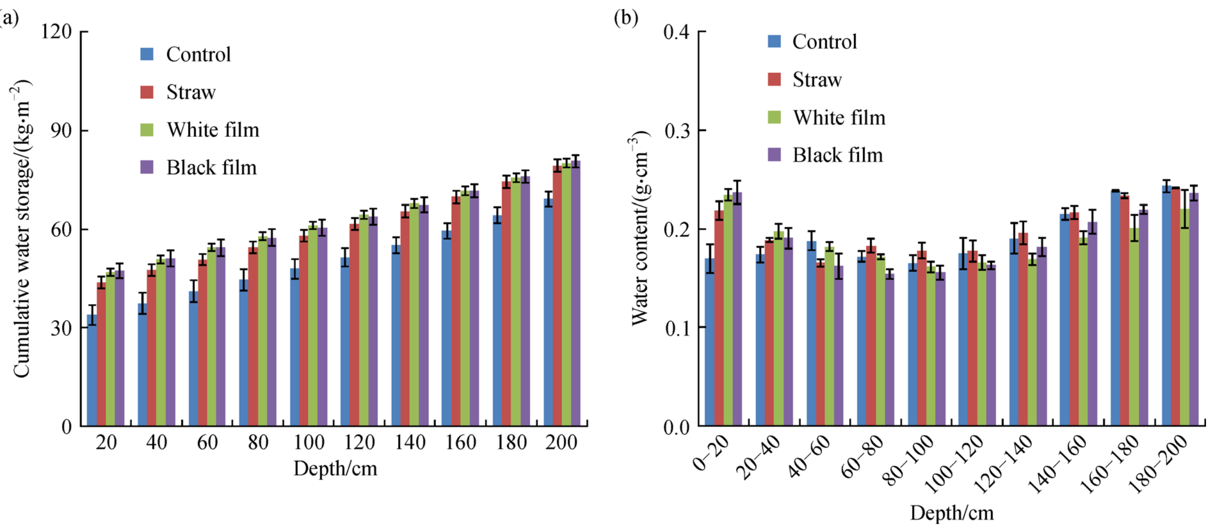

Fig. 2 Distribution of water with depth for the control and mulching treatments at the end of the experiment. (a) Cumulative water storage to 2 m depth; (b) soil volumetric water content.

significantly more than for the white film (Fig. 4a). The effects of the mulching treatments on biomass N were similar to biomass C except that there was no significant difference between the straw mulch and the white film treatment (Fig. 4b).

3.6 Soil nitrate content and distribution with depth

Nitrate content in the control increased with depth to 80–100 cm and declined with increasing depth below100 cm (Fig. 5). In all mulch treatments, the maximum NO_3^--N contents also occurred at 80–100 cm, but the NO_3^--N contents at 0–20 cm were greater than the control in all cases (Fig. 5). The total NO_3^--N in the profile ranged from 18 to 21 $g \cdot m^{-2}$, but did not differ significantly between any of the treatments.

4 Discussion

The three mulches in this experiment had different effects on soil temperature. Several investigators have reported that the soil thermal regime under straw mulching was different from that of bare soil, with soil temperatures often being lower under mulched surfaces than in non-mulched soils[24,25]. This was because straw covering of the soil surface has a higher albedo and lower thermal conductivity than bare soil, which reduces the solar energy reaching the soil thereby reducing the magnitude of temperature increases in the summer[26]. By contrast, the slightly higher minimum temperature under the straw mulch is likely to be due to the thermal insulation effect of the straw during the winter. Soil temperature under the film mulches on the other hand were higher than the control from July to December and the black film was not as effective in raising soil temperatures (Fig. 1), which may have been due to the lower light transmission of black film[27]. Subrahmaniyan and Zhou[28] also found that soil temperature were highest under transparent film mulch, followed by degradable film and then black polyethylene film mulches.

Mulching increased the soil water content presumably as a result of reduced evaporation[29]. Furthermore, the

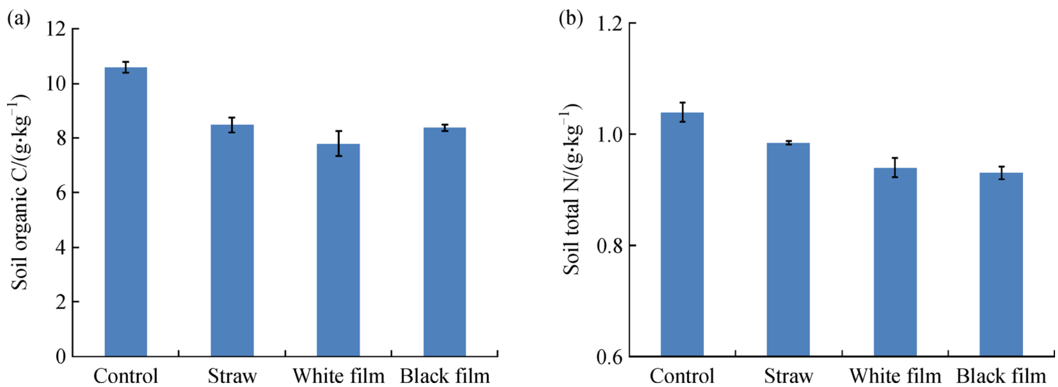

Fig. 3 Soil organic C (a) and total N (b) contents for the control and mulching treatments at the end of the experiment

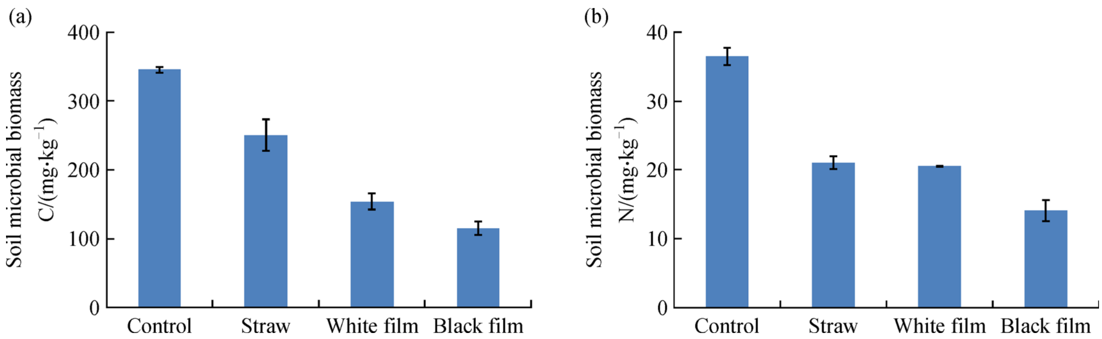

Fig. 4 Soil microbial biomass C (a) and N (b) for the control and mulching treatments at the end of the experiment

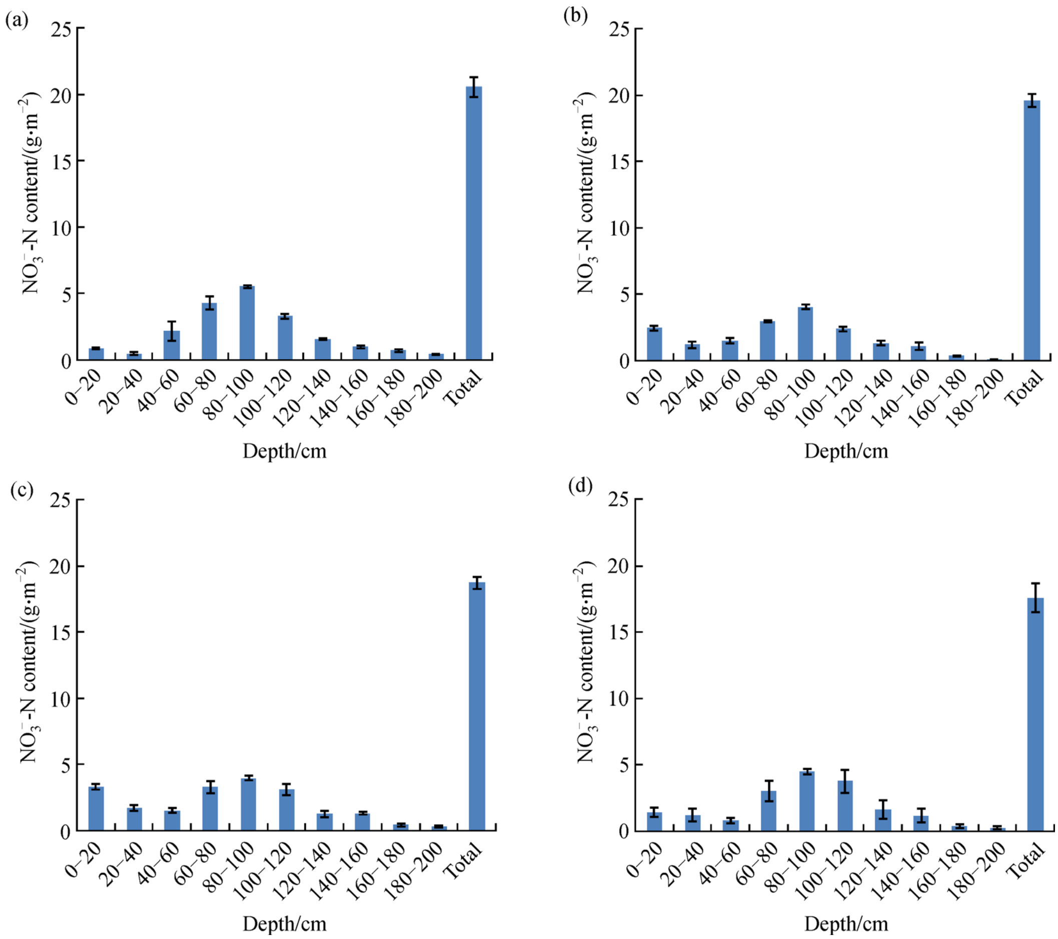

Fig. 5 Distribution and total content of NO_3^--N in the soil for the control and the mulching treatments at the end of the experiment. (a) Control; (b) straw; (c) white film; (d) black film.

collection and infiltration pathway, particularly for the plastic film treatments, was likely to have led to more efficient delivery of rainwater to the roots. Our observation of greater water content under the mulches is consistent with the observations of Cheng et al.[29] and Jiang et al.[30]. The elevated NO_3^--N concentrations near the soil surface are likely to be the result of reduced water infiltration and flow beneath the mulches, therefore reduced leaching.

Given the central role of soil organic C in several soil biological, chemical and physical processes that affect soil fertility and the maintenance of soil fertility, a change in soil organic C is a key parameter in judging the sustainability of mulching treatments[31,32]. However, the data in this experiment are from a one-year investigation and this is a very limited time period for organic matter changes[33,34], so large changes are not expected. Soil organic carbon in the three mulching treatments were significantly lower than that of the control, which is contrary to the observations of Guan et al.[35] and Liang et al.[36]. Their results showed that the soil organic matter under straw mulch was higher than that of the control, mainly because the soil organic C was enhanced by the decay of mulched straw. In our study, however, the soil sample was taken from beneath the mulch a year after it had been applied. Over this period, some of the soil organic matter would have decomposed in the moister and less extreme winter temperature created by the straw mulch compared to the control[37,38]. Whatever the mechanism, it is obvious that insufficient organic C from the straw had mixed into the underlying soil to have a detectable effect on soil organic C, which could have been due to reduced water flow under the straw mulch. Our findings for the soil organic C contents beneath the plastic film mulches are, however, consistent with the findings of Guan et al.[35] and Liang et al.[36], who showed that the soil organic C declined significantly under white or black plastic film compared with the control. Reduced organic C input at the soil surface in the plastic mulches is almost certainly a key determinant of the lower soil C contents. Furthermore, Guo et al.[27] showed a greater decline in soil organic C under the white film compared to the black film because of a more favorable temperature regime for decomposition, which is consistent with our observation of a lower soil organic C beneath the white film compared to the black film. Many of the same observations and discussion points mentioned for soil organic C apply equally to soil total N.

Although the soil microbial biomass is only a small fraction of the soil organic C or N pools, it is a key indicator of soil biological activity and fertility status[39]. In this study, the soil microbial biomass content under the mulches were all significantly lower than for the control, which is consistent with the observations of Zhang et al.[40] and also consistent with increased biological activity leading to organic matter decomposition under mulches because of the more favorable environment for decomposition[27,41]. Dong et al.[42] have reported greater soil microbial biomass beneath straw mulches, which we did not observe, but this is likely to be due to limited organic C mixing with the soil at the depth of our sample, as previously mentioned.

5 Conclusions

In this study we have shown that the mulches all had the expected effects on water storage and temperature in the soil. However, the benefits of mulching need to be evaluated not just in relation to these properties, because our data also indicate depletion in the soil organic C, total N and microbial biomass particularly under the plastic mulches. These are key soil parameters, which are drivers of soil fertility and its long-term maintenance. If the short-term benefits of mulching on water retention and storage are offset by deterioration of properties such as organic matter turnover, nutrient release during mineralization, stabilization of soil structure by organic matter and microbial growth, and water absorption by soil organic matter, it is possible that the benefits of mulching, particularly with plastic films, can be short lived and in the longer term there may be a detrimental effect on soil properties and the ability of the soil to sustain crop growth.

Acknowledgements This study was financially supported by the National High-tech R&D Program of China (2013AA102904, 2011AA100503), the Sci-tech Coordination and Innovation Project of Shaanxi Province (2016KTZDNY03-06), and Chinese "111" Project (B12007). The manuscript was completed while Dr. Benhua Sun was an academic visitor supported by the Chinese Scholarship Council at Royal Agricultural University, UK.

Compliance with ethics guidelines Xiaomin Pi, Tongxun Zhang, Benhua Sun, Quanhong Cui, Yun Guo, Mingxia Gao, Hao Feng, and David W. Hopkins declare that they have no conflict of interest or financial conflicts to disclose.

This article does not contain any studies with human or animal subjects performed by any of the authors.

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