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Evaluating the effects of plastic film mulching patterns on cultivation of winter wheat in a dryland cropping system on the Loess Plateau, China

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ABSTRACT

Plastic film mulching (PFM) can increase or stabilize crop yields worldwide when applied to agricultural planting systems, especially in arid and semi-arid areas. Although the adverse effects that are caused by residual plastic film, such as plastic pollution, are becoming a global concern, the application of PFM will not be replaced by other materials in the short-term in agriculture. It is important to understand the various PFM patterns (different mulching periods and coverage rates) that impact on soil physicochemical properties and characteristics of crop growth. Therefore, based on a field experiment that we established in 2002, we conducted consecutive field observations from 2013 to 2016 to determine the optimum PFM mulching period and coverage rate. Three mulching periods were included: (I) summer fallow period (FM), (II) growth period (GM), and (III) whole growth year (WM). Two coverage rates were included: (i) 50%, half mulching (HM), and (ii) 100%, total mulching (TM). That is, there were six different PFM treatments. No mulching (NM) over the growth years was considered the CK treatment. PFM increased canopy height and leaf area index of winter wheat (*Triticum aestivum* L.) in the growing season by 29.5% and 19.4%, respectively. Average winter wheat grain yields of various PFM patterns were 5318.5 kg ha^{-1} and 4557.7 kg ha^{-1} in 2013–2014 and 2015–2016, respectively; these yields were 13.8% and 23.7% higher than NM in 2013–2014 and 2015–2016, respectively. However, the difference in the growth characteristics and grain yield of winter wheat under various PFM patterns resulted from the change in the mulching period and coverage rate. Winter wheat grain yield and biomass increased with GM and WM compared with FM and NM in normal rainfall years. PFM coverage rates improved yield significantly ($P < 0.05$) and influenced soil nutrient concentrations. HM maintained or increased soil organic matter (SOM) and total nitrogen concentrations, but TM decreased SOM concentration by 8.3%. Water use efficiency (WUE) and rainfall use efficiency (RUE) were improved by various PFM patterns. Furthermore, WM had the most significant impact on SOM concentrations, GM was second, and FM was minor. Considering the costs and benefits of PFM patterns, the half coverage rate of PFM during the whole year (FWH) had the best index (BI) value, and the total coverage rate of PFM during the growth period (FGT) and the half coverage rate of PFM during the growth period (FGH) had higher BI values than other PFM patterns; the values for BI for FWH, FGT, and FGH were 10.3, 8.9, and 8.5, respectively. In conclusion, ignoring the amount of PFM pollution in the environment (or use biodegradable film instead of polyethylene film), FWH was the best PFM pattern with the highest WUE and RUE in dryland rainfed agriculture. But, to decrease the amount of PFM application and pollution, FGH was more beneficial for soil health with a low coverage rate and short mulching period. FGH was the optimal pattern for PFM when applied to winter wheat on the Loess Plateau, China based on our field experiment.

1. Introduction

Global food demand is growing continuously (Tilman et al., 2011), and the Food and Agriculture Organization (FAO) suggested that crop grain production must increase by more than 1.4 times in 2050 to meet the growing human population and the increased need for animal feed (Bruinsma, 2009). Plastic film mulching (PFM) technology is one of the most effective strategies to increase yield worldwide (Lobell and Field,

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2007; Kasirajan and Ngouajio, 2012a, 2012b; Gan et al., 2013; Zhang et al., 2020). It has been applied widely in agricultural practice, especially in cold, arid and semi-arid regions (Gao et al., 2019; Gan et al., 2013). China is the largest user of PFM technology in the world (Gao et al., 2019; Daryanto et al., 2017), and the application (i.e., amount, cover area, regions, and density of the material used) of PFM technology has increased rapidly in recent decades. The amount of PFM applied to crops has increased dramatically from about 6 Mt to 1470 Mt from 1982 to 2017, which is an increase $>$ 200 times in 35 y (Liu et al., 2014; Gao et al., 2019). Meanwhile, there is a continuous tendency to increase the application of PFM in future agricultural development. Additionally, the crop area covered by PFM has also expanded, and the regions that use PFM have been extended from arid and semi-arid regions in the north to high altitude areas with cold weather in the south of China (Gao et al., 2019; Zhang et al., 2020). The area of PFM increased from about 11.7×10^4 ha to 18.7×10^6 ha from 1982 to 2017. The density of PFM that is utilized increased 3–10 times (i.e., the application rate reached 34.8 kg ha^{-1} in Xingjiang province in the northwest of China in 2011) from 1991 to 2011 (Yan et al., 2014). Covered crops have also been expanded from cash crops to staple foods (Yan et al., 2014; Gao et al., 2019).

Applying PFM technology has produced substantial economic benefits, increased grain yield, and eased the pressure on global food supply. Numerous studies have shown that PFM increased crop yield by 20–50% (Liu et al., 2014; Gan et al., 2013; Gao et al., 2019; Zhang et al., 2020). Using a global meta-analysis, Zhang et al. (2020) found that PFM benefited yield for both cash and cereal crops by increasing immediate season yield an average of 25%−42% compared with no mulching. Gao et al. (2019) also reported that average grain yield of the four major crops (i.e., *Zea mays* L., *Triticum aestivum* L., *Anemone vitifolia Buch* L., and *Solanum tuberosum* L.) increased by 24.3% when PFM technology was applied in most cases ($n = 1839$), but a few cases ($n = 221$) showed a significant reduction of 16.1% in average grain yield. Thus, PFM plays a vital role in ensuring food security in China and in the global food supply.

Improvements in grain yield from PFM technology varied with different regions (Gao et al., 2019; Zhang et al., 2018, 2020). PFM increased yields by 32.6%, 29.6%, 23.1%, 20.6%, 17.0%, and 4.7% in Central, Northwest, Eastern, North, Northeast, and Southwest China, respectively (Gao et al., 2019). Moreover, the distribution of rainfall significantly changed the yield-increasing effect of PFM technology in dryland agriculture. PFM systems typically have increased yields of 50–100%, 30–90%, and 10–40% in a dry year, normal rainfall year, and wet rainfall year, respectively, compared with the same crops grown under control (Zhang et al., 2013).

Various PFM materials (i.e., polyethylene plastic film, biodegradable film, and liquid film) and patterns (i.e., different mulching periods and coverage rates) have been applied in agricultural practices (Gan et al., 2013; Kasirajan and Ngouajio, 2012a, 2012b). Some studies have shown that bio-degradable film and liquid film have a smaller negative impact on the soil environment. However, there are no large-scale applications because it is expensive and had less effect on increasing yields. The mulching period and coverage rate by PFM are usually the major factors that affect regional grain yields. Because a large proportion of PFM is used during the growing season for crops, mulching during the fallow period has been ignored (He et al., 2016b).

The summer fallow period is a vital period for recharging soil water that was consumed by the winter wheat during the last growing season in arid and semi-arid agricultural regions (He et al., 2016a; Zhang et al., 2020). There is an emerging consensus that there is a significant correlation between soil water storage in the profile (0–300 cm) before sowing and winter wheat grain yield (He et al., 2016b). Full surface coverage (i.e., coverage rate of 100%) with no soil surface exposure is beneficial to crop growth and yield in the short-term. This PFM pattern reduces inefficient soil evaporation (E), provides better root growth and beneficial microbial survival (Li et al., 2004), and promotes the uptake of water and nutrients. However, continuous use of PFM in the long-term may increase consumption of water and nutrients by crops and result in more residual plastic fragments (Zhang et al., 2020). Continuous use PFM may lead to excessive water consumption in the soil profile that forms a dry layer, which affects sustainable development in agricultural areas where irrigation is limited.

Partial surface coverage (i.e., coverage rate between 0% and 100%) is used to enlarge the proportion of the bare area where planting occurs. The same planting density in agricultural regions is maintained with reasonably high planting density in the covered area to ensure food supply, increase rainfall infiltration, reduce water and nutrient consumption, and reduce the application and residue of PFM. The agricultural 'white revolution' of PFM technology may also bring 'white pollution' (Liu et al., 2014). Between 1950 and 2015, about 4900 Mt of mostly non-biodegradable plastic waste was produced, which is 60% of all plastic ever produced; with the application of PFM technology, a considerable part of that plastic film residue was brought into farmland ecosystems (Geyer et al., 2017). Because of nearly 30 y of application of PFM technology and lack of awareness of plastic residue in China, plastic residues in soil have reached 71.9–259.1 kg ha^{-1} in the Northwest farmland of the Loess Plateau and the wind-sand area of the Northeast (Yan et al., 2014; Zhang et al., 2020).

Residual plastic pollution (i.e., micro-plastics or nano-plastics) in soils are global health concerns, given its prevalence in terrestrial ecosystems (Zhang et al., 2020). In particular, submicrometre plastics were taken up by crops through a crack-entry mode, and this seriously threatened human health and the ecological environment once micro-plastics or nano-plastics entered the food chain (Rillig and Lehmann, 2020; Li et al., 2020). Because global climate change increases stress on water resources, the existence of limited arable land area, increasing food demand by humans, and increasing drought potential in semi-arid and arid regions, PFM use will increase continuously (Zhang et al., 2020). Although there have been several recent studies that searched for plastic film substitutes, which included a technique that used biodegradable plastic film and straw cover (Zhao et al., 2019), there was no significant increase in grain yield (Ren et al., 2017). Therefore, polyethylene plastic film will continue to be used in agricultural production, so it is urgent to decrease the application of plastic film and plastic residuals in agriculture.

Winter wheat (*Triticum aestivum* L.) is one of the fundamental cereals and is ranked only after corn (*Zea mays* L.) and rice (*Oryza sativa* L.) in terms of amount of acreage planted. It has deep roots and is relatively drought-tolerant (Jin et al., 2007; He et al., 2016b; Xue et al., 2019), and $>$ 75% is grown in semi-arid and arid agricultural regions (Li, 2004; He et al., 2016a). It covers an area of 4.3 million ha in northwest China, which accounts for 56% of the total agricultural cultivatable area in China (He et al., 2016a; Xue et al., 2019; Li et al., 2014), and it is a major source of grain and livestock feed on the Loess Plateau (Liu et al., 2014).

The Loess Plateau is a typical arid and semi-arid rainfed agricultural region that is a crucial area of food production in northwestern China (Li, 2004; He et al., 2016b; Ma et al., 2018). Water resources are also stressed more seriously because global climate change has significant impacts on dryland cropping systems (Chmielewski et al., 2004). Surface water resources are unavailable for irrigation, and the groundwater is too deep and sparse (usually below 80 m) to use for crops in this region (Zhang et al., 2013; Qiao et al., 2018). Rainfall is the only source of soil water supply in rain-fed agricultural areas. Moreover, low rainfall with uneven seasonal distribution and high soil evaporation (E) are typical characteristics of arid and semi-arid areas (Gan et al., 2013), which seriously affect the stability and the yield of crops (Zhang et al., 2016; Gan et al., 2013). Previous numerous studies have shown that about one-third of the annual rainfall occurred during the growing season for winter wheat (from October to next June), and $>$ 60% annual rainfall occurred during the summer fallow period (from July to September) (Zhang et al., 2013; He et al., 2016b). That is, there is an asynchrony between the winter wheat growing season and rainfall distribution, which greatly affects the growth of crops, water supply, and the

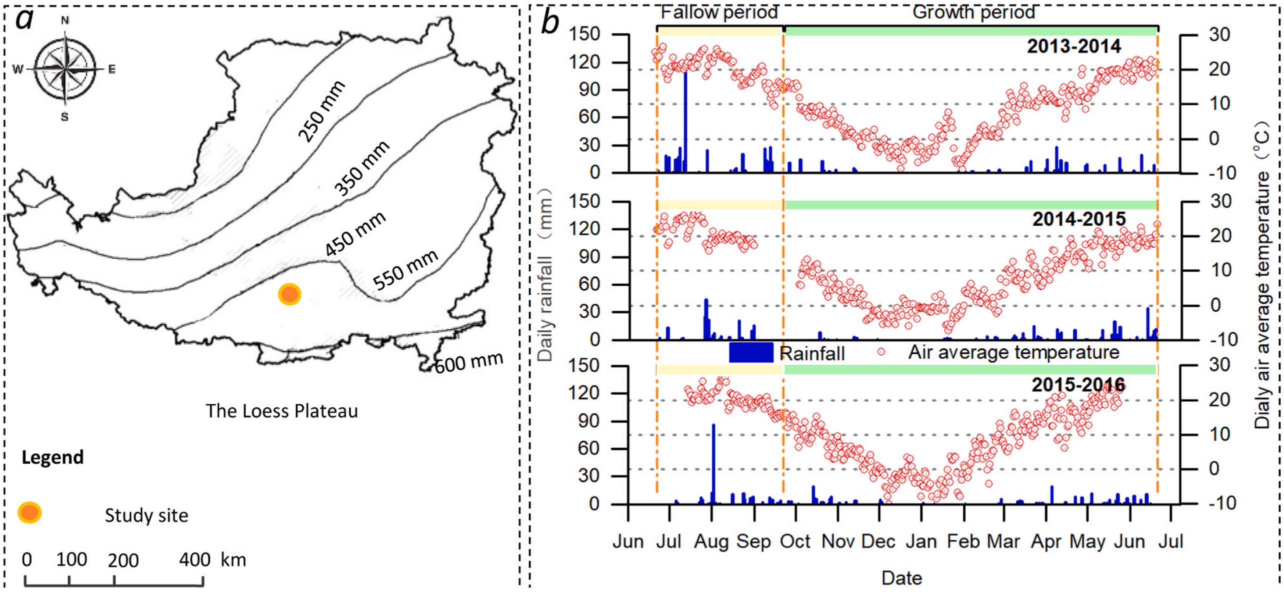

Fig. 1. (a) The location of the study site on the Loess Plateau, China and (b) the daily rainfall and mean air temperature from 2013 to 2016. Note: the summer fallow period of winter wheat is from late June to late September, and the growth period is from late September to late June the following year.

formation of grain yield (He et al., 2016b).

Hence, the objective of the research was to optimize the PFM mulching period and coverage rate, to increase regional water use efficiency and food production, to reduce the application of plastic film, and to reduce the negative effects of PFM on farmland ecosystems. The research aimed (i) to compare and to evaluate the impact of various patterns of PFM on soil attributes and plant growth, and (ii) to screen suitable patterns (i.e., mulching period and coverage rate) for rain-fed agricultural production and for environmental sustainability.

Based on previous research, we proposed two hypotheses. The first hypothesis (H1) is that half mulching (HM, the coverage rate is 50%) and total mulching (TM, the coverage rate is 100%) PFM applications have significantly different effects on soil water content and nutrient conditions, but not in grain yields. It could be that because the former has a larger exposed area than the latter, HM operates just like rain micro-collection measures to promote water infiltration or evaporation. Secondly, we hypothesized (H2) that continuous PFM applications increased grain yield and WUE, and the WM (i.e., mulching in the whole growth year) group was better than GM (i.e., mulching in the growth period) and FM (i.e., mulching in the summer fallow period) groups. The mulching period for PFM will result in better hydrothermal conditions in the soil, increased rate of winter wheat emergence and plant growth, and higher grain yields. However, PFM may decrease soil evaporation, which helps to regulate evapotranspiration (ET).

2. Materials and methods

2.1. Study site

Field experiments started in 2002, and all treatments were conducted continuously at Changwu Agro-ecological Experimental Station on the Loess Plateau (35°14’N, 107°40’E, 1200 m above sea level), Changwu

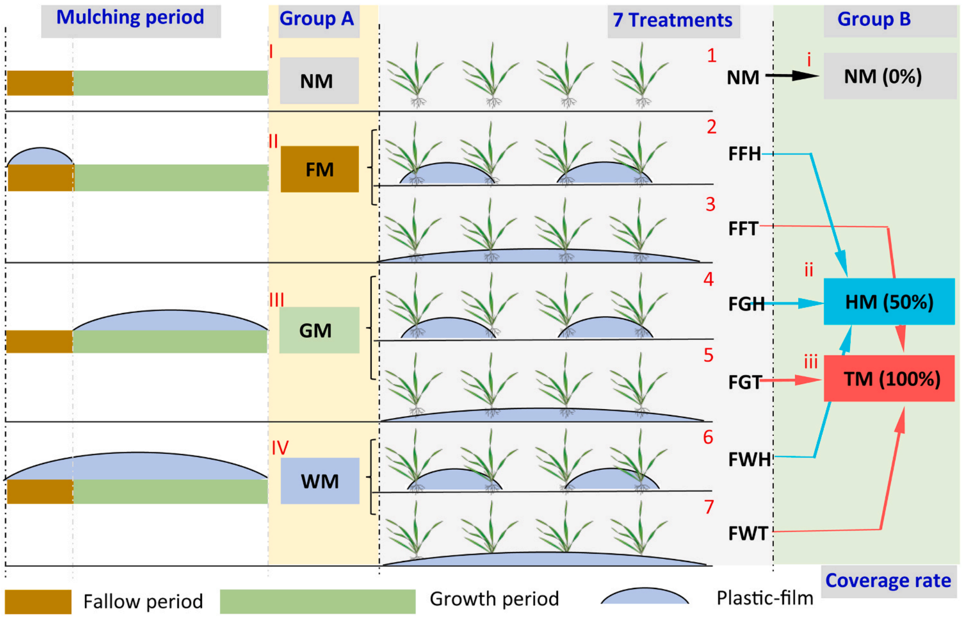

Fig. 2. The experiment of optimizing various PFM patterns was tested from 2013 to 2016 on the Loess Plateau, China, seven treatments included four different mulching periods and three different coverage rates. Note: Group A and Group B were divided based on the mulching period and coverage rate of plastic film mulching. Group A included NM, FM, GM and WM; Group B included NM, HM and TM. NM, no mulching; FM, mulching in the fallow period of the winter wheat; GM, mulching in the growth period of the winter wheat; WM, mulching in the entire year of the winter wheat; HM, half mulching (the coverage rate is 50%); and TM, total mulching (the coverage rate is 100%). FGH, half mulching during growth period; FGT, total mulching during growth period; FFH, half mulching in summer fallow period; FFT, total mulching in summer fallow period; FWH, half mulching during whole year; and FWT, total mulching during whole year.

County, Shaanxi Province, China (Fig. 1). The study site was located in a warm, temperate, semi-humid, continental monsoon climate with an annual mean temperature of 9.1 °C, the lowest monthly mean temperature was −4.7 °C in January, and the highest monthly mean temperature was 22.1 °C in July. Annual mean rainfall was 573.3 mm (1957–2016), about 55.0% of which fell in the summer fallow period (from late June to late September). The water table was at a depth > 80 m, and groundwater was unavailable for crop growth. The soil is classified as a Cumulic Haplustoll (USDA Soil Taxonomy), with a bulk density (BD) of 1.34 g cm^{-3}, a field capacity (FC) of 21.2%, and a permanent wilting point of 7.5% (gravimetrically). SOM, total N, total P, available P, and available K were 12 g kg^{-1}, 0.90 g kg^{-1}, 1.2 g kg^{-1}, 16.2 mg kg^{-1}, and 147.4 mg kg^{-1}, respectively, and the soil pH was 8.3 before sowing in 2002. Data collected from 2013 to 2016 were used in this study.

2.2. *Experimental design and management*

Seven treatments were applied in this experiment (Fig. 2): (1) conventional tillage with no mulching (0%, NM), (2) half coverage rate of PFM during the summer fallow period (50%, FFH), (3) total coverage rate of the PFM during the summer fallow period (100%, FFT), (4) half coverage rate of PFM during the growth period (50%, FGH), (5) total coverage rate of PFM during the growth period (100%, FGT), (6) half coverage rate of PFM during the whole year (50%, FWH), and (7) total coverage rate of PFM during the whole year (100%, FWT).

Based on the mulching period and coverage rate of PFM, treatments were divided into group A and group B (Fig. 2). Group A contained four mulching periods: (I) no mulching controls, NM, (II) mulching during the summer fallow period (FM) with two treatments, FFH and FFT, (III) mulching during the growth period (GM) with two treatments, FGH and FGT, and (IV) mulching during the whole year (WM) with two treatments, FWH and FWT. Group B included three coverage rates: (I) coverage rate of 0%, (NM), (II) coverage rate of 50% (HM) with three treatments, FFH, FGH, and FWH, and (III) coverage rate of 100% (TM) with three treatments, FFT, FGT, and FWT. Each treatment was replicated three times in plots that were 7.0 m x 5.0 m in a complete randomized design. Twenty-four rows of winter wheat were planted in each plot. Row spacing was 20 cm in NM, FFH, FFT, FGT, and FWT treatments, but row spacing was 10 cm under FGH and FWH. The interval between the rows of the plastic film was 60 cm, and six rows of wheat were planted in each film. Urea and calcium superphosphate were applied at the sowing soil depth to provide 150 kg N and 75 kg P_2O_5 per hectare during each year.

Winter wheat was planted using a local cultivar, Changhan 58, which was used from 2002 to 2014, and Changhang 1 was used beginning in 2015, with a seeding rate of 170 kg ha^{-1}. Mulching was then applied to the soil surface using white, transparent polyethylene film that was 600 mm wide, 800 mm long, and 0.015 mm thick. Winter wheat was planted in late September and harvested in late June of the following year. Sowing dates from 2013 to 2015 were Sep 26, Sep 24, and Sep 27, respectively, and harvest dates from 2014 to 2016 were June 24, June 27, and June 26, respectively.

2.3. *Sampling and measurements*

2.3.1. *Measurement of soil physical properties*

Soil samples were collected using cutting rings (volume 100 cm^3, inner diameter 5.05 cm) during the 2015–2016 harvest period of winter wheat (late June 2016) at a depth of 10 cm. Five points were selected randomly in each plot, and two cutting ring soil samples were collected at each point for the determination of saturated hydraulic conductivity (K_S) and BD. K_S was determined by the constant-head method, and BD was measured after collecting with a cutting ring and oven-drying the samples at 105 °C to a constant weight.

Soil compaction (SC) was measured with a recording cone penetrometer (model CP40II, Rimik, Toowoomba, Australia) at the jointing stage of winter wheat in 2016 (mid-March). The metal probe was pressed 7.5 cm into the soil, and each treatment had nine random readings (replicates).

The soil weight water content (θ) was determined using a soil drill (inner diameter 4.00 cm) to collect soil samples at the sowing stage (Sep 26, 2015) and at harvesting (Jun 24, 2016) of winter wheat. θ measurements were taken from the soil surface to a 300 cm depth; measurements were taken at 10 cm intervals within the top 100 cm (topsoil) and at 20 cm intervals within the bottom 200 cm (subsoil). Although this field experiment was established in 2002, we did not collect data in a few years, especially before 2015, for several reasons (i.e., lack of fund support); a detailed database began in 2015.

2.3.2. *Determination of crop agronomic traits*

Canopy height (H) and leaf area index (LAI) of winter wheat were estimated during the critical stages in 2016 (April 14, April 29, May 5, May 12, May 29, and June 23). H was determined using a ruler from the root of the winter wheat to the top of the spike that included the length of the awn; 10 winter wheat plants were selected randomly in each plot. LAI was measured using a LI-2200 Plant Canopy Analyzer (PCA) (LI-COR, Inc., Lincoln, Nebr). Three replicates were taken for each treatment.

During harvest, we removed two rows of winter wheat that represented marginal effects, and we randomly selected four consecutive rows from the remaining 22 rows in each plot, and then threshed, air-dried, and weighed them during 2013–2016. Attributes of the spike (i.e., spike length and spike number) and grain yield components (i.e., grain number, spike number per ha, and 1000-grain weight) of winter wheat were estimated in 2015–2016, but the database did not include data from 2013 to 2014 and 2014–2015 because we changed cultivars of winter wheat or the wheat was damaged by the hail.

2.3.3. *Measurement of soil chemical properties*

Soil samples from three replicates of each treatment were taken after the harvest (late-June 2016) with a hand-operated soil auger to a depth of 20 cm. Roots were removed with forceps before chemical extraction. Nitrate (NO_3^-–N) was extracted from fresh soil with 2 mol L^{-1} KCl (Henriksen and Selmer-Olsen, 1970) (< 2 mm), and the concentration was measured using a spectrophotometer (UV–vis 8500II, China), and SOM concentration was determined by $K_2Cr_2O_7$–H_2SO_4 oxidation (Souza et al., 2016). Total N (TN) concentration was determined by the Kjeldahl method (Bremner, 1996). Ammonium N was extracted with 0.5 mol L^{-1} KCL, and the concentration was determined colorimetrically by H_2O_2 oxidation in a flow analyzer. Available P was extracted by 0.5 mol L^{-1} $NaHCO_3$, and the concentration was determined by molybdenum–antimony colorimetry. Total P (TP) concentration was determined colorimetrically using $HClO_4$–H_2SO_4 oxidation. Available K concentration was determined by atomic absorption spectrometry. The pH of air-dried (< 2 mm) soil was measured using a pH meter in a soil: water ratio of 1:5.

2.4. *Calculations and analysis*

Soil water storage in 300 cm soil profile (SWS_{300}, mm) was calculated as:

$$SWS_{300} = \sum_{i}^{n} hi \times \rho i \times \theta i \times 10 \tag{1}$$

where *hi* is the thickness of the soil layer (cm), ρi is the BD in each layer (g cm^{-3}, the mean value was 1.30), θi is the soil moisture by weight, *n* is the number of layers, and *i* is the soil depth, $i = 10, 20, 30, \ldots 300$.

Evapotranspiration (*ET*, mm) was calculated using the soil water-balance equation (Xie et al., 2005):

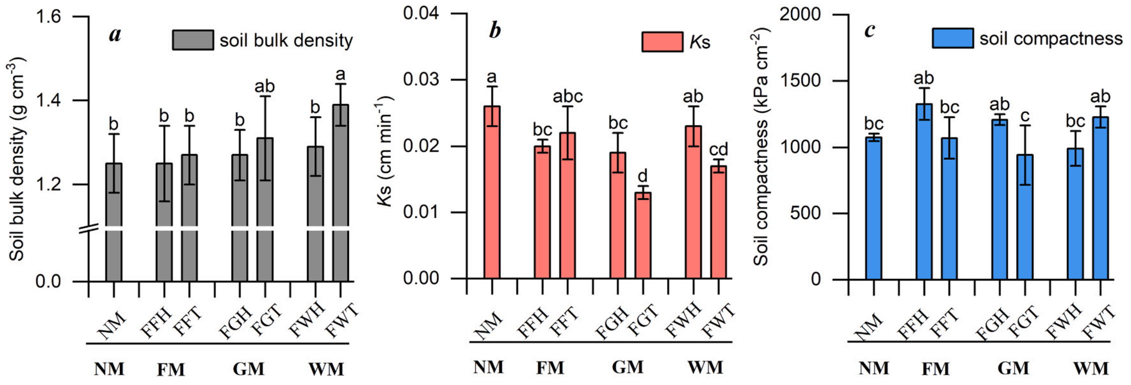

Fig. 3. (a) Changes in soil bulk density, (b) *Ks*, and (c) the soil compactness during harvest of winter wheat on the Loess Plateau, China under various PFM treatments in 2015–2016. Note: NM, no mulching; FM, mulching in the fallow period of the winter wheat; GM, mulching in the growth period of the winter wheat; WM, mulching in the whole year of the winter wheat; HM, half mulching (the coverage rate is 50%); TM, total mulching (the coverage rate is 100%). FGH, half mulching during growth period; FGT, total mulching during growth period; FFH, half mulching in summer fallow period; FFT, total mulching in summer fallow period; FWH, half mulching during the whole year; FWT, total mulching during the whole year.

$$ET = E + T = R + \Delta SWS + C - D - S \tag{2}$$

where E is soil evaporation (mm), T is crop transpiration (mm), R is rainfall during a specific growth stage (mm), ΔSWS is the difference in SWS between two growth stages, C is the upward flow into the root zone, D is the downward drainage out of the root zone, and S is the surface runoff. The water table at the site was at a depth of about 50–80 m, so upward flow into the root zone was negligible. The downward drainage and runoff were assumed to be negligible to a depth of 300 cm because the experimental field was flat and located in a semi-arid region with low rainfall. There was no runoff in the experiment, and the field was not irrigated.

Eq. 2 was thus simplified as:

$$ET = E + T = R + \Delta SWS \tag{3}$$

WUE (kg ha^{-1} mm^{-1}) and RUE (kg ha^{-1} mm^{-1}) were calculated as in Xie et al. (2005):

$$WUE = Y/ET \tag{4}$$

$$RUE = Y/(RF + RG) \tag{5}$$

where Y is the grain yield (kg ha^{-1}), ET is the total evapotranspiration throughout the growing season (mm), and RF and RG are the rainfall during the summer fallow and growing seasons, respectively.

The economic benefit (EB) was calculated as:

$$Economic\ benefit(O/I) = Increased\ Output \div Increased\ Input \tag{6}$$

where Increased Output and Increased Input (Yuan ha^{-1}) are based on the control treatment.

We chose BD, *Ks*, SOM, LAI, Y, RUE, and EB to calculate the best index (BI), which was calculated as:

$$Best\ index\ (BI) = \sum_{i=1}^{n} \frac{f(x_i)}{f(x_{\min})} - \sum_{j=1}^{n} \frac{g(x_j)}{g(x_{\min})} \tag{7}$$

where x is for different treatments, i = 1, 2, …6 (*Ks, SOM, LAI, Y, RUE, EB*) and j = 1, 2 (BD, pH).

The data were analyzed by multivariate analyses of variance (MANOVAs) and Fisher's least significant difference tests using a significance level of $P < 0.05$. Duncan's multiple comparisons were used to determine significant differences between the treatment means. SPSS version 19.0 (SPSS Inc., Chicago, USA) was used for all statistical analyses. The figures were plotted using Microsoft PowerPoint 2018 (Microsoft Corporation., New Mexico, USA) and Origin 9.3 (OriginLab Corporation., Massachusetts, USA).

3. Results

3.1. Distribution of rainfall during different winter wheat growth periods

In the decade from 2007 to 2017, a larger percentage of rainfall fell during the summer fallow season of winter wheat (Fig. 1). Average rainfall during the summer fallow period for winter wheat (*RF*, from July to September) accounted for 58.9 ± 11.2% (307.2 mm) of total rainfall (*R*, from July to next June); lower proportions of 42.3% (192.4 mm, 2014–2015) and 47.8% (197.4 mm, 2015–2016) of rainfall

Table 1
Key soil chemical properties of the soil layers in the 0–20 cm depth under the various PFM patterns on the Loess Plateau, China among the 2013–2016.

Treatment	SOM (g kg^{-1})	Total N (g kg^{-1})	NO_3^--N (mg kg^{-1})	NH_4^+-N (mg kg^{-1})	Total P (g kg^{-1})	Available P (mg kg^{-1})	Available K (g kg^{-1})	pH
NM	14.5±1.2 b	0.90±0.07 bc	15.07±5.82 bc	6.11±0.60 a	0.78±0.03 a	12.3±2.8 ab	112.9±9.6 c	8.34±0.05 a
FFH	16.1±0.7 a	1.07±0.10 a	69.30±9.86 a	5.98±1.65 ab	0.84±0.05 a	14.5±2.6 a	144.2±10.0 a	8.11±0.14 b
FFT	13.5±0.7 c	0.89±0.03 bc	30.45±10.66 b	4.75±0.77 b	0.81±0.03 a	11.4±2.6 ab	119.9±3.0 bc	8.30±0.08 a
FGH	15.6±0.3 a	0.96±0.09 b	19.73±7.38 bc	5.05±1.05 ab	0.80±0.11 a	9.7±2.7 b	129.7±7.5 b	8.29±0.09 a
FGT	14.1±0.4 bc	0.95±0.04 bc	17.42±8.60 bc	4.92±0.96 ab	0.78±0.08 a	9.2±3.9 b	121.9±13.4 bc	8.36±0.01 a
FWH	14.4±0.5 b	0.92±0.02 bc	10.08±1.98 c	5.46±0.71 ab	0.78±0.02 a	10.9±1.2 b	123.7±4.6 bc	8.35±0.05 a
FWT	13.3±0.6 c	0.86±0.07 c	11.33±3.45 c	5.07±0.81 ab	0.83±0.07 a	10.9±1.4 b	114.3±10.0 c	8.35±0.02 a

Note: The number following ± is the standard deviation. Different letters within a column indicate significant differences among the treatments at $P < 0.05$ using Duncan's test. Different colors within a column from green to white and red represent the order of numerical values. NM, no mulching; FGH, half mulching during growth period; FGT, total mulching during growth period; FFH, half mulching in summer fallow period; FFT, total mulching in summer fallow period; FWH, half mulching during whole year; FWT, total mulching during whole year.

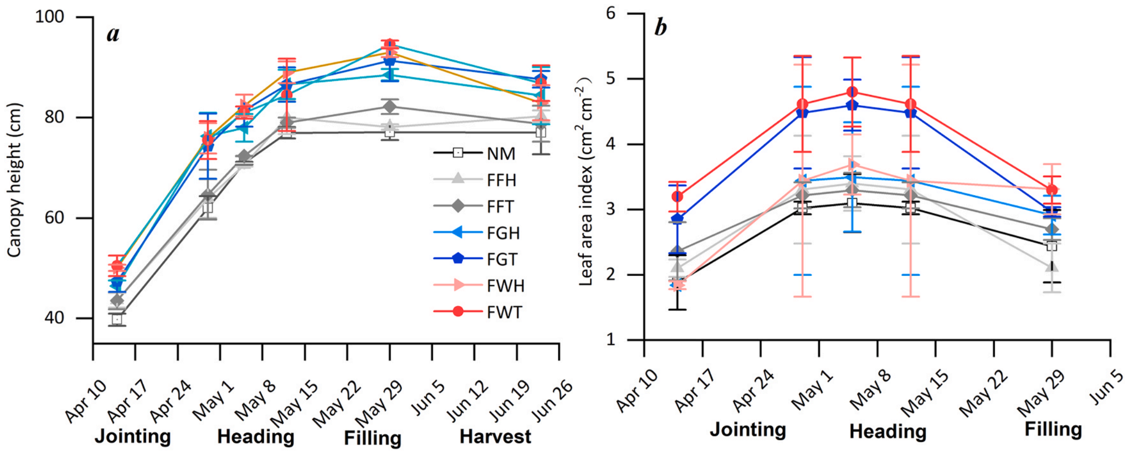

Fig. 4. (a) Dynamic changes in canopy height of winter wheat and (b) the leaf area index during the growth period of winter wheat under various PFM patterns in 2015–2016. Note: NM, no mulching; FGH, half mulching during growth period; FGT, total mulching during growth period; FFH, half mulching in summer fallow period; FFT, total mulching in summer fallow period; FWH, half mulching during whole year; FWT, total mulching during whole year.

fell during that period in some years. During 2013–2014, a higher proportion of 59.8% (392.2 mm) fell during the summer fallow period. Rainfall during the period from the sowing of winter wheat to harvest (*RG*) was 38.4 ± 12.4% of *R*, with a higher proportion in 2013–2014 (40.2%), 2014–2015 (57.7%), and 2015–2016 (52.2%).

3.2. Differences in soil physical properties with various PFM patterns

Soil physical properties, such as soil BD, K_s, and SC, were affected significantly at harvest in 2016 under various PFM patterns (Fig. 3). BD increased under all PFM patterns (Fig. 3a); FGT and FWT increased BD by 4.8% and 11.2% more than NM, respectively. Under the same coverage rate of PFM, the effect of WM and GM on BD was greater than FM and NM. In the different mulching periods, HM had a weaker impact on soil BD than TM. *Ks* decreased under various PFM patterns (Fig. 3b); FFH, FGH, FWT, and FGT decreased *Ks* by 23.1%, 26.9%, 34.6% and 50.0% more than NM, respectively ($P < 0.05$), but FFT and FWH decreased *Ks* by 15.4% and 11.5% more than NM, respectively ($P > 0.05$). FM had minimal impact on K_s compared with GM and WM. Under various PFM patterns, FFH, FGH, and FWT had higher SC than NM, but FGT decreased SC (Fig. 3c).

3.3. Changes in soil chemical nutrients and attribution under various PFM patterns

Key soil nutrients concentrations changed significantly in the tillage layer (0–20 cm) after various continuous PFM patterns were applied for 15 y (from 2002 to 2016), and the average concentration of soil nutrients during 2013–2016 was highly variable under different PFM patterns (Table 1). SOM concentration was 7.7% and 11.0% higher under FGH and FFH, respectively, and 6.9% and 8.3% lower under FFT and FWT, respectively, compared with NM ($P < 0.05$). Meanwhile, total N and SOM concentrations showed similar trends. Total N concentration after the harvest was 6.7% and 18.9% higher under FGH and FFH, respectively, and 1.1% and 4.4% lower under FFT and FWT than NP ($P < 0.05$), respectively. Ammonium N concentration did not differ significantly among the treatments, except under FFT ($P < 0.05$). Total P and available P concentrations did not differ significantly among treatments. Available K concentration in the 0–20 cm layer was 14.9% and 27.8% higher under FGH and FFH than under NM ($P < 0.05$), respectively. Only the FFH treatment had a significant effect on pH value in the 0–20 cm layer.

Table 2
Yield components of winter wheat and the characteristic of the spike with various PFM patterns in 2015–2016.

Treatments	Spike length (cm)	Grain number	Spike number	Spike number per ha (× 10^6)
NM	11.9 ± 0.2 a	36.0 ± 5.0 bc	18.4 ± 1.4 ab	2.8 ± 0.2 b
FFH	11.5 ± 0.5 a	34.3 ± 6.4 bc	18.7 ± 1.6 ab	2.9 ± 0.6 ab
FFT	11.3 ± 0.1 a	36.0 ± 3.2 ab	19.7 ± 0.6 a	3.3 ± 0.4 ab
FGH	11.4 ± 0.7 a	39.5 ± 5.5 ab	19.9 ± 0.5 a	2.8 ± 0.3 b
FGT	11.9 ± 1.4 a	38.8 ± 6.4 ab	19.3 ± 2.2 a	3.4 ± 0.3 ab
FWH	11.8 ± 0.1 a	39.1 ± 0.9 ab	20.9 ± 0.6 a	3.5 ± 0.2 a
FWT	11.5 ± 0.9 a	33.7 ± 6.7 ab	20.3 ± 0.8 a	3.3 ± 0.3 ab

Note: The number following ± is the standard deviation. Different letters within a column indicate significant differences among the treatments at $P < 0.05$ using Duncan's test. NM, no mulching; FGH, half mulching during growth period; FGT, total mulching during growth period; FFH, half mulching in summer fallow period; FFT, total mulching in summer fallow period; FWH, half mulching during whole year; FWT, total mulching during whole year.

3.4. Growth characteristics and yield components of winter wheat under various PFM patterns

Various PFM patterns increased plant H and LAI of winter wheat by 29.5% and 19.4% in 2015–2016, respectively. The effects of FGT and FWT were outstanding (Fig. 4). The mean percentage increase in winter wheat plant height was 28.5% during six different periods (Apr 14, 29; May 5, 12, 29; Jun 23) with all PFM patterns, and the mean percentage increase in winter wheat LAI during five different periods (Apr 14, 29, May 5, 12, 29, Jun 23) was 19.4% with all PFM patterns. During harvest, plant H had increased by 4.2%, 2.3%, 9.5% ($P < 0.05$), 13.7% ($P < 0.05$),7.6%, and 12.7% ($P < 0.05$), under FFH, FFT, FGH, FGT, FWH, and FWT, respectively (Fig. 4a). GM and WM had a better effect on plant H than FM and NM under different PFM mulching periods. LAI increased under various PFM patterns before the filling stage of winter wheat, although LAI under FGT and FWT was better than under NM (Fig. 4b). Compared with NM, FM had almost no effect on LAI in winter wheat during different PFM mulching periods. The spike length of winter wheat barely changed under various PFM patterns. FFT, FGT, FWH, and FWT increased spike number by 5×10^5, 6×10^5,7×10^5, and 5×10^5 per hectare compared with NM, respectively (Table 2).

3.5. Soil water consumption

Under various PFM patterns, mean soil water content in the 300 cm profile of the winter wheat field was the highest during the wintering

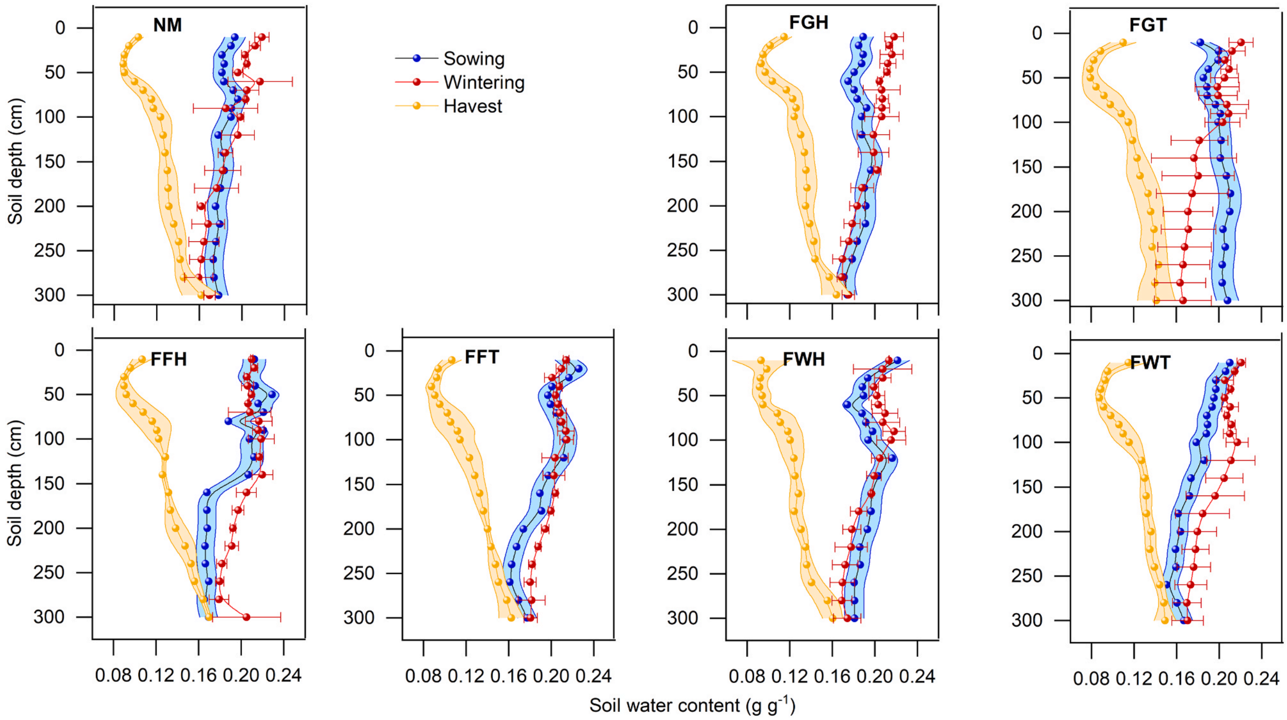

Fig. 5. Soil water content in the 0–300 cm profile under various PFM patterns at the sowing, wintering, and harvest stage of the winter wheat in 2015–2016. Note: NM, no mulching; FGH, half mulching during growth period; FGT, total mulching during growth period; FFH, half mulching in summer fallow period; FFT, total mulching in summer fallow period; FWH, half mulching during the whole year; FWT, total mulching during the whole year.

Table 3
Soil water storage (SWS_{300}), evapotranspiration (ET), water-use efficiency (WUE) and rainfall-use efficiency (RUE) of winter wheat for different treatments during September 2015 to June 2016.

Treatment	SWS_{300} (mm)		ET (mm)	WUE (kg mm^{-1} ha^{-1})	RUE (kg mm^{-1} ha^{-1})
	Sowing	Harvest			
NM	717.6 ± 21.5 cd	507.7 ± 36.1 ab	458.3 ± 36.1 cd	8.2 ± 1.1 b	15.1 ± 1.5 d
FFH	747.0 ± 22.4 bc	516.8 ± 13.1 a	478.5 ± 13.1 bcd	8.6 ± 1.9 ab	16.4 ± 1.1 cd
FFT	752.1 ± 22.6 bc	504.3 ± 18.0 ab	496.2 ± 18.0 bc	8.7 ± 1.6 ab	17.4 ± 1.5 bc
FGH	735.0 ± 22.1 bc	515.6 ± 18.1 a	467.8 ± 18.1 cd	9.1 ± 0.9 a	17.0 ± 1.3 bc
FGT	797.2 ± 23.9 a	470.9 ± 35.1 b	574.6 ± 35.1 a	8.6 ± 0.4 ab	19.8 ± 1.7 ab
FWH	761.9 ± 22.9 ab	493.0 ± 21.6 ab	517.3 ± 21.6 b	10.2 ± 0.9 a	21.2 ± 1.1 a
FWT	693.6 ± 20.8 d	491.8 ± 3.8 ab	450.2 ± 3.8 d	10.1 ± 0.7 a	18.2 ± 1.5 bc

Note: The number following ± is the standard deviation. Different letters within a column indicate significant differences among the treatments at $P < 0.05$ using Duncan's test. NM, no mulching; FGH, half mulching during growth period; FGT, total mulching during growth period; FFH, half mulching in summer fallow period; FFT, total mulching in summer fallow period; FWH, half mulching during whole year; FWT, total mulching during whole year.

period in 2015–2016, but lowest during the harvest period when the soil was the driest (Fig. 5). Before winter wheat sowing, the average soil water content of the upper layer (0–150 cm) was higher than the lower layer (150–300 cm) in the entire profile under various PFM treatments. In contrast, the upper layer was drier than the lower layer during harvest, and soil water content decreased sharply during harvest compared with the planting season. The soil water content curves during sowing and harvest showed an intersection point of about 300 cm, but the intersection of FGT was obviously < 300 cm.

Most PFM patterns increased soil water storage in the 0–300 cm profile (SWS_{300}) during the sowing stage of winter wheat, but decreased storage during harvest. Partial PFM patterns increased ET, and all PFM patterns improved WUE and RUE (Table 3). Before winter wheat sowing, SWS_{300} under the FWT treatment decreased by 24 mm (3.3%) more than NM, but the SWS_{300} of other PFM treatments was higher than that of NM. During harvest, SWS_{300} decreased significantly compared with that during sowing; FGT had the lowest SWS_{300} among the PFM patterns, but FGH and FFH still maintained a high SWS_{300}. Various PFM patterns also increased ET, and ET under FGT and FWH was significantly higher than NM ($P < 0.05$). WUE increased under various PFM patterns, and the highest WUE value was 10.2 kg mm^{-1} ha^{-1} under FWH, and WUE was 10.1 kg mm^{-1} ha^{-1} and 9.1 kg mm^{-1} ha^{-1} under FWT and FGH, respectively. RUE increased under all PFM treatments; FWH, FGT, FWT, FFT, FGH, and FFH increased RUE by 40.4%, 31.1%, 20.5%, 15.2%, 12.6%, and 8.6% compared with NM, respectively (Table 3).

3.6. Grain yield and dry biomass

The grain yield and dry biomass of winter wheat increased under various PFM patterns if they did not suffer from natural disasters (Fig. 6). The average grain yield of winter wheat under various PFM treatments in 2013–2014 was 5318.5 kg ha^{-1}; yield of NM was 4674.1 kg ha^{-1}. Therefore, there was an average yield increase of 13.8% under PFM treatments. FFH, FWT, and FGH treatments increased grain yield by 18.7%, 15.8%, and 14.8%, respectively. The aboveground dry biomass of winter wheat improved significantly under PFM patterns, and the dry biomass under FWT increased by 1409.0 kg ha^{-1} (15.1%). Grain yield and dry biomass decreased sharply compared with normal

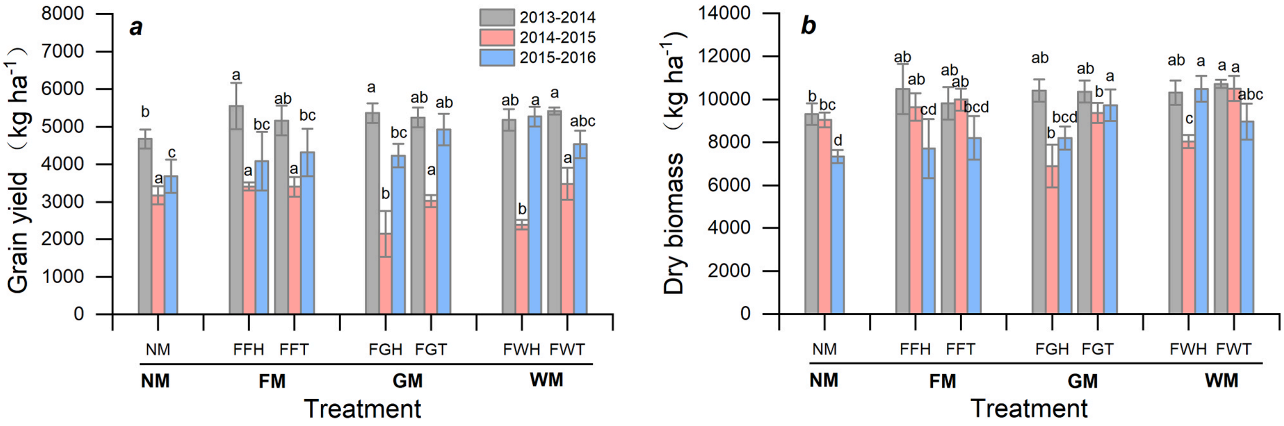

Fig. 6. (a) Difference in grain yield (b) and dry biomass of winter wheat under various PFM patterns on the Loess Plateau, China from 2013 to 2016. Note: NM, no mulching; FM, mulching in the fallow period of the winter wheat; GM, mulching in the growth period of the winter wheat; WM, mulching in the whole year of the winter wheat; HM, half mulching (the coverage rate is 50%); TM, total mulching (the coverage rate is 100%). FGH, half mulching during growth period; FGT, total mulching during growth period; FFH, half mulching in summer fallow period; FFT, total mulching in summer fallow period; FWH, half mulching during whole year; FWT, total mulching during whole year.

years because of the hail disaster during the filling period of winter wheat in 2014–2015. Nevertheless, compared with NM, FM increased grain yield by 9.5% under the different mulching periods, but GM and WM almost reduced grain yield. Under different PFM coverage rates, grain yield and biomass decreased more severely under HM, but FGH and FWH reduced grain yield by 20.5%, and 23.2% compared with NM, respectively, and biomass also showed a consistent decreasing trend. Grain yield of winter wheat in 2015–2016 was 3684.6–5720.3 kg ha^{-1}, which increased under the various PFM patterns. Grain yield under FWH and FGT was 5270.3 and 4920.6 kg ha^{-1}, respectively, which was an increase of 43.0% and 33.5% compared with NM ($P < 0.05$), respectively. FWH and FGT treatments also exhibited higher yield of dry biomass than other treatments of 10,489.4 kg ha^{-1}and 9727.2 kg ha^{-1}, respectively, which were increased of 42.9% and 32.5% compared with NM, respectively.

4. Discussion

4.1. Change in physical and chemical properties of soil under PFM

Physical properties of soil in the tillage layer changed at the end of the growing season under PFM technology (field surface management), but more changes came from human disturbance (e.g., tillage, planting, etc.). Under the same human disturbance, soil BD changed during harvest during different mulching periods of PFM after a year of winter wheat growth. BD increased under WM and GM, but the change in BD was not significant under FM. In other words, BD of the tillage layer of soil changed during harvest when PFM was applied during the growing season.

Compared with the deeper layer soil, BD of the tillage layer was more susceptible to external factors. For example, alternating drying and wetting changed soil BD significantly in the tillage layer; especially after a heavy rainfall, BD in the soil increased in the short-term. The tillage layer of the soil was compacted when rainfall intensity was higher than the infiltration rate of rainwater. The original soil mass increased with rainwater, and the soil of the tillage layer was compacted and soil BD increased, and the compaction under PFM was higher than NP. PFM acted like an obstacle for rainwater infiltration, which allowed rainwater to enter the soil only through the mulch gap. Therefore, the infiltration rate of rainwater and cumulative infiltration in PFM treatments were smaller than NP. More water remained on the membrane or in the soil of the tillage layer, which resulted in greater compaction of the soil under PFM and increased BD that was greater than NP. The wet-dry cycle was long and complicated, with repeated freezing and thawing of the soil from sowing to the harvest of winter wheat. As a result, BD increased during the harvest. Moreover, rainfall and soil texture were also important factors that affected soil BD in dryland farming. Rainfall directly affected the wet-dry cycle, and soil texture determined the expansion and contraction of the soil, which affected the soil compaction process and changed the soil BD.

Under the different PFM mulching periods, neither FM nor NM was covered with plastic film during the growth period of winter wheat. Therefore, soil BD did not change significantly during harvest. But plastic film was applied to both WM and GM during the growth period, and so BD increased. Under different PFM coverage rates, HM of the exposed area was still $<$ 50% coverage, water and air were lost from the uncovered area, and the compaction from water accumulation under the membrane was weakened, which eventually reduced its impact on BD.

PFM changed soil BD during different stages of crop growth (Wang et al., 2017; Zhang et al., 2015). With similar soil texture in dryland agricultural areas, rainfall is an important factor that affects BD. Wang et al. (2017) reported that a 7-y continuous application of PFM increased soil BD by 5% during maize harvest in Yuzhong (silt loam texture, $<$0.0002 mm 22.0–22.1%; mean annual rainfall, 388 mm), and PFM increased BD by 6% during maize harvest in Huining (silt loam texture, $<$ 0.0002 mm 22.0–22.1%; mean annual rainfall, 410 mm). Larger rainfall had a greater effect on soil BD. During different growth periods of corn, soil BD increased gradually with the increase in rainfall and the process of the wet and dry cycles. PFM increased BD gradually from May to a high in November in the *Ferric Acrisol* rain-fed region with crop rotation (silt loam texture, $<$0.0002 mm 40%; mean annual rainfall, 879 mm) (Zhang et al., 2015). Zhang et al. (2015) showed that PFM had the largest soil BD in NM with straw mulching in erodible loess soil. However, some studies showed different results. Subrahmaniyan et al. (2018) reported that FWT treatment decreased soil BD in a 3-y experiment. Anikwe et al. (2007) showed that there was no significant difference in PFM or NM, but PFM decreased soil BD slightly. After many years of PFM application, residual plastic fragments and its degraded micro-plastics or nano-plastics promoted soil clay to be cemented together, compacted soil under machinery, reduced *f*, cut off pore connectivity, and increased BD (Jiang et al., 2017; Ng et al., 2018). In some studies, the accumulation of residual fragments after many years reduced soil BD. Therefore, the amount of plastic film residue can change BD.

In addition, almost all studies have shown that PFM reduced K_S significantly due to residual fragments, which cut off pore connectivity of the soil and reduced water-conducting pores. PFM significantly reduced Ks and affected infiltration and recharge of rainwater (Jiang et al., 2017; Ng et al., 2018). Soil physical and hydraulic properties were degraded gradually with plastic film fragments. Removing the plastic residue decreased the adverse effect on the soil environment (Li et al., 1999). Hence, it is advantageous to use new degradable materials instead of traditional polyethylene plastic film to maintain soil health (Kasirajan and Ngouajio, 2012a, 2012b; Ng et al., 2018).

Soil nutrients and pH were affected by the cumulative effect with a variety of continuous PFM patterns applied for > 10 years. This difference will be more obvious as the number of application years of various PFM patterns increase. In detail, the coverage rate of PFM (or bare surface area) changed the SOM concentration by affecting the soil's physical and biochemical processes. SOM concentration was maintained or increased by HM, but reduced by TM. Zhang et al. (2017) suggested that PFM did not necessarily lead to a decrease in SOM in the long term, especially in regions with poor water and high heat. Inconsistently, PFM reduced SOM concentration in the Northeast of China with more rainfall than on the Loess Plateau (Li et al., 2007).

PFM coverage rates changed SOM concentrations (Zhang et al., 2015). TM with no exposed surface area significantly reduced water, heat, and gas exchange processes between the soil and atmosphere interface (Zhou et al., 2020), which led to soil water content, temperature, and CO_2 concentrations that were higher than under HM or NM. This stimulated soil microorganisms and enzymatic activity to break down a large amount of humus (an important component of SOM) into small molecules (Mo et al., 2017; Wang et al., 2016). Simultaneously, a better hydrothermal environment promoted microorganisms and fungi to use these molecules i.e., (secretions contained protein and carbohydrates) to multiply and to promote the decomposition of SOM for the absorption and utilization by roots (Zhu et al., 2018). Finally, increasing soil respiration (microbial and root respiration) ultimately increased SOM and nutrient consumption, which resulted in mineralization of SOM that was faster than other treatments.

PFM regulated soil temperature and promoted crop growth when it was cold in early spring (He et al., 2016b; Zhou et al., 2009), and our results indicated that various PFM patterns increased LAI and H in April (early spring) (Fig. 4). PFM improved hydrothermal conditions in the rhizosphere micro-environment of winter wheat, and winter wheat grew better under these treatments (Gan et al., 2013), but the better hydrothermal environment promoted the mineralization of SOM. However, small plants did not consume SOM much during cold weather. During the stage of the rapid growth of winter wheat (after the jointing stage), H and LAI of winter wheat increased rapidly. More solar radiation was trapped in the winter wheat canopy, the larger LAI was beneficial for crop photosynthesis, and T promoted the absorption and utilization of soil water content and other nutrients by increasing plant roots. Especially under FGT and FWT treatments, better LAI and H led to decomposition of SOM. During the summer fallow period, crop residues were plowed into the tillage layer with high temperatures and frequent rainfall.

Hydrothermal conditions under GM, FM, and WM were better than under NM (Gan et al., 2013; Fan et al., 2016), which was beneficial to the residual mineralization of winter wheat roots and increased the decomposition of microorganisms (Niu et al., 2004). As our first hypothesis (H1), HM had higher SOM and higher total N concentrations than TM during the same mulching period. The NO_3^-–N was easily leached with rainfall (Ma et al., 2018; Zhang et al., 2012). Mulching during the summer fallow period reduced rainwater leaching and finally caused the nutrient accumulation in the plow layer to be higher than during other mulching periods.

4.2. Consumption and depletion of soil water resources

Consumption of limited water resources directly affected crop yields and land productivity (He et al., 2016a). There is an emerging consensus that PFM reduces soil E (Li et al., 2013; Zhang et al., 2018). The micro-environmental hydrothermal conditions in the soil rhizosphere were improved by PFM, which may have promoted crop growth and increased crop T. So, PFM significantly reduced soil E and promoted crop T (Gan et al., 2013; Zhang et al., 2018). Under the same pattern of rainfall distribution, ET will eventually be different under various PFM. After > 10 y of application of PFM technology, and with the consumption and depletion of soil water, the differences in soil water consumption of various PFM patterns became apparent during 2015–2016 (after PFM had been applied for 15 y).

However, it has not been possible to quantify the proportion of PFM that affected E and T using the water balance equation (Xie et al., 2005). The impact on ET varied depending on factors, such as PFM coverage rates and mulching periods. There was no doubt that TM reduced more soil E than HM or NM. Meanwhile, soil E was also affected by various PFM mulching periods, and there was excessive soil E with high temperatures and intensive rainfall during the summer fallow period for winter wheat. Although the summer fallow period only accounted for 1/4 of the winter wheat growing year, a large proportion of soil E was attributed to ET during the growth period during the whole growth year for winter wheat. Therefore, soil E decreased significantly when the plastic film was applied in FM and WM treatments, and there was no crop T during this period. The more intense crop T resulted from the higher crop H and LAI during the growth period, and FWT and FGT had higher crop T than other PFM treatments. FGT treatment had no mulching cover during the summer fallow period of high temperatures and strong E, which resulted in its maximum ET. On the contrary, FWT was mulched during the summer fallow period, which reduced strong soil E, and ET was the least (Gan et al., 2013). Excessive soil E affected ET substantially and accounted for a large proportion during the summer fallow period. Another reason for this result was that continuous FWT mulching resulted in soil desiccation in the deeper layer (Fig. 5) that restored less water in the profile (Table 3).

Under various PFM patterns, WUE and RUE increased (Turner, 2004). Because the exposed area of soil was reduced with different mulching periods and coverage rates, this reduced surface E and increased the effective crop T; this resulted in increased WUE (Wang et al., 2009). The trend in WUE was the same as H2 under different mulching periods, but our results were not completely consistent with H2. FGT had excessive soil E, promoted crop growth, and increased crop T, which led to significantly higher ET than other treatments, even if grain yield of winter wheat increased, but WUE was not changed significantly. Hence, this minimized soil E on the soil surface and improved crop T (Zhang et al., 2018). The soil water consumption depth of FWT was deeper than other treatments to meet the soil water consumption of winter wheat growth, which may lead to soil desiccation, and a permanent dry layer may form in severe cases. The dry soil layer indicated that it was not conducive to the sustainable use of water in water-limited regions. He et al. (2016b) suggested that FGH did not affect ET significantly in yearly averages (2009–2014) on the Loess Plateau, but it increased the ET by 6% and 10% during the dry growing seasons of 2009–2010 and 2010–2011, respectively.

4.3. Yield and biomass

Most PFM patterns had a positive effect on grain yield and biomass of winter wheat (Li et al., 2001). Winter wheat is sown in late September, and it is harvested in middle or late June of the following year, which is a growth period > 9 mo. This is a longer growing period than other crops, which resulted in complex and long-term physical, chemical, and biochemical processes during the formation of grain yield and biomass. A 5-y experiment showed that the FGH treatment increased grain yield in most years from 2008 to 2013 on the Loess Plateau (He et al., 2016b), especially in normal dry years. But in extremely dry years, PFM may even reduce grain yields (He et al., 2016b).

A meta-analysis of PFM in northwestern China indicated that PFM increased grain yield of potatoes (*Solanum tuberosum* L.), corn, and wheat by 43.1% compared with traditional cultivation, and it increased

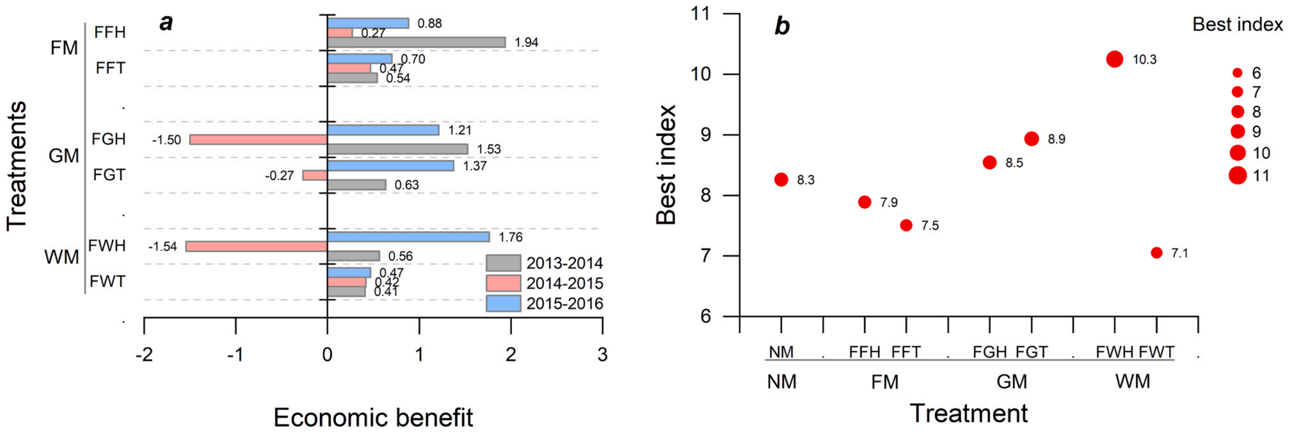

Fig. 7. (a) Differences in economic benefit and (b) best index under various PFM patterns. Note: NM, no mulching; FM, mulching in the fallow period of the winter wheat; GM, mulching in the growth period of the winter wheat; WM, mulching in the whole year of the winter wheat; HM, half mulching (the coverage rate is 50%); TM, total mulching (the coverage rate is 100%). FGH, half mulching during growth period; FGT, total mulching during growth period; FFH, half mulching in summer fallow period; FFT, total mulching in summer fallow period; FWH, half mulching during whole year; FWT, total mulching during whole year.

grain yield of winter wheat by 19.8% (Ma et al., 2018). Zhang et al. (2013) suggested that HM increased grain yield of winter wheat on the Loess Plateau significantly. Abundant rainfall in the summer fallow period or higher soil water storage at sowing time was accompanied by higher grain yield (Zhang et al., 2013). Therefore, soil water supply for winter wheat growth was one of the key factors that increased or stabilized grain yield and biomass (Gan et al., 2013). Also, nutrient supply was a limiting factor for wheat production in arid and semi-arid barren regions. Related research indicated that grain yield of winter wheat might be reduced with insufficient nitrogen fertilizer n northwestern China (He et al., 2016a). Under the same PFM mulching period, different soil water content and temperatures caused by the various PFM patterns changed the effective tiller emergence of winter wheat and resulted in differences in grain yield and biomass. Nevertheless, PFM does not always have a positive effect on grain yield of winter wheat, and adverse effects may be observed under extreme weather events (e.g., persistent drought, hail, and storms, etc.). Extreme weather events will have irreversible impacts on the grain yield of crops. For example, grain yield under HM treatment was reduced significantly due to hail during the grain filling period in 2015.

4.4. Economic benefits (EB) and the best index (BI) under various PFM patterns

Because EB is still the primary concern of households and farmers in developing countries, the input-output ratio is also crucial to them (He et al., 2018). By taking the costs of various inputs (mulching materials) for PFM into consideration, EB was calculated for evaluating various PFM patterns. Regardless of the year of a natural disaster, the EB of FGH, FFH, and FWH was better under various PFM treatments (Fig. 7a). At present, the key to the sustainable agricultural crisis is that the direct EB of farmers is not necessarily consistent with our common interests to maintain the fertility of farmland soil health. Numerous experts and scholars are committed to producing more grain yield with lower environmental costs (Zhang et al., 2016; Yao et al., 2018). Thus, minimizing the negative impact of PFM on the soil's physical, chemical, and biological properties, maintaining soil health, maximizing limited rainfall resources, and increasing crop yield are future agricultural development trends (Chen et al., 2014). BD, *Ks*, SOM, LAI, Y, RUE, and EB were chosen to calculate the best index (BI), and the BI values of FWH, FGT, and FGH were 10.3, 8.9, and 8.5, respectively (Fig. 7b). Using a biodegradable film or removing plastic film fragments may be options to increase BI and to minimize the negative effects of PFM on the soil environment (Ma et al., 2018).

5. Conclusion

Significant differences were observed when field treatments were conducted for >10 y. PFM has a negative influence on the physical properties of the soil's arable layer, such as increased soil BD and reduced *Ks*, but PFM had a smaller impact under HM (FFH, FGH, and FWH) on BD and *Ks* than TM (FFT, FGT, and FWT). Additionally, HM maintained the concentrations of SOM and total N in the arable layer better than TM. Simultaneously, the better LAI and H of winter wheat occurred with GM (FGH and FGT) and WM (FWH and FWT) rather than SM (FFH and FFT) or NM. GM and WM had an outstanding positive impact on increasing the yield of winter wheat. However, FWT depleted the water in the 300 cm soil profile, which promoted dry soils. Based on the BI value, the top three PFM patterns were FWH (10.3), FGT (8.9), and FGH (8.5). Therefore, FWH and FGT were more suitable PFM patterns for reducing film pollution without using biodegradable film instead of polyethylene film. FWH was the best PFM pattern because the plastic film reduced soil evaporation completely during the whole year. To decrease the application of PFM as much as possible, FGH was more beneficial to soil health due to its low coverage and short mulching period. This treatment is the optimal pattern for applying PFM to winter wheat cultivation on the Loess Plateau and similar regions currently.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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