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Combined ditch buried straw return technology in a ridge–furrow plastic film mulch system: Implications for crop yield and soil organic matter dynamics

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ABSTRACT

A ridge–furrow plastic film mulch (RP) configuration can increase crop and straw yields in semiarid areas of China. This study advocated for a novel soil tillage practice (ditch buried straw return) in a ridge–furrow plastic film mulch system. There were three treatments: (i) flat cultivation, CK; (ii) ridge–furrow plastic film mulch with no straw return (RP − S); and (iii) ridge–furrow plastic film mulch with ditch buried straw return (RP + S). Field experiments were conducted from 2015 to 2018 on the Loess Plateau of China to study the effects of straw incorporation on maize growth, biomass, water use efficiency, soil organic carbon, and total nitrogen sequestration capacity in RP systems. The mean rate of straw decomposition in RP + S reached 81 % at harvest of each year. The RP systems provided suitable hydrothermal conditions for maize growth. Both RP treatments promoted maize growth, particularly biomass accumulation and plant height under RP + S. The RP + S treatment also had greater concentrations of soil organic carbon and total nitrogen in surface soil at harvest, higher total nitrogen accumulation, nitrogen content and crude protein in maize grain, and higher maize yields and water use efficiencies than the other two treatments. In summary, the introduction of ditch buried straw return to RP is an effective measure for promoting the sustainable development of film mulching systems in semiarid regions of China by improving soil fertility and increasing crop yields.

1. Introduction

Meeting the demand for increased grain production requires improved productivity of existing cropping systems (Godfray et al., 2010; Zhang et al., 2013). *In situ* soil and water management is a feasible way of improving dryland agricultural productivity (Wang et al., 2016). A recent technique using ridge–furrow plastic film mulch (RP) has been effective for increasing crop productivity in semiarid areas of China (Gan et al., 2013). However, this process produces maize residues that are discarded, resulting in huge waste of straw resources and serious environmental pollution (Fan et al., 2005). While the adoption of RP can increase maize yields, studies have shown that the technology can reduce soil organic carbon storage (Lee et al., 2019), which is not conducive to the sustainable development of regional agriculture. In addition, many studies have shown that crop residue removal causes a substantial loss of organic carbon from the agroecosystem and straw return can preserve soil organic carbon (Laird and Chang, 2013; Lou et al., 2012; Malhi et al., 2011). In China, straw produced in agricultural production continues to be removed from farmland, causing a decline in soil organic matter accumulation and microbial diversity (Zhu et al., 2014). In recent years, the effective management of crop residues has become an important issue for the Chinese government (Li et al., 2018).

Straw return is a widely recognized strategy for improving soil quality and crop productivity, and is an important management practice in global organic agriculture (Seufert et al., 2012). Returning crop straw to the soil can enrich soil organic matter, which is important for maintaining soil quality and increasing agricultural productivity (Chatterjee, 2013; Dikgwatlhe et al., 2014), and enriching nutrient elements like nitrogen, phosphorus, and potassium in the soil (Xie et al., 2014). Long-term additions of straw combined with N annually and P every second year could improve soil water-holding capacity and maintain higher soil water contents under moisture stress (Fan et al., 2005). China is one of the largest straw production countries, especially

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maize straw (Li et al., 2018). Yet, the proportion of straw that is directly returned to fields is low, especially in the arid and semiarid areas of the Loess Plateau as low soil water contents and infrequent rainfall often lead to low decay rates that affect crop growth. Indeed, inappropriate straw application can have a negative effect on the soil environment and crop productivity (Zhou et al., 2004). Straw incorporation causes microbial N immobilization, reducing the amount available for crop growth. Wang et al. (2009) reported that the incorporation of 13,500 kg ha^{-1} straw into field per year without chemical fertilizer reduced maize yield according the results of two-year short-term experiment. In addition, low soil temperatures caused by straw mulching can freeze wheat seedlings and roots during winter, with negative effects on germination and tillering (Yang et al., 2006). Therefore, straw return technologies need to be updated to reflect low decomposition rates under prevalent environmental conditions in the Loess Plateau and create a more suitable decomposition environment to fully release the nutrients in straw and reduce spatiotemporal conflicts with crop growth.

Ditch buried straw return (DBSR) is a novel method that may solve the abovementioned issues with straw residues. Digging ditches in the banded-zone in rows with no crop planted and burying straw into the ditches separates the straw decomposition and crop growth zones, avoiding competition for water and elements due to the concurrent straw decomposition and crop absorption (Wang et al., 2015; Yang et al., 2019). DBSR has the potential to increase soil N retention, thus increasing crop N uptake and minimizing N leaching in rice–wheat rotation systems. However, current technology is only suitable for areas where precipitation and soil moisture conditions are appropriate (Yang et al., 2019). In dry areas where film mulching systems are widely used, the common straw return method of mixing straw pieces with topsoil in the field (Wang et al., 2016, 2018; Zhang et al., 2016) can break the film. To overcome the shortcomings of this common method, we combined DBSR technology with RP technology to create a sustainable agricultural management model suitable for implementation in arid and semiarid areas to improve the efficiency of straw utilization.

This study estimated the benefit of an agricultural management model combining RP and DBSR on crop production in rainfed agricultural areas, and clarified the effect of this technology on maize growth, water use efficiency and soil nutrients to provide a reference for the application of straw return and mulching technology in dryland farmland in northern China. We hypothesized that (1) DBSR combined with RP improves soil hydrothermal conditions and accelerates the straw decomposition rate; (2) deep straw burial after maize harvest increases the straw decomposition rate to avoid the negative impact of straw decomposition on crop growth in the next season; and (3) adopting this composite technology improves soil fertility and water conservation and increases maize yield.

2. Materials and methods

2.1. Description of experimental sites

The experiment was conducted at the Changwu Agricultural Ecology Experimental Station of the Chinese Academy of Sciences, located in Changwu county, Shaanxi province, China (35°12′ N, 107°40′ E, 1200 m a.s.l). Average annual precipitation is 584 mm, annual average temperature is 9.1 °C, frost-free period is 171 d, groundwater depth is 50–80 m. It is a typical rainfed agricultural area, with no irrigation applied during the crop growing season. Average daily temperature and precipitation during the three maize growing seasons (2016–2018) of the experiment are shown in Fig. 1. The soil is black loess, with 11.8 g·kg^{-1} organic matter, 0.87 g·kg^{-1} total nitrogen, 3.15 mg kg^{-1} mineral nitrogen, 14.4 mg kg^{-1} available phosphorus, and 144.6 mg kg^{-1} effective potassium in the surface soil (0–20 cm).

2.2. Experimental design

Maize variety Xianyu 335 was used in this experiment. The field experiment was conducted for three consecutive years from 2016 to 2018. A completely randomized experiment with three treatments and three replicates was established shortly after harvest of the previous season's maize crop in October 2015, the size of each plot was 32 m^2 (4 m × 8 m). The treatments were (i) conventional flat cultivation (CK), which represent common agricultural practices in the study area; (ii) ridge–furrow plastic film mulch (RP − S), the ratio of large ridge width: small ridge width was 40cm: 60 cm, and the height of large and small ridge was 10 cm and 15 cm, respectively; and (iii) combining ridge--furrow plastic film mulch and ditch buried straw return (RP + S), size of ridges were same as RP − S. For the RP − S treatment, the straw was returned just below the large ridge of the RP, in a 40 cm wide × 25 cm deep trench molded by a trencher, and whole maize straw was buried (Table 1; Fig. 2). The RP − S and RP + S treatments started in autumn after harvest of the previous season's maize crop; there are approximately seven months of fallow season after harvest (Table 1). During the fallow season, soil water is conserved for use by the subsequent maize crop. Compound fertilizer was applied to a depth of 20 cm to supply 225 kg N ha^{-1} and 120 kg P ha^{-1} before laying the plastic film in RP − S and RP + S as well as in CK. No irrigation or herbicides were applied during the maize growing period.

2.3. Determination of plant height, leaf area index, and aboveground dry matter

Plant samples were collected at 20, 40, 60, 80, 100, 120, and 140 days after sowing (DAS) the maize. Robust maize plants of uniform growth were collected to measure plant height, leaf area index (LAI), and aboveground dry matter accumulation. The LAI was represented by the ratio of leaf area of each plant to the average land area occupied; in our study, the ratio was 0.12 m^2 plant^{-1}.

2.4. Measurement of soil temperature and properties

Briefly, after harvest of maize in October in each year (2016–2018), five subsamples were collected from the 0–20 surface layer of both large and small ridges respectively in one plot, following five-point sampling method and mixed; subsequently, five subsamples from furrows were collected in same way and mixed with ridge-samples as one soil sample. Soil temperatures were measured at 5 and 15 cm depth within plant rows in the furrow using a digital thermometer (Shenyang Huashengchang Mechanical and Electrical Equipment co., LTD, Shenyang, China) at 8:00, 14:00, and 20:00 on the observation day at 20, 40, 60, 80, 100, 120, and 140 DAS; with the daily temperature expressed as the average of the three time points. A 5 cm diameter soil drill, with drilling points located within plant rows in the furrow, was used to collect soil samples every 20 cm for the determination of soil moisture content in each layer using the weight loss method at 0, 20, 40, 60, 80, 100, and 120 DAS:

$$SWC\ (\%) = (F - D)/D \times 100\%$$

where F is the fresh weight (g) of each soil sample, and D is the dry weight (g) of each soil sample (excluding the aluminum boxes) after drying soil samples at 105 °C to constant weight.

Soil water storage to a depth of 2 m every 20 cm was calculated as follows:

$$SWS\ (mm) = SWC \times h \times p \times 10$$

where SWC is soil water content (%), h is the depth of soil layer (20 cm), and p is the volume weight of soil (g cm^{-3}).

The calculation of maize water use efficiency was as follows:

$$WUE\ (kg\ ha^{-1} mm^{-1}) = G\ /\ (SWS_2 - SWS_1 + P)$$

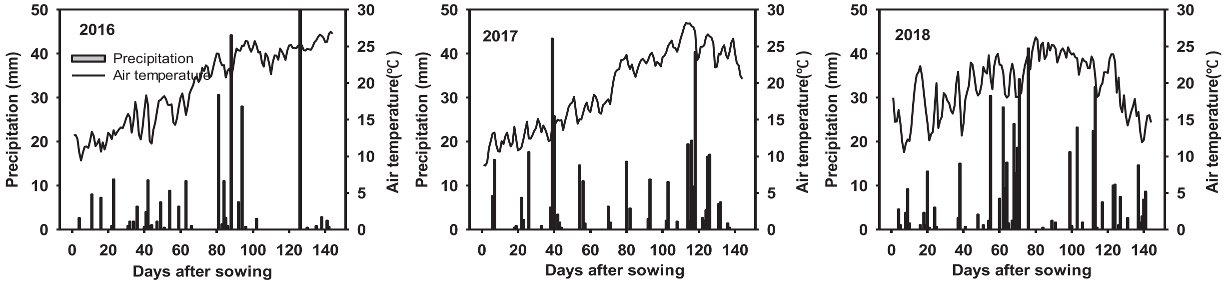

Fig. 1. Daily average temperatures (°C) and rainfall (mm) at the experimental site in three maize growing seasons (2016–2018).

Table 1
The sequence of all management operations and their timing under each treatment during the 3 consecutive maize growing seasons from 2016 to 2018. CK, conventional flat cultivation; ridge–furrow plastic film mulch without straw return (RP − S), ridge–furrow plastic film mulch with straw return (RP + S).

Growing season	Treatment	Management operations	Point in time	Treatment	Management operations	Point in time	Treatment	Management operations	Point in time
2016	CK	Fertilizer application	Apr.2016	RP − S	Fertilizer application	Oct.2015	RP + S	Fertilizer application	Oct.2015
		Tillage	Apr.2016		Tillage	Oct.2015		Tillage	Oct.2015
		Sowing	Apr.2016		Ridge forming and mulching	Oct.2015		Dig trenches to place straw	Oct.2015
		Harvesting	Sep.2016		Sowing	Apr.2016		Ridge forming and mulching	Oct.2015
					Harvesting	Sep.2016		Sowing	Apr.2016
								Harvesting	Sep.2016
2017	CK	Fertilizer application	Apr.2017	RP − S	Fertilizer application	Oct.2016	RP + S	Fertilizer application	Oct.2016
		Tillage	Apr.2017		Tillage	Oct.2016		Tillage	Oct.2016
		Sowing	Apr.2017		Ridge forming and mulching	Oct.2016		Dig trenches to place straw	Oct.2016
		Harvesting	Sep.2017		Sowing	Apr.2017		Ridge forming and mulching	Oct.2016
					Harvesting	Sep.2017		Sowing	Apr.2017
								Harvesting	Sep.2017
2018	CK	Fertilizer application	Apr.2018	RP − S	Fertilizer application	Oct.2017	RP + S	Fertilizer application	Oct.2017
		Tillage	Apr.2018		Tillage	Oct.2017		Tillage	Oct.2017
		Sowing	Apr.2018		Ridge forming and mulching	Oct.2017		Dig trenches to place straw	Oct.2017
		Harvesting	Sep.2018		Sowing	Apr.2018		Ridge forming and mulching	Oct.2017
					Harvesting	Sep.2018		Sowing	Apr.2018
								Harvesting	Sep.2018

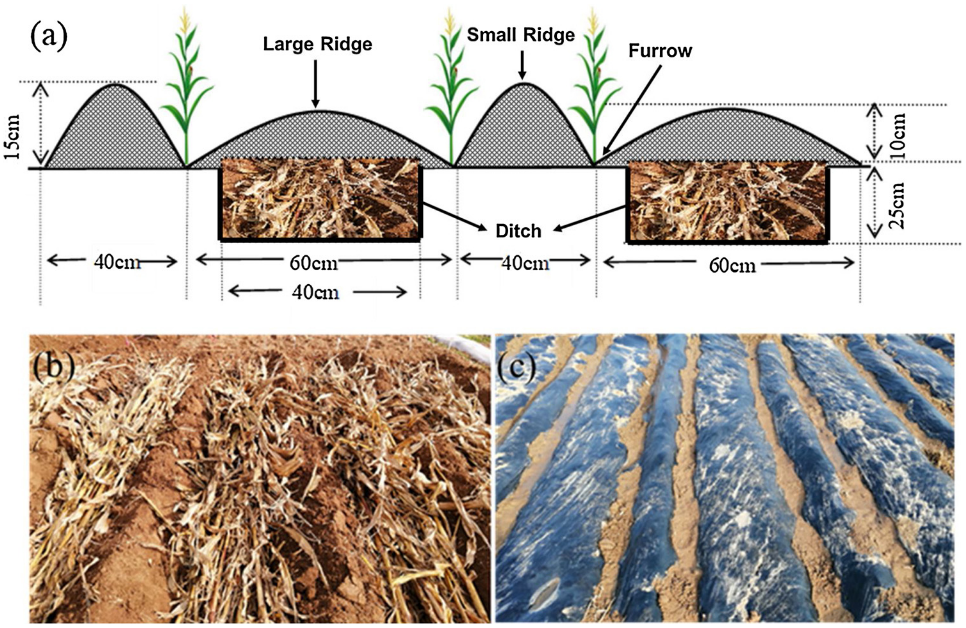

Fig. 2. Schematic diagram (a) for the treatment of combined ditch buried straw return in a ridge–furrow plastic film mulch system (RP + S), ditch buried straw return before ridge forming for RP + S (b), and experimental plots for RP + S after ridge forming and film mulching (c).

where G is maize grain yield (kg ha^{-1}), SWS_2 is soil water storage (mm) at harvest, SWS_1 is soil water storage (mm) before sowing, and P is precipitation (mm) during the growing season.

Total soil nitrogen content was determined using the Kjeldahl method, and soil organic matter was determined using the potassium dichromate-sulfuric acid method (Bao, 2000). Maize kernel quality was determined with a near-infrared grain analyzer (DA7250, Perton, Sweden).

2.5. Measurement of straw decomposition rate

The straw decomposition rate in the RP + S treatment was determined using the nylon mesh bag method. In the RP + S treatment, 120 nylon mesh bags (15 cm long × 15 cm wide, 1 mm bore diameter) were buried in the non-plant rows, each filled with 30 g of air-dried straw. Six bags were sampled every 20 days until maize harvest; the straw in each bag was rinsed with water and dried to a constant temperature at 70 °C before determining the straw decomposition rate, as follows:

$$SDT\ (\%) = 100 \times (W_0 - W_n)/W_0$$

where SDT is straw decomposition rate (%), W_0 is initial weight of straw (g) in nylon mesh bag, W_n is weight of straw (g) in nylon mesh bag at sampling time, n.

2.6. Statistical analysis

SPSS 19.0 software and Sigmaplot 12.5 were used for data analysis and visualization. Differences between treatments were determined using one-way ANOVA, with the least significant difference (LSD) used to identify differences between means with a significant treatment effect at $p < 0.05$.

3. Results

3.1. Soil moisture conditions

As the maize plants grew, the surface soil moisture content showed obvious temporal heterogeneity, which was significantly higher in the RP treatments (RP − S and RP + S) than those in CK (Fig. 3). At 40 DAS, during the flare opening stage, maize plants needed a large amount of water for growth, leading to a sharp drop in surface soil moisture content, more so in the CK treatment. At 60 and 80 DAS, rainfall events supplemented the surface soil moisture in RP − S and RP + S, but CK continued to decline (Fig. 3a, c). In 2017, the lack of sufficient rainfall during mid- to late-growth (Fig. 1) resulted in a decline in soil moisture content in the three treatments at 60, 80 and 100 DAS, more so in CK than RP − S and RP + S, but the situation was reversed after rainfall later in the season (Fig. 3b).

Soil moisture storage to 2 m depth changed significantly with maize growth stage (Fig. 4). During early growth, The RP treatments had significantly more stored soil moisture than CK. However, as maize accumulated aboveground biomass (60 and 80 DAS), CK had significantly more stored soil moisture than RP − S and RP + S (Fig. 10c). With sufficient rainfall in 2018, soil moisture increased throughout maize growth, which minimized the fluctuations in soil water storage in each treatment, relative to that in 2016 and 2017.

3.2. Soil temperature

Soil temperatures at 5 cm and 15 cm depth showed similar changes with maize growth (Figs. 5 and 6). The CK treatment had significantly lower surface soil temperature than the RP − S and RP + S treatments, with no significant differences between the RP treatments (Fig. 6). At 60 DAS, after the maize canopy covered the soil surface, the surface soil temperature under RP remained significantly higher than that of CK (Fig. 5a, b).

3.3. Soil nutrients

The effect of RP and DBSR on soil total nitrogen were mainly reflected in top soil layers (0–40 cm). Straw return significantly increased soil total nitrogen (Fig. 7). Variation in soil organic matter was consistent with soil total nitrogen content between treatments and with soil depth. Notably, RP − S had significantly lower soil organic matter content than CK, while RP + S had significantly higher soil total nitrogen and organic matter content than RP − S in three years and CK in 2018 (Figs. 7 and 8).

3.4. Decomposition rate of maize straw

In general, the maize straw decomposition rate at harvest of each year was more than 80 % (Fig. 9). After the maize straw was returned to the field in 2017, a high proportion of straw had decomposed, with a straw decomposition rate above 70 %, reaching 72 % after the 200 days of the following season. The straw decomposition reached 83 % at the end of the growing season in 2018. (Fig. 9a). The mean decomposition rate was 81 % in past three years (Fig. 9b).

3.5. Plant growth dynamics

The RP + S treatment produced significantly taller plants than the other two treatments in the three maize growing seasons, especially at 60 and 80 DAS; both RP treatments always produced significantly taller plants than CK (Fig. 10a). In all three growing seasons, the LAI in each treatment consistently increased until ~100 DAS, and then declined with age. The maize crop in the RP + S treatment had a significantly higher LAI at 60 and 80 DAS than the other two treatments (Fig. 10b).

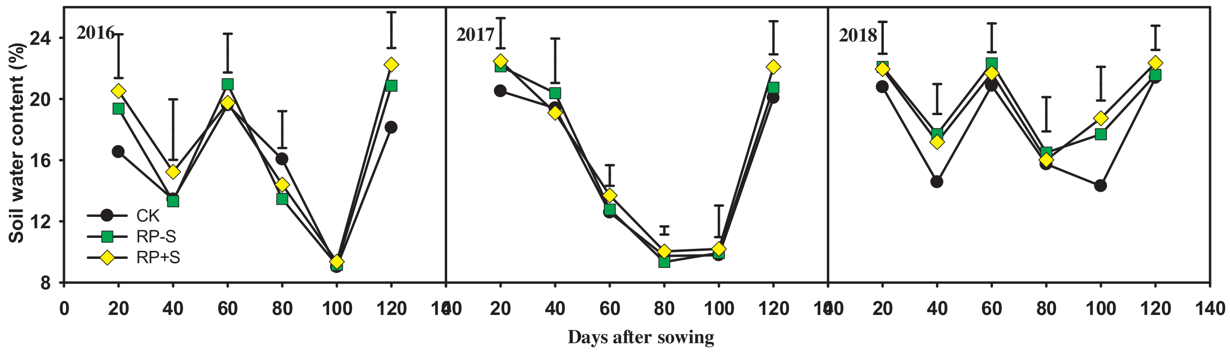

Fig. 3. Dynamic change in soil water content (0–20 cm) under conventional flat cultivation (CK), ridge–furrow plastic film mulch without straw return (RP − S), ridge–furrow plastic film mulch with straw return (RP + S) in three maize growing seasons (2016–2018). Vertical bars represent the LSD ($p < 0.05$) for different treatments.

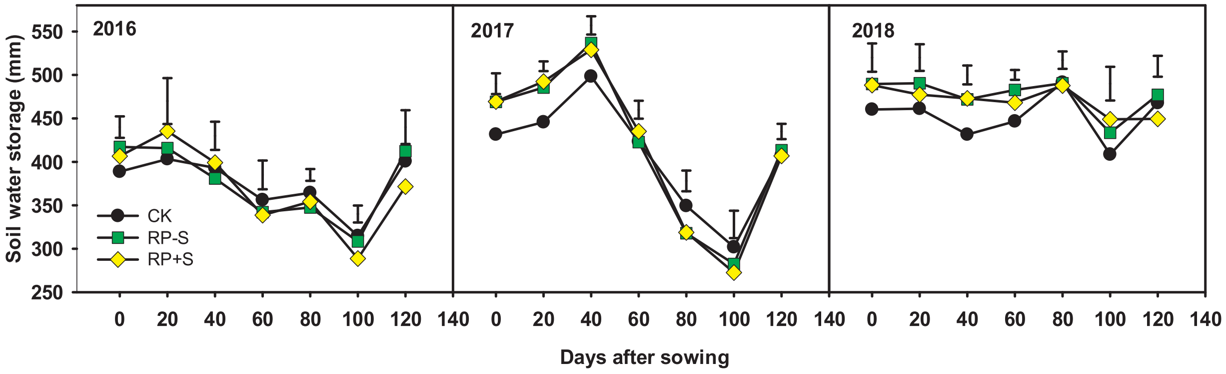

Fig. 4. Dynamic change in soil water storage to 2 m depth under conventional flat cultivation (CK), ridge–furrow plastic film mulch without straw return (RP − S), ridge–furrow plastic film mulch with straw return (RP + S) in three maize growing seasons (2016–2018). Vertical bars represent the LSD ($p < 0.05$) for different treatments.

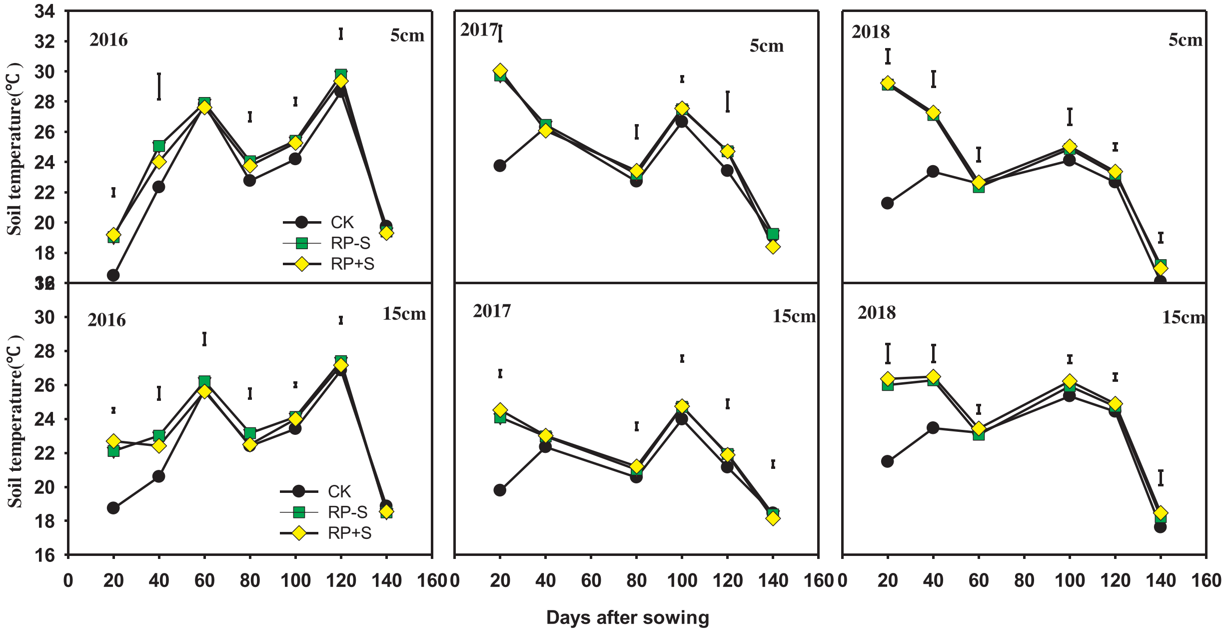

Fig. 5. Dynamic change in soil temperature at 5 cm and 15 cm soil depth under conventional flat cultivation (CK), ridge–furrow plastic film mulch without straw return (RP − S), ridge–furrow plastic film mulch with straw return (RP + S) in three maize growing seasons (2016–2018). Vertical bars represent the LSD ($p < 0.05$) for different treatments.

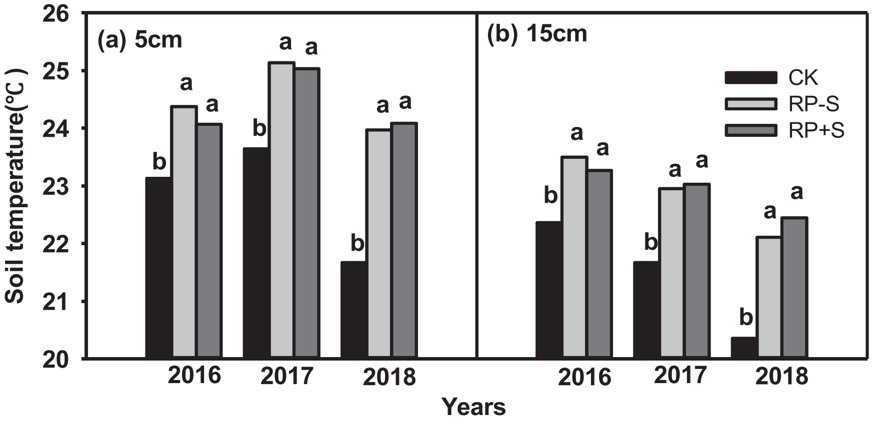

Fig. 6. Average in soil temperature at (a) 5 cm and (b) 15 cm under conventional flat cultivation (CK), ridge–furrow plastic film mulch without straw return (RP − S), ridge–-furrow plastic film mulch with straw return (RP + S) in three maize growing seasons (2016–2018). Different letters denote significant differences between the treatments ($p < 0.05$).

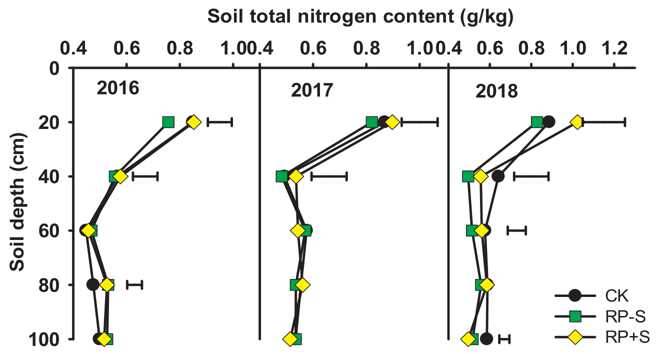

Fig. 7. Change in soil total nitrogen content in the 0–100 cm soil profile under conventional flat cultivation (CK), ridge–furrow plastic film mulch without straw return (RP − S), ridge–furrow plastic film mulch with straw return (RP + S) in the end of three maize growing seasons (2016–2018). Horizontal bars represent the LSD ($p < 0.05$) for different treatments.

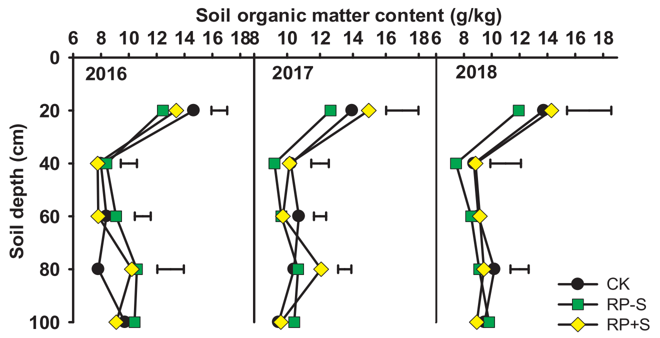

Fig. 8. Change in soil organic matter content in the 0–100 cm soil profile under conventional flat cultivation (CK), ridge–furrow plastic film mulch without straw return (RP − S), ridge–furrow plastic film mulch with straw return (RP + S) in the end of three maize growing seasons (2016–2018). Horizontal bars represent the LSD ($p < 0.05$) for different treatments.

The RP treatments always accumulated significantly more aboveground biomass than CK, with no significant differences between RP − S and RP + S (Fig. 10c).

3.6. *Maize yield and water use efficiency*

Regardless of whether straw was returned to the field, the RP treatments had significantly more kernels per spike, higher 100-grain weighs, and higher yields than CK. The RP − S treatment produced 28–61 % higher maize yields than CK, with the RP + S treatment increasing yields by a further 4–12 % (Table 2). Since maize plants under RP − S and RP + S had greater dry matter accumulation and taller plants, their water consumption was significantly higher than CK (Table 3). Compared with CK, RP + S significantly improved crop water use efficiency, especially in the low rainfall year (2017). The RP treatments were more effective at using precipitation; the PUE under RP − S increased by 45–61 % compared to CK, and a further 4–10 % under RP + S to 30.37–43.35 kg·hm^{-2} mm^{-1} (Table 3).

3.7. *Nitrogen transport and crude protein content in maize*

RP + S had significantly higher nitrogen accumulation in aboveground plant parts than CK, with no significant difference observed between RP + S and RP − S. The RP + S treatment transferred more nitrogen to grain than RP − S, and had a higher grain nitrogen content (Table 4). The crude protein content in grain differed significantly between treatments, CK < RP − S < RP + S, indicating that increased nitrogen accumulation in the grain may increase crude protein levels.

4. Discussion

4.1. *Combining RP with DBSR resulted in more suitable hydrothermal conditions*

Water deficiency is the main factor limiting the improvement of agriculture productivity in semiarid areas (Mupangwa et al., 2008). In northwest China, rainfed soils in semiarid areas are usually infertile and water deficient (Chang et al., 2012; Zhang et al., 2016). Long-term additions of straw have improved soil water-holding capacity and maintained higher soil water contents under soil moisture stress (Fan et al., 2005). In our study, combining RP with DBSR did not significantly increase soil moisture content or storage, compared to RP; while both RP treatments increased soil moisture content compared to CK. Our study was based on RP with the straw buried in trenches, such that the effect of soil moisture retention under the film mulching system masked the effect of DBSR. Another study reported significant increases in water use efficiency with increasing straw incorporation rate (Wang et al., 2018). In our study, water use efficiency did not differ between RP − S and RP + S in 2018, but RP + S had significantly higher water use efficiency than RP − S in 2016 and 2017. We found that rainfall during the maize growing season also affected crop water use efficiency under straw return. In the relatively low rainfall years (2016 and 2017), RP + S had significantly higher precipitation utilization efficiency than the other treatments, while relatively high rainfall in 2018 minimized any differences between the RP treatments for water use efficiency.

The greatest demand for soil moisture occurred during the initial stage of decomposition (Yang et al., 2016). More organic matter at the beginning of decomposition, resulted in more water retention which is less easily accessible to plants and hence straw retention could affect maize emergence and growth (Zhou et al., 2004). However, there was no evidence for moisture competition in our study; RP + S and RP − S had similar soil water storage and content during maize growth (Figs. 3 and 4), which may be due to the application of DBSR immediately after

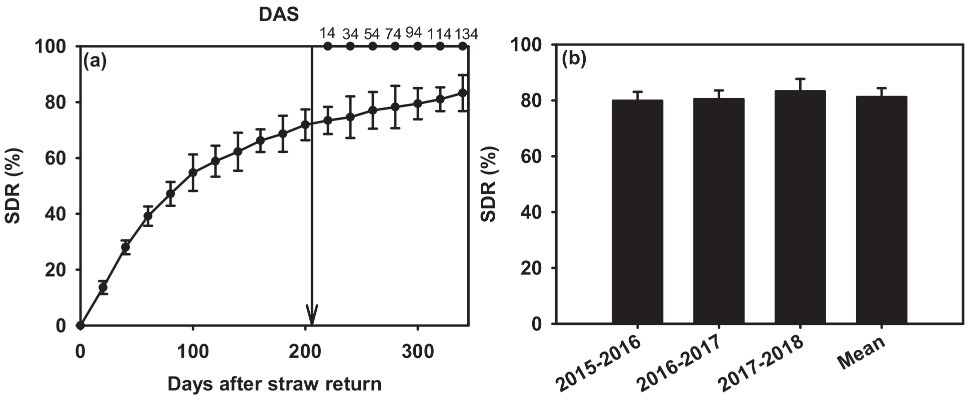

Fig. 9. (a) Dynamics of the decomposition rate of maize straw (SDR) in ridge–furrow plastic film mulching with DBSR over follow season in 2017 and maize growing season in 2018. Point in represent an average SDR of three replications and the bars were standard deviations. The vertical arrow around DAS = 210 represent the sowing date of maize, and the numbers at the top right represents the days of maize growth after sowing (DAS). (b) Average SDR across each growing season. Bars represent the standard deviations among the three replications.

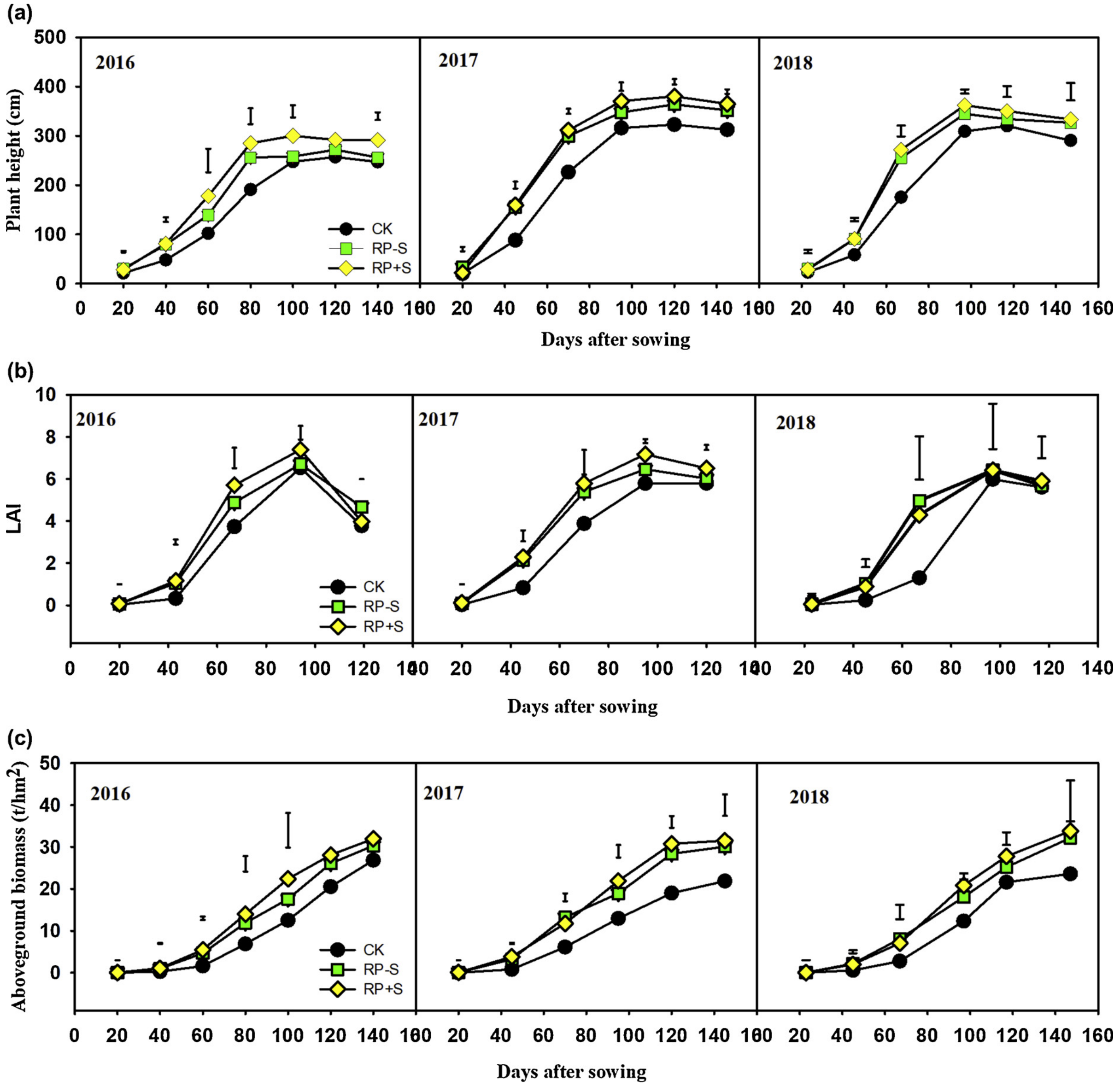

Fig. 10. Crop performance in terms of the dynamic change in (a) plant height, (b) LAI, and (c) aboveground dry matter biomass under conventional flat cultivation (CK), ridge–furrow plastic film mulch without straw return (RP − S), ridge–furrow plastic film mulch with straw return (RP + S) in three maize growing seasons (2016–2018). Vertical bars represent the LSD ($p < 0.05$) for different treatments.

Table 2
Maize yield and yield components under conventional flat cultivation (CK), ridge–furrow plastic film mulch without straw return (RP − S), ridge–furrow plastic film mulch with straw return (RP + S) in three maize growing seasons (2016–2018).

Year	Treatment	Effective spike numbers (10 000·hm^{-2})	Kernel number per spike	100-grain weight (g)	Yield (kg·hm^{-2})
2016	CK	8.03c	503.22b	26.88a	7841.96c
	RP − S	8.27b	646.89ab	28.33a	11826.83b
	RP + S	8.36a	674.44a	33.24a	13269.26a
2017	CK	8.03b	526.22b	26.62b	11250.14c
	RP − S	8.26ab	543.44b	32.09a	14405.33b
	RP + S	8.27a	605.89a	31.49a	15780.32a
2018	CK	8.13b	440.64b	28.18b	10631.1c
	RP − S	8.36ab	694.97a	33.97a	17091.96b
	RP + S	8.61a	696.01a	34.1a	17785.05a

the previous maize harvest. Straw decomposition during the fallow period removed the negative impact on water use in the next season's crop. RP + S decreased topsoil water evaporation meanwhile harvested most of the precipitation during the fallow season (Fig. 1), which ensured the demand for soil moisture in the initial stage of straw decomposition in the fallow period. The above results suggest that combining RP and DBSR after the previous maize harvest avoids the varying demands of straw and crops on soil water resources. A previous study showed that soil moisture content affected straw decomposition, thereby affecting the diversity and activity of microbial communities associated with straw decomposition (Chen et al., 2014), and lower water contents reduced the rate of straw decomposition. The combination of RP and DBSR since harvest of the previous season's maize provided suitable soil temperature and moisture conditions to increase the decomposition rate of straw (up to 81 % at the end of the season) at our study sites with 300–500 mm of rainfall; whether this technology can be implemented in more arid rainfed agriculture areas requires further investigation.

Table 3

Water use efficiency and precipitation utilization efficiency under conventional flat cultivation (CK), ridge–furrow plastic film mulch without straw return (RP − S), ridge–furrow plastic film mulch with straw return (RP + S) in three maize growing seasons (2016–2018).

Year	Treatment	Water consumption (mm)	Water use efficiency (kg·mm^{-1}·hm^{-2})	Precipitation during growing season (mm)	Precipitation utilization efficiency (kg·hm^{-2}·mm^{-1})	Yield (kg·hm^{-2})
2016	CK	467.27b	16.67c	436.9	17.96c	7841.96c
	RP − S	469.42a	25.2b	436.9	27.8b	11826.83b
	RP + S	475.22a	27.96a	436.9	30.37a	13269.26a
2017	CK	388.06b	25.4c	364	27.06c	11250.14c
	RP − S	419.59a	34.14b	364	39.36b	14405.33b
	RP + S	426.10a	37.1a	364	43.35a	15780.32a
2018	CK	469.5b	22.64b	471.4	22.55b	10631.1c
	RP − S	483.84a	35.34a	471.4	36.26a	17091.96b
	RP + S	510.23a	35.02a	471.4	37.73a	17785.05a

Table 4

Grain crude protein, grain nitrogen concentration, grain nitrogen content, and aboveground nitrogen accumulation under conventional flat cultivation (CK), ridge–furrow plastic film mulch without straw return (RP − S), ridge–furrow plastic film mulch with straw return (RP + S) in two maize growing seasons (2017–2018).

Year	Treatment	Crude protein (%)	Grain nitrogen content (%)	Grain nitrogen accumulation (t·hm^{-2})	Aboveground nitrogen accumulation (t·hm^{-2})
2017	CK	8.21c	1.46 c	0.20b	0.77a
	RP − S	8.34b	1.76 b	0.27a	0.94a
	RP + S	8.49a	1.99 a	0.28a	1.01a
2018	CK	8.52c	1.19 c	0.13c	0.88b
	RP − S	9.34b	1.37 b	0.23b	1.25a
	RP + S	9.54a	1.41 a	0.25a	1.12a

4.2. Combining RP with DBSR resulted in suitable nutrition conditions

Film mulching systems stimulate mineralization resulting in the loss of SOC (Hadden and Grelle, 2016; Lee et al., 2019; Yin et al., 2013). Indeed, in our study, the SOC content in the surface soil layer under RP was lower than that of CK at the end of the three maize growing seasons (Fig. 8). Previous studies have shown that crop residue incorporation into the soil is a suitable strategy for increasing soil organic matter contents in agricultural production systems (Malhi et al., 2012; Niu et al., 2011). In our study, after three years of continuous straw returning, the RP + S treatment had significantly higher SOC content in the surface soil than RP − S and CK; that is, straw buried into farmland acts as an important source of organic matter and soil organic carbon (Lu, 2015), suggesting that straw incorporation is an effective practice for improving soil fertility in semiarid regions of China.

Nitrogen immobilization during straw decomposition can cause microbes and crops to compete for available nitrogen in the soil, which in turn affects crop growth (Azam et al., 1991). However, our results showed that straw return did not affect crop nitrogen uptake (Table 4; Fig. 10); this may be related to the nitrogen application rate used in the experiment. In addition, the rate of straw decomposition in RP + S increased after seven months of fallow after harvest and could offer nitrogen to the soil, thereby increasing the crop's utilization of nitrogen from the straw (Fig. 7; Wang et al., 2018). Combining RP and DBSR increased grain nitrogen and crude protein contents to improve grain quality compared to CK. This result is consistent with those of straw return under no-tillage and conventional tillage (Vita et al., 2007). Soil total nitrogen content is a commonly used parameter for evaluating soil fertility (Huang et al., 2009). Tillage practices and cropping systems are often directly related to changes in soil nitrogen content in agricultural soils, and straw return is a positive and effective agriculture measure for improving soil structure (Zhang et al., 2009). In our study, RP + S had higher soil total nitrogen contents than RP − S treatments in the surface soil, while with no significant effect at deep layers.

4.3. Grain yield increased by combining RP with DBSR

The productivity of grain crops is affected by soil fertility in farmland on the Loess Plateau (Fan et al., 2005; Liu et al., 2010); some studies have shown that nutrient release from straw is slow in the field, and the effects of straw return on crop yield are not obvious in the short-term (Brunetto et al., 2011; Partey et al., 2011). Our results indicated that the improved soil hydrothermal conditions under DBSR combined with RP after the previous maize harvest facilitated aboveground maize growth, and lead to higher yields than RP − S and CK. In contrast, a previous study found that straw return without chemical fertilizers decreased maize yield (Wang et al., 2009). We added urea as an external source of nitrogen fertilizer and had similar results to other studies that added nitrogen fertilizer into straw return fields (Wang et al., 2015; Zhu et al., 2014).

5. Conclusions

The improper handling of maize straw can cause enormous environmental and production problem in China. Although returning straw to the field is a very effective and sustainable way, how to quickly decompose straw in arid and semi-arid regions where soil moisture is limited needs attention. To address the situation, we developed an innovative straw return technology, combining RP with DBSR, for a rainfed agricultural region on the Loess Plateau in northwestern China to decompose straw and minimize these issues. We found the composite technology significantly improved soil hydrothermal conditions and improved nutrient availability, which further enhanced crop growth and increased yields. We suggest that the combination of RP and DBSR is an effective agricultural management practice, which can be used in water-limited environments to promote the adoption of straw retention practice, thereby reducing regional environmental pressures caused by agricultural production residues on the Loess Plateau.

Declaration of Competing Interest

None.

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