Agricultural Water Management 171 (2016) 1–9

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Soil water storage and winter wheat productivity affected by soil surface management and precipitation in dryland of the Loess Plateau, China

Gang He[a,b], Zhaohui Wang[a,b,*], Fucui Li[a,b], Jian Dai[a,b], Qiang Li[a,b], Cheng Xue[a,b], Hanbing Cao[a,b], Sen Wang[a,b], Sukhdev S. Malhi[c]

[a] State Key Laboratory of Crop Stress Biology in Arid Areas, Northwest Agricultural and Forestry University, Yangling 712100, Shaanxi, China
[b] Key Laboratory of Plant Nutrition and the Agri-environment in Northwest China, Ministry of Agriculture/College of Natural Resources and Environment, Northwest Agricultural and Forestry University, Yangling 712100, Shaanxi, China
[c] Department of Renewable Resources, University of Alberta, Edmonton, Alberta, Canada

ARTICLE INFO

Article history:
Received 27 September 2015
Received in revised form 8 March 2016
Accepted 9 March 2016
Available online 16 March 2016

Keywords:
Grain yield
Rainfall harvest
Summer fallow
Plastic mulch
Straw retention
Planting legume

ABSTRACT

Because of asynchrony between the winter wheat growing season and precipitation, soil water supply is the main factor constraining winter wheat production. Hence, increasing soil water conservation is a crucial approach for improving winter wheat productivity in dryland. A 5-year-long, location-fixed field experiment was conducted to determine the effects of plastic mulch, straw retention, planting legume, and straw-legume on soil water and winter wheat grain yield. In comparison to the control, average rainfall harvest during summer fallow was increased by 9% by plastic mulch and mainly occurred in wet summers, and not affected by straw retention, but respectively decreased by 22% and 17% by planting legume and straw-legume. Average soil water storage at sowing was increased by 5% in plastic mulch and occurred in most summers, as well as also increased by 3% in straw retention but only occurred in one wet summer, and decreased by 5% in both planting legume and straw-legume and occurred in most cases. Average ET was not affected by plastic mulch and straw retention, but respectively decreased by 7% and 5% by planting legume and straw-legume. As a result, plastic mulch caused a 6% increase in the average grain yield of winter wheat, but straw retention, planting legume, and straw-legume decreased it by 8%, 6%, and 5%, respectively. Overall, plastic mulch is a beneficial measure for increasing rainfall harvest during summer fallow and soil water storage at sowing, and preferable for harvesting more grain yield, but the straw retention, planting legume and straw-legume showed hardly any benefit for grain yield of winter wheat in dryland.

1. Introduction

Wheat is a major global food crop, ranking third after maize and rice. Annual global wheat production is estimated to be 620 million Mg (Uauy et al., 2006), of which about 75% is from dryland agricultural areas (Li, 2004). Thus, dryland wheat production plays an important role in ensuring global food security. The Loess Plateau is a typical dryland agricultural area in China, where winter wheat is one of the main food crops and covers an area of 4.3 million ha, accounting for 20% of the total land. As almost no surface water is available and the underground water table is usually 50–80 m below the soil surface and thus too deep to use, precipitation is the sole water source for winter wheat and other crop production in most areas of the Loess Plateau. Therefore, the predominant constraining factor for winter wheat production is the limited and unevenly distributed annual precipitation (Wang et al., 2009), which is around 200–600 mm. Of this amount, 50–60% occurs between July and September and is concurrent with the summer fallow between two growing seasons of winter wheat. Another problem is the low water use of the crops, which is mainly due to the inefficient rainfall harvest and high soil water loss by evaporation (Kang et al., 2002). Similar prob-

* Corresponding author at: College of Natural Resources and Environment, Northwest Agricultural and Forestry University, Yangling 712100, Shaanxi, China.
E-mail address: w-zhaohui@263.net (Z. Wang).

http://dx.doi.org/10.1016/j.agwat.2016.03.005
0378-3774/

lems also exist in other dryland regions of the world (Ciais et al., 2005).

Soil surface management is an effective approach for reducing soil water evaporation, increasing soil water storage, and improving crop productivity in dryland. Mulching the soil surface with plastic film has become a widely used method to improve crop productivity in drylands (Xie et al., 2005), including mulching all of the soil surface or part of it (mulching on the ridges and seeding in the furrows) during all or part of the growing season (Li et al., 1999). Plastic mulch typically decreases soil water loss by evaporation, increases crop transpiration (Wang et al., 2009), and thus successfully promotes crop growth and increases crop yield. Owing to plastic mulch applications, spring wheat grain yield was increased by 23% in the west of Loess Plateau (Li et al., 1999) and winter wheat grain yield was increased by 30% in the middle part of Loess Plateau (Zhang et al., 2013). However, additional information is needed, regarding whether plastic mulch always increases crop yields under different precipitation levels. Mulching the soil surface with crop straw is another method to increase soil water retention and promote crop growth, owing to its effective role in controlling soil water evaporation (Salado-Navarro et al., 2013). Wheat straw retention during the maize growing season resulted in a 10% increase in the grain yield in Uzbekistan (Devkota et al., 2013). However, maize straw retention during the wheat growing season had no effect on wheat grain yield in Mexico (Verhulst et al., 2011), and it even decreased the wheat grain yield by 7% in the North China Plain (Chen et al., 2007). However, most studies have mainly focused on straw retention during the crop growing season. Information about the use of straw retention during the fallow season, especially in the rainy summer fallow season before winter wheat sowing, is still sparse. In addition, covering the soil surface with legumes and non-legumes not only lowers the risks of soil erosion during the rainy season (Tonitto et al., 2006), but also reduces soil water evaporation (Alliaume et al., 2014). Owing to planting hairy vetch during the fallow season, sorghum grain yield was increased by 45% in southeastern United States (Sainju et al., 2006). However, wheat grain yield was not affected by planting black bean in northwestern China (Zhang et al., 2009), and even decreased by 73% owing to planting winter pea, filed pea, and hairy vetch during the fallow season in the middle of United States (Nielsen and Vigil, 2005). The effects of planting cover crop during the fallow season on grain yield varied with regions, but it is still unknown in the Loess Plateau under different precipitation levels.

The fallow season is an important time for soil to restore the water that was consumed by crop during the previous growing season. Therefore, increased rainfall harvest during the fallow season and soil water storage at sowing is important for crops in the next growing season. However, water management is usually overlooked during the fallow season, when the cropland is typically left in bare fallow conditions without crop cover or other materials, especially in the Loess Plateau (Zhang et al., 2007). Under the bare fallow conditions, rainfall harvest during the summer fallow is generally low due to the high soil water evaporation under high air temperature and runoff caused by heavy rainfall over short time periods. Therefore, water management during the summer fallow should receive more attention, and year-round water management is of great significance for winter wheat production in drylands. Mulching the soil surface with different materials or cover crops is a practical measure to regulate soil water, promote crop growth, and obtain a good harvest. In this study, we used a 5 year long, randomized complete block-design, location-fixed field experiment in a typical dryland region of the Loess Plateau to determine the soil water storage and winter wheat grain yield affected by different soil surface managements and their responses to precipitation.

2. Materials and methods

2.1. Experimental site

The experiment was initiated in September 2008 and lasted for five consecutive years until September 2013 at Shilipu (35°12′N, 107°45′E), Changwu County, Shaanxi Province, which is a typical dryland and rainfed agricultural area in the central part of the Loess Plateau, China. In this area, the altitude is 1200 m above sea level and the underground water table is around 50–80 m, which means that groundwater is unavailable for crop growth. At the experimental site, the annual average temperature is 9.1 °C and the average annual precipitation (1957–2013) is 579 mm, about 55% of which occurs in the summer from late June to mid September. Winter wheat and spring maize are the major local cereal crops, and each is harvested once per year. Winter wheat is usually sown in late September or early October, and it is harvested in middle or late June of the following year. The experimental field had been used for winter wheat production for a long time prior to this experiment. The soil is loess-derived and classified as a silt loam texture according to the US Department of Agriculture (USDA) soil classification system, and its basic properties in the top 0–40 cm layer are measured with the methods described by Bao (2007) and presented in Table 1.

2.2. Experimental design and management

The experiment included five soil surface management practices in each year: (1) control (the local conventional practice), (2) plastic mulch, (3) straw retention, (4) planting legume, and (5) straw-legume (Fig. 1). In the control, the soil surface was prepared with no mulching and winter wheat was sown with the conventional flat planting, and all the straw was removed from the field at the harvest of winter wheat, and the soil was ploughed to a depth of 40 cm about two weeks after the harvest, and the soil surface was under bare fallow conditions during the summer fallow. In the plastic mulch, the soil surface was formed into alternating ridges and furrows using a plastic mulch machine before winter wheat sowing. The ridges were mulched with clear plastic film (thickness = 0.008 mm) during winter wheat growing season and the furrows were left uncovered for seeding. During the summer fallow, clear plastic film was still left on the ridge continuously along with all the wheat stubble and crushed straw returned to the furrow to cover the soil surface. Until the end of summer fallow (2–3 weeks before the next winter wheat sowing), the plastic film was removed from the field. For the straw retention, planting legume, and straw-legume, the soil surface was prepared and winter wheat was sown as same as the control during winter wheat growing season. In the straw retention, all the wheat stubble and crushed straw was returned to cover the soil surface during the summer fallow. In the planting legume, all the straw was removed from the field at winter wheat harvest and "Huaidou" (a widely used local soybean cultivar (*Glycine max* L. Merr.)) was seeded at a rate 150 kg ha^{-1} as a cover crop. Until the end of summer fallow, the soybean was mowed and chopped into less than 5 cm segments. The straw-legume during the summer fallow combined the straw retention and planting legume, i.e., wheat straw was treated as same as the straw retention and soybean was sown as same as the planting legume. At the end of summer fallow, the soil in the plastic mulch, straw retention, planting legume, and straw-legume were ploughed to a depth of 40 cm, at the same time straw and/or legume on the soil surface were incorporated evenly into soil using a plow.

Table 1
Basic physical and chemical properties of the 0–40 cm soil sampled from the experimental field at sowing of winter wheat in 2008.

Soil layer (cm)	Bulk density ($g\,cm^{-3}$)	Organic C ($g\,kg^{-1}$)	Total N ($g\,kg^{-1}$)	Available P ($mg\,kg^{-1}$)	Available K ($mg\,kg^{-1}$)	pH (H_2O)	Mineral N	
							NO_3^- –N ($mg\,kg^{-1}$)	NH_4^+-N ($mg\,kg^{-1}$)
0–20	1.4	8.5	0.77	4.5	130	8.2	13.1	2.6
20–40	1.3	6.3	0.58	1.6	122	8.2	8.6	1.8

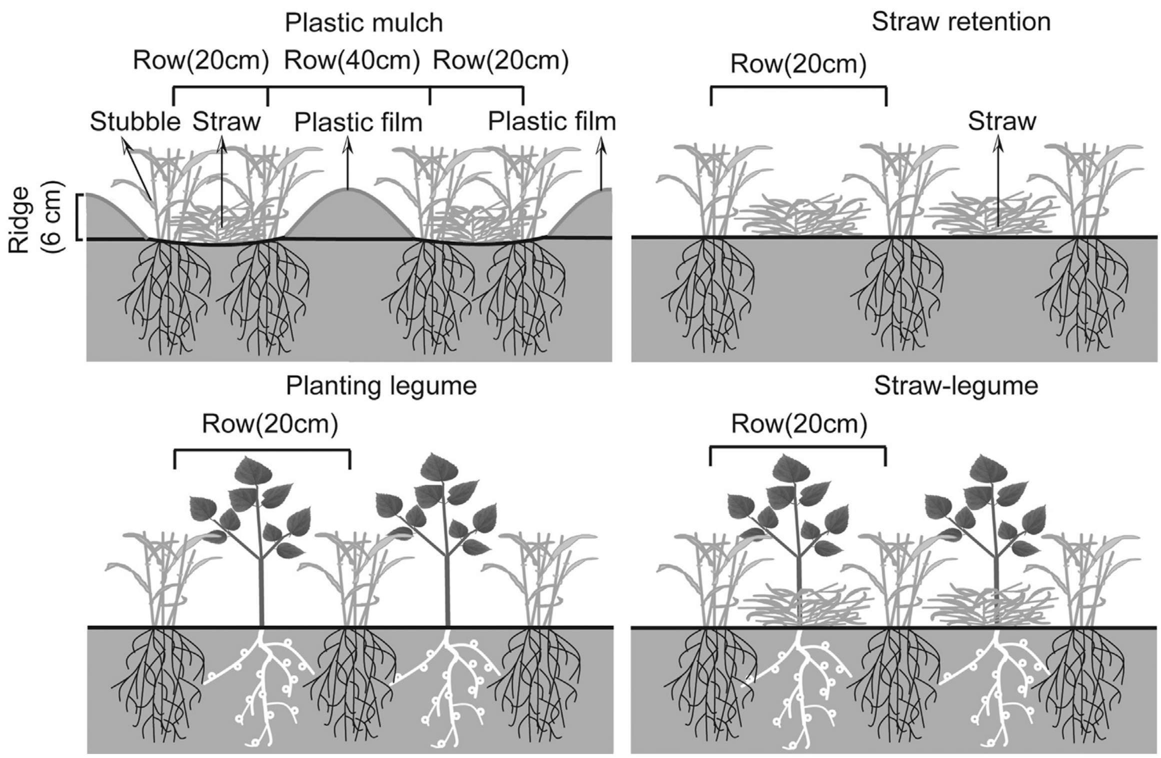

Fig. 1. Schematic diagram showing the treatments of plastic mulch, straw retention, planting legume, and straw-legume in the field experiment from 2008 to 2013.

Table 2
Seeding and harvest times for soybean and winter wheat, and N from soybean return to soil in the field experiment from 2008 to 2013.

Items	2008	2009	2010	2011	2012	2013
Sowing time of soybean	–	27 Jun	1 Jul	30 Jun	2 Jul	16 Jun
Harvest time of soybean	–	23 Sep	11 Sep	1 Sep	3 Sep	1 Sep
Harvest time of wheat	–	22 Jun	28 Jun	27 Jun	30 Jun	14 Jun
Sowing time of wheat	23 Sep	2 Oct	22 Sep	23 Sep	22 Sep	28 Sep
Dry weight of soybean ($Mg\,ha^{-1}$)	–	1.40	3.18	3.81	4.19	4.00
N from soybean returned to soil ($kg\,N\,ha^{-1}$)	–	42.2	85.5	96.0	114.2	100.3

Table 2 shows the average dry matter and N contents of the soybean returned to the soil. Then, soil in each plot was mixed with basal fertilizers and flattened with a rotary tiller. Each treatment was replicated four times in a randomized complete block-design, and the plot size was 22 m × 6 m.

The N and P fertilizer application rates were calculated based on the relevant available soil nutrients and the target winter wheat grain yield of the control with the method proposed by Zhang et al. (2012). The N and P rates were 138 kg N ha^{-1} and 105 kg P_2O_5 ha^{-1} for all the plots in 2008–2009 and 2009–2010, and 150 kg N ha^{-1} and 105 kg P_2O_5 ha^{-1} in 2010–2011, 2011–2012, and 2012–2013, respectively. In the first four experimental years, three fourths of the N fertilizer was applied as basal fertilizer two weeks before winter wheat sowing, and the remaining N fertilizer was applied with the top-dressing method into the 0–10 cm soil layer by opening a narrow furrow between the crop rows when the frozen soil melted in the early spring (20 February 2009, 8 March 2010, 5 March 2011, and 18 March 2012, respectively). All the N fertilizer in 2012–2013 and all the P fertilizer in each year was applied before winter wheat sowing. The N fertilizer was supplied as urea, and the P fertilizer was supplied as triple superphosphate. Since the soil is sufficient in available K, no K fertilizer was applied.

Winter wheat was sown at a rate of 150 kg ha^{-1} for all the treatments, and its variety was a widely used local cultivar "Changwu521". The crop was grown using natural precipitation without any supplemental irrigation during the five experimental years. Herbicide was used early in the reviving stage of winter wheat every year to control weeds.

2.3. Sampling and measurements

2.3.1. Winter wheat

The winter wheat was harvested using a combined harvester, and fresh weight of grain from each plot was weighed in the field, and ~1 kg of grain from each plot was sampled and oven dried to calculate the water content of the fresh grain. The grain yield was expressed as dry weight and calculated from the fresh grain weight from each plot and its water content.

2.3.2. Soybean

Just before it was mowed at flowering, five to ten soybean plants were sampled randomly from each plot, and separated into stems and roots. After being washed, air-dried and weighed, subsamples of 100 g stems and 10 g roots were oven dried at 90 °C for 30 min and at 70 °C for 48 h for the dry weight and biomass calculation, and determination of the plant N concentration and N uptake.

2.3.3. Soil

Five soil cores at depths of 0–40 cm with 10 cm increments and two soil cores at depths of 40–300 cm with 20 cm increments were collected with an auger (inner diameter 4 cm) from each plot at the time of winter wheat sowing and harvest. Soil from the same layer in each plot was merged, and ~500 g of thoroughly mixed soil was collected as a sample for the soil analyses. The soil water content for each sample was determined gravimetrically after oven drying the soil samples at 105 °C for 24 h.

2.4. Data calculation

2.4.1. Soil water storage

Soil water storage (WS, mm) was calculated as (Wu et al., 2015):

$$WS = \sum_{i}^{n} \rho_i \times \mathrm{h}_i \times \mathrm{w}_i \times 10/100,$$

where, ρ_i(g cm^{-3}) is soil bulk density; h_i(cm) is soil layer depth; w_i(%) is soil water content on a gravimetric basis; n is the number of soil layer; $i = 20, 40, 60, \ldots, 300$.

2.4.2. Rainfall harvest

Rainfall harvest (RH, mm) in soil during the summer fallow was calculated as (Li et al., 2014):

$$\mathrm{RH} = \mathrm{WS}_2 - \mathrm{WS}_1,$$

where, WS_2 is the soil water storage in the 0–300 cm soil layer at winter wheat sowing for the subsequent growing season at the end of summer fallow and WS_1 is the soil water storage in the 0–300 cm soil layer at winter wheat harvest of the previous growing season, when is the start of the summer fallow.

2.4.3. Evapotranspiration

Evapotranspiration (ET, mm) for each growing season of winter wheat was determined as (Huang et al., 2008):

$$\mathrm{ET} = \mathrm{P} + \Delta\mathrm{WS},$$

Where, P is the effective precipitation (mm) during the winter wheat growing season, obtained from a standard rain gauge installed at the experimental site, and ΔWS is the change of soil water storage (mm) in the 0–300 cm soil layer between sowing and harvest of one cropping season.

2.5. Statistical analyses

The statistical analyses were conducted using the SAS software package. The significance of the effect from the treatments each year was evaluated with a one-way analysis of variance (ANOVA). A two-way ANOVA was used to determine the significance of the main factors (treatment, year) on the average values from all years. When the ANOVA results were significant, the least significant difference(LSD) test was used to determine the significance of the difference between means with a significance level of $P < 0.05$.

3. Results

3.1. Precipitation

In the Loess Plateau, a typical rainfed dryland, the annual precipitation was unevenly distributed over the years. Over the five experimental years, the annual precipitation, including that occurring during the summer fallow before winter wheat sowing and that during the crop growing season was 513, 475, 666, 722 and 447 mm during 2008–2009, 2009–2010, 2010–2011, 2011–2012 and 2012–2013, respectively (Fig. 2). Based on the Generalized Precipitation Classification Scheme (Sun et al., 2010) and the yearly average precipitation during summer fallow or wheat growing season at the experimental site over the past 56 years from 1957 to 2013, the summer fallow before winter wheat sowing in 2008–2009, 2009–2010 and 2012–2013 was categorized as dry, that in 2013–2014 was normal, and that in 2010–2011 and 2011–2012 was wet; the winter wheat growing season in 2009–2010, 2010–2011 and 2012–2013 was categorized as dry, and that in 2008–2009 and 2011–2012 was normal (Table 3).

3.2. Rainfall harvest during the summer fallow

As the field experiment initiated in September 2008, rainfall harvest values were only obtained for the experimental years after 2008–2009. Compared with the control, the yearly averages show that the rainfall harvest was increased by 9% by the plastic mulch, but not affected by the straw retention, and decreased by 22% and 17% by the planting legume and straw-legume, respectively (Table 4). However, due to the variance in summer rainfall each year, the effects of the soil surface managements on rainfall harvest varied yearly. During the wet summers, plastic mulch and straw retention increased rainfall harvest by 22% and 21% in 2010–2011, and by 13% and 8% in 2011–2012, respectively. Plastic mulch had no effect on rainfall harvest during the dry and normal summers. Straw retention decreased the rainfall harvest by 34% in the dry summer of 2012–2013, although it had no effect in the other dry summer of 2009–2010 or the normal summer of 2013–2014. During both dry and normal summers, planting legume and straw-legume respectively decreased rainfall harvest by 23% and 15% in 2009–2010, and by 58% and 46% in 2012–2013, and by 57% and 56% in 2013–2014. In the wet summer of 2010–2011, planting legume increased the rainfall harvest, whereas straw-legume showed no effect. In the other wet summer of 2011–2012, planting legume decreased the rainfall harvest by 13%, though straw-legume had no significant effect.

3.3. Soil water storage at winter wheat sowing

In comparison with the control, the yearly average soil water storage at sowing was significantly increased by 5% and 3% in the plastic mulch and straw retention, but decreased by 5% in both the planting legume and straw-legume (Table 5). Moreover, the results also varied with year. Plastic mulch increased the soil water storage by 6%, 5%, 5%, and 7% in 2010–2011, 2011–2012, 2012–2013, and 2013–2014, but no change was measured during the dry summer of

Table 3
Precipitation of summer fallow and growing season in the field experiment from 2008 to 2014.

Precipitation	2008–2009	2009–2010	2010–2011	2011–2012	2012–2013	2013–2014
Summer fallow	270 (Dry)[a]	280 (Dry)	458 (Wet)	453 (Wet)	285 (Dry)	332 (Normal)
Growing season	243 (Normal)[b]	195 (Dry)	208 (Dry)	269 (Normal)	162 (Dry)	–

[a] Precipitation amount of summer fallow (precipitation status).
[b] Precipitation amount of growing season (precipitation status).

Table 4
Rainfall harvest (mm) in the 0–300 cm soil layer affected by different soil surface managements during summer fallow in the field experiment from 2009 to 2014.

Soil surface managements	2009–2010	2010–2011	2011–2012	2012–2013	2013–2014	Average
Control	132 ± 15(23)ab[§]	227 ± 10(9)c	259 ± 12(9)b	117 ± 15(26)a	178 ± 15(17)a	183 ± 5(5)b
Plastic mulch	145 ± 7(10)a	277 ± 10(7)a	294 ± 5(3)a	99 ± 6(12)ab	178 ± 7(8)a	198 ± 3(3)a
Straw retention	128 ± 5(9)ab	274 ± 6(4)a	281 ± 7(5)a	77 ± 15(39) bc	160 ± 20(26)a	184 ± 4(4)b
Planting legume	101 ± 5(9)c	256 ± 12(9) ab	226 ± 6(5)c	50 ± 11(45)d	76 ± 8(22)b	142 ± 4(6)c
Straw-legume	112 ± 2(4)bc	249 ± 12(10) bc	254 ± 4(3)b	63 ± 8(24)cd	79 ± 5(13)b	152 ± 2(3)c
Average	124 ± 3B	257 ± 7A	263 ± 5A	81 ± 10C	134 ± 6B	
$LSD_{0.05}$ for treatment	26	24	18	22	39	13
$LSD_{0.05}$ for year	21					
Precipitation status of summer	Dry	Wet	Wet	Dry	Normal	
F Values of variance analysis						
Year	334**					
Treatment	28**					
Year × Treatment	5**					

Data are given as the average of 4 replications. Different lowercase letters after the parenthesis in the same column and different upper case letters after the data in the same row indicate significant differences among treatments at P < 0.05.
[§] Average value ± standard error (coefficient of variation).

2009–2010. In contrast, straw retention only significantly increased the soil water storage by 3% in the wet summer of 2011–2012. Planting legume and straw-legume decreased the soil water storage by 3% and 4% in the wet summer of 2011–2012, by 8% and 6% in the dry summer of 2012–2013, and by 13% and 12% in the normal summer of 2013–2014, respectively, but caused no effects in 2009–2010 or 2010–2011.

3.4. Evapotranspiration (ET) during the growing season

The yearly averages showed that the ET was decreased by 7% and 5% in the planting legume and straw-legume, but not affected by the plastic mulch and straw retention (Table 6). Planting legume and straw-legume decreased the ET by 9% and 9% in the normal growing season of 2011–2012, and by 21% and 19% in the dry season of 2012–2013, respectively, but did not significantly affect it in other years. In contrast to averages, plastic mulch increased the ET by 6% and 10% in the dry growing seasons of 2009–2010 and 2010–2011, respectively. Straw retention also increased the ET by 7% in the dry growing season of 2009–2010.

3.5. Grain yield

In comparison with the control, the yearly average grain yield over the study period was increased by 6% in the plastic mulch, and respectively decreased by 8%, 6%, and 5% in the straw retention, planting legume, and straw-legume (Table 7). The results also varied with year. The grain yield was increased by 44%, 8% and 13% for the plastic mulch in 2008–2009, 2009–2010 and 2010–2011, respectively, and not affected in 2011–2012, whereas decreased

Table 5
Soil water storage (mm) in the 0–300 cm soil layer at sowing of winter wheat affected by different soil surface managements during summer fallow in the field experiment from 2009 to 2014.

Soil surface managements	2009–2010	2010–2011	2011–2012	2012–2013	2013–2014	Average
Control	516 ± 5(2)ab[§]	649 ± 6(2)b	736 ± 9(2)b	585 ± 17(6)b	599 ± 10(3)b	617 ± 5(2)c
Plastic mulch	523 ± 7(3)a	687 ± 5(1)a	771 ± 11(3)a	613 ± 4(1)a	642 ± 7(2)a	647 ± 5(1)a
Straw retention	516 ± 9(3)ab	676 ± 11(3)ab	761 ± 5(1)a	588 ± 14(5)ab	624 ± 23(7)ab	633 ± 6(2)b
Planting legume	501 ± 10(4)b	664 ± 11(3)ab	713 ± 3(1)c	541 ± 10(4)c	521 ± 3(1)c	588 ± 4(1)d
Straw-legume	500 ± 6(2)b	655 ± 12(4)b	708 ± 3(1)c	550 ± 3(1)c	528 ± 6(2)c	588 ± 1(1)d
Average	511 ± 6D	666 ± 4B	738 ± 5A	575 ± 8C	583 ± 6C	
$LSD_{0.05}$ for treatment	18	30	18	27	37	12
$LSD_{0.05}$ for year	22					
Precipitation status of summer	Dry	Wet	Wet	Dry	Normal	
F Values of variance analysis						
Year	415**					
Treatment	37**					
Year × Treatment	4**					

Data are given as the average of 4 replications. Different lowercase letters after the parenthesis in the same column and different upper case letters after the data in the same row indicate significant differences among treatments at P < 0.05.
[§] Average value ± standard error (coefficient of variation).
** P < 0.01.

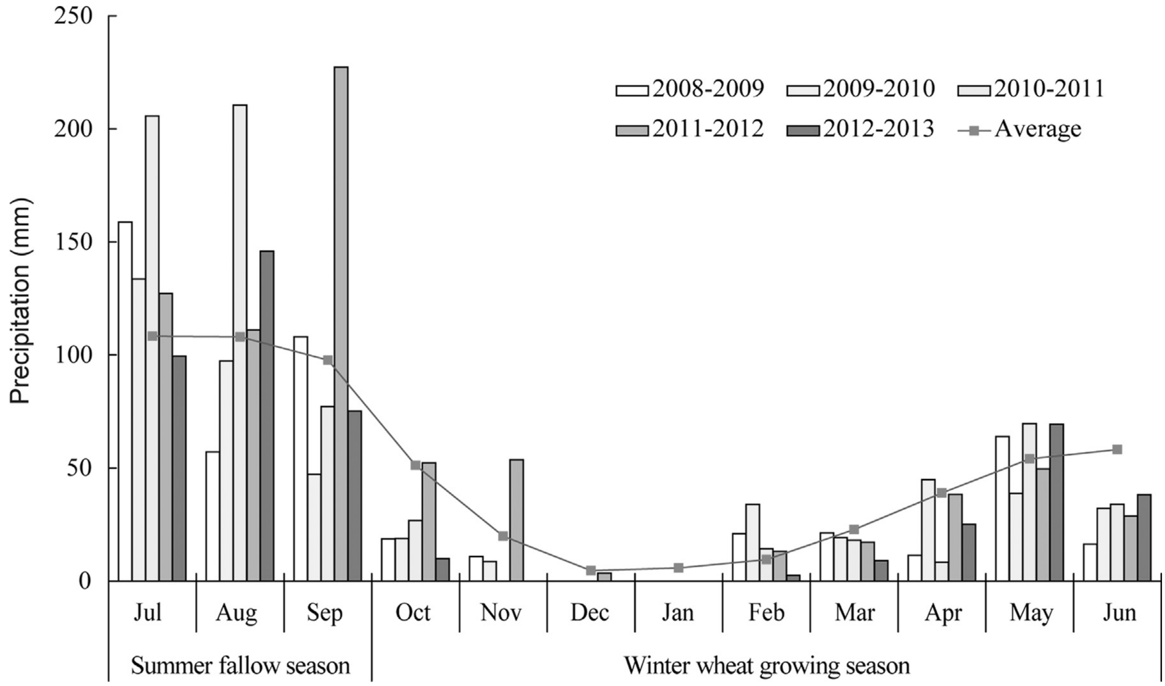

Fig. 2. Distribution of the monthly precipitation at the experimental site over the 5 year experiment (2008–2013).
Note: Source of precipitation data (2008–2013): Changwu Agro-ecological Experimental Station of the Loess Plateau of the Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources. Average means the long term monthly average of precipitation from 1957 to 2013, and the data source is China meteorological data sharing service system.

Table 6
ET of winter wheat (mm) affected by different soil surface managements during summer fallow in five experimental years from 2008 to 2013.

Soil surface managements	2008–2009	2009–2010	2010–2011	2011–2012	2012–2013	Average
Control	366 ± 16(9)a[§]	290 ± 5(3)b	379 ± 7(4)b	537 ± 6(2)a	325 ± 27(16)a	379 ± 5(3)a
Plastic mulch	378 ± 16(9)a	308 ± 2(1)a	418 ± 8(4)a	525 ± 6(2)a	310 ± 6(4)a	388 ± 4(2)a
Straw retention	357 ± 7(4)a	309 ± 7(4)a	404 ± 10(5)ab	518 ± 10(4)a	286 ± 30(21)ab	375 ± 6(3) ab
Planting legume	357 ± 7(4)a	288 ± 5(3)b	385 ± 14(7)ab	491 ± 4(2)b	258 ± 13(10)b	355 ± 3(1)c
Straw-legume	357 ± 7(4)a	290 ± 2(2)b	409 ± 11(5)ab	490 ± 7(3)b	262 ± 7(5)b	362 ± 2(1)bc
Average	363 ± 6C	297 ± 3D	399 ± 3B	512 ± 4A	288 ± 15D	
$LSD_{0.05}$ for treatment	33	12	34	19	44	15
$LSD_{0.05}$ for year	17					
Precipitation status of growing season	Normal	Dry	Dry	Normal	Dry	
F Values of variance analysis						
Year	305[**]					
Treatment	6[**]					
Year × Treatment	1					

Data are given as the average of 4 replications. Different lowercase letters after the parenthesis in the same column and different upper case letters after the data in the same row indicate significant differences among treatments at $P < 0.05$.
[§] Average value ± standard error (coefficient of variation).
[**] $P < 0.01$.

by 16% in 2012–2013. For the straw retention, the grain yield was decreased by 8% in 2011–2012, and by 24% in 2012–2013, but not affected in other years. Planting legume decreased the grain yield by 12% and 37% in 2009–2010 and 2012–2013, respectively, but did not significantly affect in other years. The straw-legume showed no significant effects on the grain yield in any year except for the 2012–2013, when it was decreased by 31%.

4. Discussion

4.1. Soil water storage and rainfall harvest

Soil water consumption by winter wheat during the growing season is mainly derived from the soil water storage at sowing due to lower precipitation during the growing season. Hence, increasing soil water storage at sowing is crucial for subsequent winter wheat growth. In the present study, plastic mulch increased soil water storage at sowing in most cases. Similarly, plastic mulch during the winter and early spring fallow also increased soil water storage at spring maize sowing in northwestern China (Fan et al., 2005). Increasing rainfall harvest during fallow season is a crucial approach to increase soil water storage at sowing. In a spring maize-fallow cropping system, plastic mulch during the winter and early spring fallow increased rainfall harvest in western China (Liu et al., 2009). In the present study, the increased rainfall harvest by plastic mulch mainly included three reasons. Firstly, residual plastic film on the ridge soil can help the water from rainfall flow into the furrow, where the soil surface is covered with straw, and this can give more time for the water to penetrate into the soil before being evaporated. Secondly, plastic film on the ridge soil and straw retention on the furrow soil insulated the soil surface, constrained the water

Table 7
Grain yield of winter wheat (kg ha^{-1}) affected by different soil surface managements during summer fallow in five experimental years from 2008 to 2013.

Soil surface managements	2008–2009	2009–2010	2010–2011	2011–2012	2012–2013	Average
Control	3301 ± 162(10)b§	3365 ± 203(12)ab	5070 ± 68(3)b	7639 ± 98(3)ab	3877 ± 205(11)a	4651 ± 111(5)b
Plastic mulch	4741 ± 201(8)a	3646 ± 122(7)a	5751 ± 162(6)a	7278 ± 218(6)bc	3243 ± 80(5)b	4932 ± 105(4)a
Straw retention	3342 ± 188(11)b	3145 ± 86(5)bc	5021 ± 50(2)b	7032 ± 239(7)c	2931 ± 181(12)bc	4294 ± 86(4)c
Planting legume	3342 ± 188(11)b	2973 ± 123(8)c	4958 ± 49(2)b	8086 ± 291(7)a	2448 ± 100(8)d	4361 ± 47(2)c
Straw-legume	3342 ± 188(11)b	3067 ± 197(13)bc	5190 ± 70(3)b	7712 ± 59(2)ab	2673 ± 58(4)cd	4397 ± 63(3)c
Average	3614 ± 184C	3239 ± 106D	5198 ± 36B	7549 ± 109A	3035 ± 73D	
$LSD_{0.05}$ for treatment	92	380	286	583	402	200
$LSD_{0.05}$ for year	318					
F Values of variance analysis						
Year	713**					
Treatment	14**					
Year × Treatment	7**					

Data are given as the average of 4 replications. Different lowercase letters after the parenthesis in the same column and different upper case letters after the data in the same row indicate significant differences among treatments at $P < 0.05$.

§ Average value ± standard error (coefficient of variation).

** $P < 0.01$.

exchange between the soil and air, and thus decreased soil water loss by evaporation. Thirdly, the straw mulch can also improve the soil properties and then soil water transmission by improving water infiltration, saturated hydraulic conductivity, and soil water sorptivity (Blanco-Canqui and Lal, 2007), although its contribution may be poor, since the field experiment is only five years old.

In the present study, straw retention also increased soil water storage. As previously reported, wheat straw retention during the summer fallow increased soil water storage in the North China Plain (Su et al., 2007). Similar to the plastic mulch, increased soil water storage by the straw retention was still owing to the increased rainfall harvest, which was cause by the decreased soil water evaporation and improved soil properties. Importantly, increasing soil water storage and rainfall harvest by straw retention was more efficient in wet summers than in dry and normal summers. Similar result has been reported by Zhang et al. (2007). The reason for this may be that more water can pass through the straw residual on the soil surface and penetrate into the soil in wet summers.

In the present study, soil water storage was reduced by the planting legume and straw-legume. Similarly, Aboudrare et al. (2006) in Morocco and Ward et al. (2012) in Australia showed that planting cover crops during the fallow season decreased the soil water storage owing to the low rainfall. The viewpoint was also applicative in the present study. In addition, the reduced rainfall harvest was another important reason. Similarly, Gabriel et al. (2012) also reported that planting barley during the fallow season after maize harvest reduced rainfall harvest. The reduced rainfall harvest was explained by the extra soil water consumption from transpiration by legume growth; even though the plants were able to shade the soil surface and decrease the soil water evaporation to some extent. The effect of straw-legume on conserving soil water was better than that of planting legume, especially in wet summers. This indicates that additional straw retention combined with planting legume may increase rainfall harvest and mitigate soil water loss by decreasing soil surface evaporation.

4.2. Evapotranspiration

Although the plastic mulch and straw retention did not affect the average ET, they did increase the ET during the dry growing seasons, especially in the plastic mulch. During the dry winter wheat growing season, plastic mulch in the experiment nearby (Chen et al., 2015) and straw retention in the North China Plain (Su et al., 2007) increased the ET, owing to greater soil water storage before jointing and little rainfall from jointing to maturity stage. In the present study, the increased ET was explained by the enhanced plant growth owing to higher soil water storage at sowing, as described by Li et al. (2004). The present work shows that planting legume and straw-legume decreased the ET of winter wheat. During the summer fallow, planting bean in the Loess Plateau (Zhang et al., 2007) and planting sunn hemp in southeastern US (Muñoz-Carpena et al., 2008) decreased the ET of subsequent crop. Planting legume and straw-legume decreased the ET can be explained by the lowered soil water storage at sowing, which resulted in less available soil water supply during the growing season, and thus decreased water evaporation from the soil surface and limited the transpiration of winter wheat.

4.3. Yield

In the present study, plastic mulch increased the grain yield in most years. Similarly, owing to plastic mulch only during the growing season, maize grain yield was increased by 20% in northwestern China (Liu et al., 2010) and wheat grain yield was increased by 5% in Pakistan (Rehman et al., 2009). These grain yield increases are lower than that in the present work from 2008 to 2010 (6% and 21% respectively). This can be explained by the increased soil water storage at sowing and then ET due to the extra plastic mulch during summer fallow and growing season, as higher soil water storage at sowing or ET is usually accompanied by higher grain yield (Zhang et al., 2013). However, plastic mulch did not always increase the grain yield. The year of 2011–2012 was characterized by plenty of summer rainfall and the highest growing season precipitation over the five years. In this year, whether or not plastic mulch, water was no longer the limiting factor for winter wheat production, hence plastic mulch did not affect the grain yield. Also, the year of 2012–2013 exhibited not only lower summer rainfall but also less precipitation during growing season, when the precipitation between the sowing and early grain-filling stage was very lower, only 47 mm, which was 70% lower than the long-term average (153 mm, the 56-year average). The serious water stress during this key growing stage should be the key reason for the deceased yield by decreased heading, grain forming and filling under the plastic mulch.

In the present study, straw retention reduced the grain yield, and occurred in the latter two experimental years. Similarly, straw retention also decreased spring barley yield due to higher precipitation and poor germination in Norway (Borresen, 1999). Our previous study also indicated that grain yield of winter wheat may be decreased if N fertilizer application rate was less than 187 kg N ha^{-1} in northwestern China (Huang et al., 2015). In the present study, the grain yield decrease by the straw retention can be attributed to insufficient soil N supply (Li et al., 2014), owing to the increased soil N bio-immobilization from continuous straw residue incorporation and the lack of synchrony between release of soil bio-immobilized N and crop demand for N during the growing season (Limon-Ortega et al., 2008).

Planting legume and straw-legume also reduced the grain yield, and mainly occurred in serious dry year of 2012–2013. In this year, the summer and growing season precipitation was limited, and the decreased grain yield was able to be explained by the decreased rainfall harvest, soil water storage, and then ET, a similar result was reported by Roper et al. (2012). In addition, the precipitation distribution is also a key factor affecting the response of winter wheat grain yield to planting legume and straw-legume. Grain yield was not affected during years when adequate rainfall occurred in the summer before winter wheat sowing. This indicates that adequate rainfall in summer can mitigate the negative impacts on grain yield caused by planting legume and straw-legume.

5. Conclusion

The grain yield of winter wheat and soil water were significantly affected by soil surface managements. Compared with the control, plastic mulch increased rainfall harvest during summer fallow and soil water storage at sowing, even ET in dry growing season, and thus increased the grain yield in most cases. However, plastic mulch had the risk of reducing grain yield in drier years or when extremely dry situations occur in the early growing season. Although straw retention also increased the rainfall harvest and soil water storage in wet summers, even increased the ET in dry growing season, it did not increase grain yield in all years. Planting legume and straw-legume did not show any benefit for rainfall harvest, soil water storage, ET, and grain yield. In conclusion, plastic mulch is a preferable measure for the increased soil water storage and grain yield in dryland.

Acknowledgements

This work was supported by National Key Basic Research Special Funds under Grant (2015CB150404), China Agricultural Research System (CARS—3-1-31), Special Fund for Agro-scientific Research in the Public Interest under Grant (201303104, 201103003), Agricultural Scientific Research Talent and Team Program, and National Natural Science Foundation of China (NSFC, 41401330).

References

Aboudrare, A., Debaeke, P., Bouaziz, A., Chekli, H., 2006. Effects of soil tillage and fallow management on soil water storage and sunflower production in a semi-arid Mediterranean climate. Agric. Water Manage. 83, 183–196.
Alliaume, F., Rossing, W.A.H., Tittonell, P., Jorge, G., Dogliotti, S., 2014. Reduced tillage and cover crops improve water capture and reduce erosion of fine textured soils in raised bed tomato systems. Agric. Ecosyst. Environ. 183, 127–137.
Bao, S.D., 2007. Soil and Agricultural Chemistry Analysis. China Agricultural Press, Beijing (in Chinese).
Blanco-Canqui, H., Lal, R., 2007. Impacts of long-term wheat straw management on soil hydraulic properties under no-tillage. Soil Sci. Soc. Am. J. 71, 1166–1173.
Borresen, T., 1999. The effect of straw management and reduced tillage on soil properties and crop yields of spring-sown cereals on two loam soils in Norway. Soil Tillage Res. 51, 91–102.
Chen, S.Y., Zhang, X.Y., Pei, D., Sun, H.Y., Chen, S.L., 2007. Effects of straw mulching on soil temperature, evaporation and yield of winter wheat: field experiments on the North China Plain. Ann. Appl. Biol. 150, 261–268.
Chen, Y.L., Liu, T., Tian, X.H., Wang, X.F., Li, M., Wang, S.X., Wang, Z.H., 2015. Effects of plastic film combined with straw mulch on grain yield and water use efficiency of winter wheat in Loess Plateau. Field Crop Res. 172, 53–58.
Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, C., Carrara, A., 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437, 529–533.
Devkota, M., Martius, C., Lamers, J.P.A., Sayre, K.D., Devkota, K.P., Gupta, R.K., Egamberdiev, O., Vlek, P.L.G., 2013. Combining permanent beds and residue retention with nitrogen fertilization improves crop yields and water productivity in irrigated arid lands under cotton wheat and maize. Field Crop Res. 149, 105–114.
Fan, T.L., Stewart, B., Payne, W.A., Wang, Y., Song, S.Y., Luo, J., Robinson, C.A., 2005. Supplemental irrigation and water–yield relationships for plasticulture crops in the Loess Plateau of China. Agron. J. 97, 177–188.
Gabriel, J.L., Muñoz-Carpena, R., Quemada, M., 2012. The role of cover crops in irrigated systems: Water balance, nitrate leaching and soil mineral nitrogen accumulation. Agric. Ecosyst. Environ. 155, 50–61.
Huang, G.B., Zhang, R.Z., Li, G.D., Li, L.L., Chan, K.Y., Heenan, D.P., Chen, W., Unkovich, M.J., Robertson, M.J., Cullis, B.R., Bellotti, W.D., 2008. Productivity and sustainability of a spring wheat–field pea rotation in a semi-arid environment under conventional and conservation tillage systems. Field Crop Res. 107, 43–55.
Huang, T.M., Zheng, X.F., Hou, Y.Y., Li, X., Wang, Z.H., 2015. Yield and N, P and K uptake and utilization of winter wheat affected by straw return to soil. Plant Nutr. Fert Sci. 21, 853–863 (in Chinese).
Kang, S.Z., Zhang, L., Liang, Y.L., Hu, X.T., Cai, H.J., Gu, B.J., 2002. Effects of limited irrigation on yield and water use efficiency of winter wheat in the Loess Plateau of China. Agric. Water Manage. 55, 203–216.
Li, F.M., Guo, A.H., Wei, H., 1999. Effects of clear plastic film mulch on yield of spring wheat. Field Crop Res. 63, 79–86.
Li, F.M., Wang, J., Xu, J.Z., Xu, H.L., 2004. Productivity and soil response to plastic film mulching durations for spring wheat on entisols in the semiarid Loess Plateau of China. Soil Tillage Res. 78, 9–20.
Li, F.C., Wang, Z.H., Dai, J., Li, Q., Xue, C., Zhao, H.B., Wang, X., Olesen, J.E., 2014. Summer fallow soil management–impact on rainfed winter wheat. Acta Agric. Scand. B Soil Plant 64, 398–407.
Li, S.X., 2004. Dryland agriculture in China, 1. China Agriculture Press, Beijing (in Chinese).
Limon-Ortega, A., Govaerts, B., Sayre, K.D., 2008. Straw management, crop rotation, and nitrogen source effect on wheat grain yield and nitrogen use efficiency. Eur. J. Agron. 29, 21–28.
Liu, C.A., Jin, S.L., Zhou, L.M., Jia, Y., Li, F.M., Xiong, Y.C., Li, X.G., 2009. Effects of plastic film mulch and tillage on maize productivity and soil parameters. Eur. J. Agron. 31, 241–249.
Liu, Y., Li, S., Chen, F., Yang, S., Chen, X., 2010. Soil water dynamics and water use efficiency in spring maize (*Zea mays* L.) fields subjected to different water management practices on the Loess Plateau. China. Agric. Water Manage 97, 769–775.
Muñoz-Carpena, R., Ritter, A., Bosch, D.D., Schaffer, B., Potter, T.L., 2008. Summer cover crop impacts on soil percolation and nitrogen leaching from a winter corn field. Agric. Water Manage. 95, 633–644.
Nielsen, D.C., Vigil, M.F., 2005. Legume green fallow effect on soil water content at wheat planting and wheat yield. Agron. J. 97, 684–689.
Rehman, S., Khalil, S.K., Rehman, A., Khan, A.Z., Shah, N.H., 2009. Micro-watershed enhances rain water use efficiency, phenology and productivity of wheat under rainfed condition. Soil Tillage Res. 104, 82–87.
Roper, M.M., Milroy, S.P., Poole, M.L., 2012. Green and brown manures in dryland wheat production systems in mediterranean-type environments. Adv. Agron. 117, 275–313.
Sainju, U.M., Whitehead, W.F., Singh, B.P., Wang, S., 2006. Tillage, cover crops, and nitrogen fertilization effects on soil nitrogen and cotton and sorghum yields. Eur. J. Agron. 25, 372–382.
Salado-Navarro, L.R., Sinclair, T.R., Morandini, M., 2013. Estimation of soil evaporation during fallow seasons to assess water balances for no-tillage crop rotations. J. Agron. Crop. Sci. 199, 57–65.
Su, Z.Y., Zhang, J.S., Wu, W.L., Cai, D.X., Lv, J.J., Jiang, G.H., Huang, J., Gao, J., Hartmann, R., Gabriels, D., 2007. Effects of conservation tillage practices on winter wheat water-use efficiency and crop yield on the Loess Plateau, China. Agric. Water Manage. 87, 307–314.
Sun, H., Shen, Y., Yu, Q., Flerchinger, G.N., Zhang, Y., Liu, C., Zhang, X., 2010. Effect of precipitation change on water balance and WUE of the winter wheat-summer maize rotation in the North China Plain. Agric. Water Manage. 97, 1139–1145.
Tonitto, C., David, M., Drinkwater, L., 2006. Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: A meta-analysis of crop yield and N dynamics. Agric. Ecosyst. Environ. 112, 58–72.
Uauy, C., Distelfeld, A., Fahima, T., Blechl, A., Dubcovsky, J., 2006. A NAC gene regulating senescence improves grain protein, zinc, and iron content in wheat. Science 314, 1298–1301.
Verhulst, N., Sayre, K.D., Vargas, M., Crossa, J., Deckers, J., Raes, D., Goyaerts, B., 2011. Wheat yield and tillage-straw management system x year interaction explained by climatic co-variables for an irrigated bed planting system in northwestern Mexico. Field Crop Res. 124, 347–356.
Wang, Y.J., Xie, Z.K., Malhi, S.S., Vera, C.L., Zhang, Y.B., Wang, J.N., 2009. Effects of rainfall harvesting and mulching technologies on water use efficiency and crop yield in the semi-arid Loess Plateau. China Agric. Water Manage. 96, 374–382.
Ward, P.R., Flower, K.C., Cordingley, N., Weeks, C., Micin, S.F., 2012. Soil water balance with cover crops and conservation agriculture in a Mediterranean climate. Field Crop Res. 132, 33–39.
Wu, Y., Jia, Z., Ren, X., Zhang, Y., Chen, X., Bing, H., Zhang, P., 2015. Effects of ridge and furrow rainwater harvesting system combined with irrigation on improving water use efficiency of maize (*Zea mays* L.) in semi-humid area of China. Agric. Water Manage 158, 1–9.
Xie, Z.K., Wang, Y.J., Li, F.M., 2005. Effect of plastic mulching on soil water use and spring wheat yield in arid region of northwest China. Agric. Water Manage 75, 71–83.

Zhang, S.L., Lövdahl, L., Grip, H., Jansson, P.-E., Tong, Y.N., 2007. Modelling the effects of mulching and fallow cropping on water balance in the Chinese Loess Plateau. Soil Till. Res. 93, 283–298.
Zhang, S.L., Lövdahl, L., Grip, H., Tong, Y.N., Yang, X.Y., Wang, Q.J., 2009. Effects of mulching and catch cropping on soil temperature: soil moisture and wheat yield on the Loess Plateau of China. Soil Tillage Res. 102, 78–86.
Zhang, Z.L., Liu, J.S., Wang, Z.H., Zhao, H.B., Yang, N., Yang, R., Cao, H.B., 2012. Nitrogen recommendation for dryland winter wheat by monitoring nitrate in 1 m soil and based on nitrogen balance. Plant Nutr. Fert. Sci. 18, 1387–1396 (in Chinese).
Zhang, S.L., Sadras, V., Chen, X.P., Zhang, F.S., 2013. Water use efficiency of dryland wheat in the Loess Plateau in response to soil and crop management. Field Crop Res. 151, 9–18.