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Effects of Water Saving Practices on Winter Wheat and Summer Maize Yields in South Loess Plateau of Northwest China

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Abstract

A field experiment, laid out in Randomized Complete Block Design (RCBD) with split plot arrangement having four replications, was conducted at the south edge of Loess Plateau, Shaanxi, China to evaluate the responses of winter wheat and summer maize to different water saving management practices involving four mulching and irrigation treatments, i.e., plastic mulch ridge and straw mulch furrow combined with deficit irrigation (RF+DI), straw mulch combined with deficit irrigation (SM+DI), Deficit Irrigation (DI), and Conventional Flood Irrigation (CFI). Soil temperature and moisture during the crop growth were monitored in two years. RF+DI treatment significantly increased maize yield, and it also had higher wheat yield than SM+DI treatment. SM+DI treatment increased maize yield; however, it did not increase winter wheat yield. Soil water content in RF+DI and SM+DI treatments was significantly higher than those of CFI or DI treatments. Compared with RF+DI treatment, SM+DI treatment had higher soil water content (0-20 cm); however, it had the lowest heat 741 Degree Days of Soil (DDs) among the four treatments. The low soil temperature in SM+DI plots, especially in early spring, delayed winter wheat growth stages and development, thus reduced grain yield compared with RF+DI treatment. The positive effects of ridge-furrow system on both wheat and maize yield could be explained by harmonizing soil moisture and temperature by this treatment.

Keywords: Water saving practices; Winter wheat; Summer maize; Soil temperature; Soil moisture

Introduction

The rapidly growing human population of 7.14 billion is expected to rise up to 8.1 billion by 2030. This population increase will in turn lead to a considerable additional demand for food [1]. At the same time, water use has been growing at more than twice the rate of population increase in the last century. So, a great challenge for agriculture is to produce more food from limited water which can be achieved by increasing crop water productivity [2]. Water shortage is one of the most important factors limiting crop yield worldwide, especially in dry land farming [3-5]. Therefore, different water saving practices are used to conserve water in dry land farming [6,7]. Results of the long-term research suggests that mulching significantly reduced bulk density and penetration resistance; increased organic carbon, saturated hydraulic conductivity, water stable aggregate microbial biomass carbon and soil enzyme activities. Additionally, together mulching and irrigation regulates soil as well as canopy temperature that helps in developing better root system which in turn results into better nutrient uptake and plant withstanding against high velocity winds at grain filling/maturity (reduce lodging) [8-11]. Straw mulch is one of the efficient ways to alter water distribution between soil evaporation and plant transpiration, and is applied to a number of crops, including wheat [12], maize [13-15], groundnut [16], and onion [17]. The responses of different crops to straw mulch practices, however, have been variable. Wheat grain yields were positively influenced by straw mulch treatments [18,19]. Tomato yields from straw mulched plot were higher than those from non-mulched treatments [20]. Yield responds of maize to straw mulch practices, however, remained contentious. While many researchers observed highly significant yield difference from straw compared with conventional methods [21-23]. Straw mulch significantly decreased wheat yield. The different responses of crops to straw mulch are related to their types and climatic conditions [24,25]. The ridge and furrow technique is another widely used water saving practice. In this technique, the plastic-covered ridges serve as rainfall-harvesting zones and the straw mulched furrows serve as planting zones [26]. Many researchers have studied the effects of ridges–furrow cultivation combined with plastic or straw mulch on wheat and maize crop yield and revealed that the ridge-furrow treatment produced high wheat and maize yields compared to the conventional cultivation treatment [27-30]. Ridge-furrow technique has been successfully applied to a number of crops including onion [31], sweet sorghum [32], alfalfa [33], potatoes and proso millet [34,35]. After all, ridge-furrow practices coupled with mulch seems to be one of the most effective ways to improve water use efficiency and increase crop yields. Winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) rotation is an intensive production system in north China, including the North China Plain (NCP), and Guanzhong Plain. It plays an important role in cereal production in China. For example, The NCP accounts for about 69% of wheat and 35% of maize grain yields of the whole country [36,37]. The water requirements of double cropping system of winter wheat and summer maize exceed 850 mm. Long-term average annual precipitations in the NCP ranges from 450 to 650 mm with 70% falling from July to September, the growing season of maize. During the growing season of winter wheat, rainfall could only meet 25-40% of the crop water requirements [15]. Therefore, irrigation is needed for this rotation. The groundwater is the main water resource in this region. The excessive exploitation of groundwater resources from shallow and deep aquifers has caused falling water tables and many other environmental problems (e.g. land subsidence) within the plain [36]. To increase the water use efficiency is thus an ultimate need to be fulfilled in the region. Using the different water saving methods of the dry land farming could be one solution. However, most of the studies have focused on deficit irrigation, and straw mulch [19,28]. Deficit Irrigation (DI) is an optimization strategy which is being used for the reduction of water use and for the increasing of Water Use Efficiency (WUE) in many parts of the world [19]. Few studies compare the effects of the different water saving methods both on soil moisture and temperature in winter wheat and summer maize rotation. The objective of this study was to compare the effects of different water saving practices on yield responses of winter wheat-summer maize crops at the south edge of loess plateau, and relate their responses with soil moisture and temperature.

Materials and Methods

Site description

Field experiment was conducted at the No. 1 Experimental Station of the Northwest A&F University, Yangling, Shaanxi, China (34° 17′ 56″N, 108° 04′ 07″E). The climate is temperate and sub-humid with mean annual precipitation of 632 mm and mean annual air temperature of 13ºC. Winters are long (early December-march) with scanty precipitation. Almost 60% of the precipitation occurs from July to September. Mean annual pan evaporation of the area is 1400 mm. The soil of the experimental field is characterized by Eum-Orthic Anthrosols. The selected properties of soil are given in Table 1.

pH	Organic matter (g/kg)	Total N (g/kg)	NO_3-N (kg/ha)	NH_4-N (mg/kg)	Olsen-P (mg/kg)	NH_4OAc-K (mg/kg)
8.25	15.2	0.67	30.4	1.9	17.2	169

Table 1: Selected chemical properties of the soil prior to planting in 2003.

Experimental design and field layout description

The study began in June, 2009. The experiment was laid out in a split plot design with four main plot treatments, namely (1) conventional flood irrigation (CFI), (2) deficit irrigation (DI), (3) straw mulch+deficit irrigation (SM+DI), and (4) plastic mulch ridge straw mulch furrow+deficit irrigation (RF+DI). The last three treatments were considered as water saving management practices. Three nitrogen fertilizer rates, i.e., 0, 120, and 240 kg ha^{-1} were the sub plot treatments. The main plot size was 4.5 × 12 m, replicated four times. Briefly, there was no straw or plastic film mulch applied in CFI and DI treatments. RF+DI treatment was consisted of intermittent ridges and furrows. The ridges were 30 cm wide and 15 cm high while the furrows were 30 cm wide. Ridges were mulched with plastic, and furrows were mulched with straw. Wheat cultivar (Xiaoyan-22) was sown as row crop system in early October and harvested in early June. Row to row space in the CFI, WS and SM+DI treatments was 20 cm, and each plot had 21 rows. In the RF+DI treatment, no wheat was sown on the ridges, each furrow had two rows. There were 16 rows in the RF+DI treatment. The plots were sprayed with weedicides. Maize cultivar (Zhengdan-958) was planted immediately after wheat harvest without tilling the soil. The holes were drilled by adze with rows 60 cm apart and 5 cm deep. Maize was seeded in each hole, and then the holes were filled with soil. In the RF+DI treatment, the ridges were mulched instantly with plastic. A more detailed description of the experiment is given by Zhou et al. [19].

Soil sampling and measurements

During the crop growing season in 2011, 2012 and 2013; the Geothermometers (Tidbit v2 Temp logger, USA) were placed 10 cm deep in soil. Soil temperature was calculated at one hour intervals during day and night. The daily mean soil temperature (°C) was considered as the average of all intra-day reading. Soil heat accumulation was measured as degree days of soil (DD soil) (Juan C. Dıaz-Perez, 2009). It was calculated as:

$$DDsoil = \sum_{i=1}^{i=n} \frac{1}{2}\left\{\frac{RZTmax + RZTmin}{2} - RZTbase\right\}$$

Where n is the number of days in the growing season, $RZTmax$ and $RZTmin$ are the daily maximum and minimum soil temperatures and $RZTbase$ is the base root zone temperature. Soil moisture was gravimetrically measured at 20 cm increments down to 200 cm after harvesting the crop, manually using a soil auger. A core of soil sample was collected from each plot. Soil water content in the top 20 cm of soil was measured with TDR in each plot at 25-30 days intervals during crop growing season. The Volumetric water contents were calculated by multiplying the gravimetric soil moisture with bulk density value for soil.Soil moisture was gravimetrically measured at 20 cm increments down to 200 cm after harvesting the crop, manually using a soil auger. A core of soil sample was collected from each plot. Soil water content in the top 20 cm of soil was measured with TDR in each plot at 25-30 days intervals during crop growing season. The Volumetric water contents were calculated by multiplying the gravimetric soil moisture with bulk density value for soil.

Statistical analysis

The data were assessed by Analysis of Variance (ANOVA) employing statistical software Statistix 8.1 and the Least Significant Difference (LSD) test at P<0.05 was opted for multiple comparisons.

Results

Crop grain yield

Compared to other water saving treatments, the RF+DI treatment produced slightly more wheat grain yield. However, the difference was not statistically significant (Table 2).

Treatments	2010	2011	2012	2013	Average	Total
RF+DI	3250A	4320A	2670A	1710A	2990A	11950A
DI	2990A	3790A	2740A	1340A	2715A	10860A
SM+DI	2990A	3560A	2830A	1360A	2685A	10740A
CFI	3020A	3950A	2910A	1120A	2750A	11000A
All means followed by different letters relating to same parameter are statistically different at (P<0.05) level using the LSD. RF: Ridge-Furrow; DI: Deficit Irrigation; SM: Straw Mulch; CFI: Conventional Flood Irrigation						

Table 2: Effect of water saving management practices on winter wheat grain yield (kg ha^{-1}).

Different water management practices significantly affected the maize yield compared to the conventional treatment. Over the five years study, total maize yield in the RF+DI treatment was 8970 kg ha^{-1} (25.23%) more than in the DI treatment and 9450 kg ha^{-1} (26.58%) more than in the CFI treatment.

Compared to the CFI and DI treatments, SM+DI treatment produced 19.04% and 17.55% more maize yield respectively (Table 3). This indicates that the use of straw or plastic as mulch has a significant influence on maize grain yield.

Treatments	2009	2010	2011	2012	2013	Average	Total
RF+DI	5570A	7740A	6700A	7860A	7680A	7110A	35550A
DI	3820B	6060B	5450C	5830C	5420C	5316C	26580C
SM+DI	5050A	7300A	6060B	7010B	6820B	6448B	32240B
CFI	4100B	5720B	5100C	6400BC	4780D	5220C	26100C

Note: numbers within a column followed by different letters are significantly different at 0.05 levels (LSD). RF: Ridge-Furrow; DI: Deficit Irrigation; SM: Straw Mulch; CFI: Conventional Flood Irrigation.

Table 3: Effect of water saving management practices on summer maize grain yields (kg ha^{-1}).

Soil moisture

The objective of this study was to compare the effects of different water saving practices on yield responses of winter wheat-summer maize crops at the south edge of loess plateau, and relate their responses with soil moisture and temperature.

Either straw or plastic film mulch had significant effect on soil moisture (Table 4). Compared with DI treatment, the average soil water storage (0-20 cm) over 2012-2013 winter wheat season at different growth stages was significantly increased with RF+DI, SM+DI, and CFI by 11.5%, 19.6% and 13.6% respectively (Table 4).

At post-harvest time of maize in 2012, water saving management practices significantly affected soil water storage at top soil but there was no remarkably difference in low profile water storages (Figure 1A), although the differences were not significant among treatments at post-harvest time of winter wheat in 2013 (Figure 1B).

Compared to CFI treatment, SM+DI and RF+DI treatment had more water at upper soil profile.

Treatments	March 2013	April 2013	May 2013	Sum
RF+DI	19.5B	42.5A	15.7B	77.7 AB
DI	18.5B	34.7B	15.5B	68.7 B
SM+DI	23.4A	42.1A	19.8A	85.3 A
CFI	18.8B	40.5AB	20.3A	79.6 AB

All means followed by different letters relating to same parameter are statistically different at ($P<0.05$) level using the LSD. RF: Ridge-Furrow; DI: Deficit Irrigation; SM: Straw Mulch; CFI: Conventional Flood Irrigation

Table 4: Soil water content (mm) at 0-20 cm depth for the different cultural practices at March (Tillering), April (Booting) and May (Late Flowering) stages during winter wheat season in 2013.

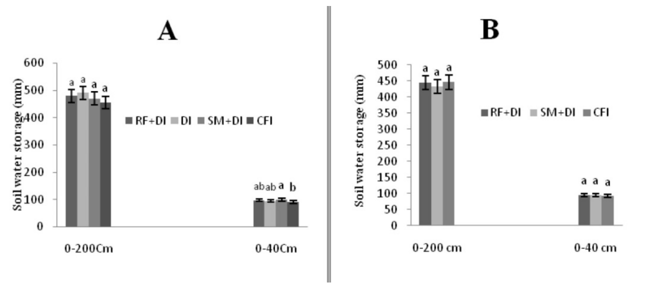

Figure 1: Soil profile (0-200 cm) water storage (mm) for different cultural practices at post-harvest time of 2012 summer maize crop (Figure 1A) and at post-harvest time of 2012-2013 winter wheat (Figure 1B). CFI: Conventional Flood Irrigation; SM: Straw Mulch; DI: Deficit Irrigation; RF: Ridge-Furrow.

Soil temperature

The interim variations in soil temperature with all the treatments during 2011-2012 and 2012-2013 wheat growing were affected by mulch practices (Figure 2). Diurnal changes in soil temperature, measured daily at 10 cm depth, showed that daily mean soil temperature was higher in straw mulch+DI than in CFI plots during the cold winter (Figure 2a). At that time, the soil temperature fell to 0.79°C in the CFI and to 1.3°C in SM+DI plots and then rose steadily, peaked at 22.5°C in CFI and 21.3°C in the SM+DI treatments. During wheat growing season in 2013 (Figure 2b), soil temperature fell from late October to early February and then rose rapidly, peaked at 24.08°C in CFI and 22.7°C in the SM+DI treatments at late May 2013. Mean diurnal soil temperature under straw mulch treatment was 0.7°C warmer than in the CFI treatment in cold winter (Figure 2b).

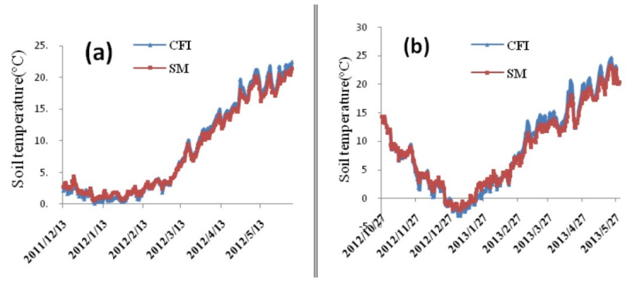

Figure 2: Changes of diurnal temperature of soil at 10 cm depth during the 2011-2012 (a) and 2012-2013 (b) winter wheat growing season in CFI and SM+DI plots. CFI: Conventional Flood Irrigation; SM: Straw Mulch; DI: Deficit Irrigation.

The soil temperature in RF+DI treatment was recorded in both plastic mulched ridge and straw mulched furrow. For the 2011-2012 wheat growing season, there was no significant difference between straw mulch furrow and plastic mulch ridge in soil temperature during winter; with the beginning of spring, plastic mulch ridge kept soil warmer than straw mulch furrow (Figure 3a). During wheat growing season in 2012-2013, the difference in soil temperature at 10 cm depth between plastic mulch ridge and straw mulch furrow evidenced that soil temperature had the same status during colder weather, but

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thereafter was a significant difference among straw mulch furrow and plastic mulch ridge in thermal regime. For 2012-2013 winter wheat growing season, the soil temperature regime was similar to that in 2011-2012, but the only difference in soil temperature of these two winter wheat growing seasons was that soil temperature in 2012-2013 winter seasons fell down to below zero in late December and early January (Figure 3b). For wheat growing period, the mean soil temperature beneath the plastic mulched ridge was higher than those of straw mulched (SM+DI) or Conventional Flood Irrigation (CFI).

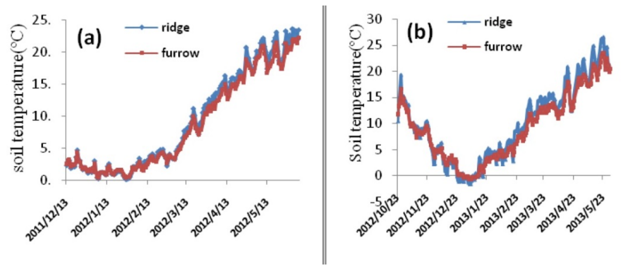

Figure 3: Changes of diurnal temperature of soil at 10 cm depth during the 2012-2013 and 2012-2013 winter wheat growing seasons in the ridge and furrow of RF+DI treatment.

The effect of SM+DI or RF+DI on soil temperature was larger during the early stages of maize growth, and their effects decreased with maize growth (Figure 4). The soil temperature at 0-10 cm depth was consistently higher in the plastic mulch ridge than the straw mulch furrow (Figure 4b). There was no significant difference in mean soil temperature during whole growing season among the treatments. However, straw mulch kept the soil cooler in hot summer compared to CFI (Figure 4a).

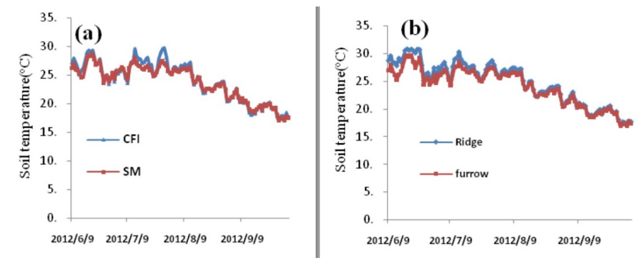

Figure 4: Diurnal trends in soil temperature (°C) at 10 cm depth under straw mulch and conventional treatments (Pannel-A), plastic mulch ridge and straw mulch furrow in RF+DI treatment (Pannel-B) during 2012 maize growing season. CFI: Conventional Flood Irrigation; SM: Straw Mulch.

Soil heat accumulation

The amount of heat accumulated in the soil, measured as soil degree-days (DD soil) or heat units, differed among seasons ($P<0.05$) and water saving management practices. The mean, maximum and minimum root zone temperatures for all water saving management practices during the three seasons are shown in Table 5. Less heat was accumulated in the soil during the 2011-2012 winter wheat growing season in SM+DI treatment compared to the CFI treatment. While plastic mulch ridge in RF+DI treatment accumulated the highest DD soil. In particular, from the begin of spring to harvest of 2011-2012 winter wheat, accumulated soil temperature under SM+DI was 611 DD soil while CFI had 647 DD soil accumulated heat. The same difference in accumulated soil temperature was found for 2012-2013 wheat season whereas SM+DI had 716 DD soil and CFI had 658 DD soil accumulated heat.

During 2012 summer maize growing season, in the RF+DI treatment, plastic mulch ridge accumulated much DD soil compared to the SM+DI, but there was no significant difference among straw mulch furrow in the RF+DI, CFI and SM+DI in soil heat accumulation. In general, the plastic much ridge accumulated more DD soil than other treatments, and there was least accumulation of heat units (DD soil) in SM+DI treatment.

Treatment	Mean (°C)	Maximal (°C)	Minimal (°C)	Accumulated heat (DDs)
2011-2012 winter wheat season				
PR in RF+DI	9.32	11.9	7.51	849 A
SF in RF+DI	8.77	10.27	7.56	780 B
SM+DI	8.32	9.73	7.2	741 C
CFI	8.59	10.58	7.11	774 C
2012 maize season				
PR in RF+DI	24.73	27.28	22.65	883 A
SF in RF+DI	24	25.77	22.45	833 B
SM+DI	23.68	25.59	22.09	816 B
CFI	24.05	26.79	21.81	844 B
2012-2013 winter wheat season				
PR in RF+DI	9.96	16.1	6.12	1200 A
SF in RF+DI	9.16	11.3	7.51	1015 C
SM+DI	8.66	11.56	6.52	967 C
CFI	8.9	12.67	6.18	1018 C

Note: Numbers within a column followed by different letters are significantly different at 0.05 levels (LSD). CFI: Conventional Flood Irrigation; SM: Straw Mulch; DI: Deficit Irrigation; PR: Plastic Mulch Ridge; SF: Straw Mulch Furrow

Table 5: the seasonal average Root Zone Temperatures (RZT) during the 2011-2012, 2012-2013 winter wheat and 2012 summer maize growing seasons as affected by different cultural practices.

Discussion

Effects of straw mulch on crop yields

Numerous reports indicate that straw mulching increases soil moisture [38-40]. However, its effects on crop yields are variable. Straw mulch can significantly affect the soil microclimate (soil temperature and water content) and hence grain yield of maize [13,17-19], wheat [15,21], radish [15], and tomatoes [16]. Current results revealed that, compared to the CFI treatment, straw mulch slightly decreased wheat yield, but significantly increased summer maize grain yield. Reason for the different responses of winter wheat and summer maize to straw mulch is related to its effect on soil moisture and temperature during the crop growth. It was depicted that soil moisture of straw mulch treatment in early spring was higher than that of the CFI treatment (Table 4); however, the soil temperature of in straw mulch treatment was lower than that in the CFI treatment (Figure 2). Compared to the moisture, soil temperature is more important for winter wheat growth in this period. Low temperature in early spring delayed wheat growth. The responses of wheat yield to straw mulch in current study are in agreement with the results of Chen et al. [20] who also observed that straw mulch had negative effect on winter wheat yield.

Compared to soil temperature, water availability is a key factor to summer maize growth during the hot summer. The straw mulch reduces soil evaporation, and conserves more moisture in soil [5,7]. Results show that it also decreased soil temperature compared to CFI treatment (Figure 4 and Table 5). These results for straw mulch effects on soil temperature are in line with the work of Zhang et al. [15], who found that soil temperatures under straw mulch at 10 cm depth were decreased in warmer period by 0-4ºC and increased in the colder period by 0-2ºC compared to non-mulched soil. Cooler soil's temperature and higher water content under straw much treatment could be the positive maize grain response in SM+DI compared to CFI treatment. Obviously the responses of different crops to straw mulch are dependent on crop types, and climate conditions.

Effects of ridge-furrow technique on crop yields

Previous studies have shown that plastic mulch and ridge-furrow technique greatly increased yield of cereals, which is mainly due to the effect of plastic film on reducing water evaporation from soil [6,7,21]. Our study also found that this technique not only slightly increased winter wheat yield, but also significantly improved summer maize grain yields compared to the other three treatments (Tables 2 and 3). Similar findings reported by other researchers stated that the integrated effect of ridge-furrow system and supplemental irrigation increased maize yield by 106% [7,21,38]. It is also reported that the ridge and furrow technique could be an optimal practice to improve runoff efficiency, rain water harvesting and crop yield [39]. This cultivation system was applied on onion [28], maize [5,7,40], wheat [21,38], sorghum [23], and alfalfa [22]. The positive effect of ridge-furrow system could be explained by the coupling of favorable changes in moisture and temperature by this treatment. Plastic mulching on the ridge led to more heat adsorption during winter, and straw mulched furrow helped soil to conserve more water for crop.

The different responses of winter wheat and summer maize yields to RF+DI system in current study is also due to the reason that RF practices reduced the area planted to wheat (from 21 rows of wheat in the CFI to 14 rows in RF+DI plots), while the planted to maize did not change [5]. Ridge-furrow rainfall harvesting system with mulches is being promoted to increase water availability for crops in areas of the Loess Plateau of China [29,39]. However, the efficiency of this system is dependent on the width ratios of ridges and furrows, cultivating crop, land topography, and regional climate. Further research is needed to find the optimum width ratios of ridges and furrows for different crops at the different regions.

Conclusion

Compared to the DI or CFI treatments, both SM+DI and RF+DI treatments had positive effects on water content in soil profiles. RF+DI treatment significantly increased maize yield, and it also had higher wheat yield than SM+DI treatment. SM+DI treatment increased maize yield; however, it did not increase winter wheat yield. The reason is that straw mulch decreased soil temperature during the early spring, that delayed winter wheat growth stages and development thus reduced final grain yield. Compared to the SM+DI treatment, the RF+DI treatment harmonizes the soil moisture and temperature. Therefore, it increases both wheat and maize yields.

Acknowledgements

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