Precipitation alters plastic film mulching impacts on soil respiration in an arid area of Northwest China

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Abstract: Plastic film mulching (PFM) has widely been used for saving water and improving crop yield around the world. However, the effect of PFM on soil respiration (R_s) remains unclear, which could be further confounded with irrigation and precipitation. To address this question, the controlled experiments were conducted in the mulched and non-mulched fields under drip irrigation from 2014 to 2016 in an arid area of the Xinjiang Uygur Autonomous Region, Northwest China. The spatiotemporal pattern of soil surface CO_2 flux as an index of soil respiration under drip irrigation with PFM were investigated, and the confounded effects of PFM and irrigation/precipitation on soil respiration were explored. The main findings are as follows: (1) The furrow, planting hole, and plastic mulch are three important pathways for soil CO_2 emission in the mulched field, of which the planting hole efflux outweighs the furrow, and the plastic mulch itself can emit up to 3.6 μmol m^{-2} s^{-1} CO_2. (2) Frequent water supplies (i.e., irrigation and precipitation) elevate soil moisture and soil respiration and enhance their variations. The resultant higher variation of soil moisture further alleviates the sensitivity of soil respiration to soil temperature leading to poor correlation and lower Q_{10} values. (3) Soil CO_2 effluxes from furrows and ridges in mulched fields outweigh the corresponding terms in non-mulched fields in arid areas. However, this outweighing relation attenuates with increasing precipitation. Furthermore, by combining the literature results we show that the difference of soil CO_2 effluxes between non-mulched and mulched fields presents a linear relation with precipitation amount, which results in negative values in arid areas and positive values in humid areas. Therefore, whether PFM increases soil respiration or not depends on precipitation amount during the crop growth period.

Keywords: plastic film mulching; soil respiration; spatial variation; irrigation; precipitation

1. Introduction

Soil respiration (R_s), the flux of microbe- and plant-respired CO_2 from the soil surface to the atmosphere, represents the second largest CO_2 flux of the terrestrial biosphere following gross primary productivity (GPP) and amounts to 10 times current rate of fossil-fuel combustion (Bond-Lamberty and Thomson, 2010;Davidson et al., 2006;Liu et al., 2016a;Reichstein and Beer, 2008). Anthropogenic activities, particularly agriculture expansion and change of cultivation practices, have brought significant challenges to CO_2 emission control considering climate change (Baker et al., 2007). The conversion of natural to agricultural ecosystems has been recognized to cause a depletion of soil organic carbon pool by as much as 60% (Lal, 2004), and additionally, soil respiration in agricultural ecosystems is relatively larger than that in natural ecosystems due to intensive cultivation (Buyanovsky et al., 1987;Raich and Tufekciogul, 2000).

A particular example is plastic film mulching (PFM), which was invented as an advanced agriculture cultivation technology for saving water and improving crop yield in 1950s and has ever since been widely applied around the world, e.g., in the tropical USA, Europe, South Korea and China. For instance, approximately 19% of the total arable land (130 million ha) in China was cultivated using PFM in 2014 (Wang et al., 2016), and specifically, the PFM area has reached 1.2 million ha in the arid Xinjiang Uygur Autonomous Region, Northwest China (Zhang et al., 2014). In a PFM field, the new method may alter the albedo, soil temperature, soil moisture, and crop growth conditions (Zhang et al., 2011), all of which can affect both heterotrophic and autotrophic respiration. Furthermore, the large-scale application of PFM may alter the regional climate, hydrologic cycle, and carbon cycle (Bonan, 2008;Li et al., 2016;Cox et al., 2000). Therefore, detecting the altered environmental conditions and CO_2 emissions in PFM fields is crucial for the maintenance of regional and global soil carbon balances in the situation of global climate change.

There are just a few studies devoting to CO_2 emissions in PFM fields, which, however, deliver contrasting results. For example, Yu et al. (2016) showed that the soil surface CO_2 emission in a mulched field in southern Xinjiang Uygur Autonomous Region of China increases by 8% relative to the non-mulched field, and the increase mainly comes from furrows instead of ridges (the readers are referred to Fig. 1 for the configuration of furrow, ridge, planting hole, mulch, etc.). However, Li et al. (2011) detected that the CO_2 concentration in soil profiles is higher in mulched fields but the soil CO_2 efflux decreases by 21% relative to the non-mulched field in northern Xinjiang Uygur Autonomous Region of China. Similar results that PFM decreased CO_2 emission were also found on the Loess Plateau of China (Xiang et al., 2014), Southwest of China (Lei, 2016) and a temperate monsoon climate area in Japan (Okuda et al., 2007). About the emitting pathways for greenhouse gases in the field, Berger et al. (2013) found that planting holes and furrows are import pathways for N_2O emission in mulched ridges. In addition, Nishimura et al. (2012) revealed in a laboratory experiment that N_2O gradually permeates the plastic mulch. These findings indicate that the pathways for the gases emission in a mulched field may include furrows, planting holes and plastic mulches, which has not been quantified for soil CO_2 efflux in PFM fields. Some experimental studies simply interpreted soil respiration from furrows as the field averaged flux (Qian-Bing et al., 2012;Liu et al., 2016b), which may lead to the underestimation of soil respiration flux because ridges usually emit more CO_2 than furrows.

In addition, irrigation and precipitation are also crucial to soil respiration due to the nature of moisture limit on soil respiration in arid and semiarid regions, to which less attentions have been paid. After irrigation and precipitation, soil moisture undergoes a wetting-drying cycle that affects soil porosity and influences the activities of root biomass and microorganisms that control soil carbon dynamics (Yan et al., 2014). Both intensity and amount of irrigation/precipitation affect soil respiration. A couple of studies indicated that soil respiration rate in a drip irrigation field is greater than that in a flood irrigation field (Guo et al., 2017;Qian-Bing et al., 2012). PFM can modify the hydrological processes induced by precipitation or irrigation in different ways and may further impact soil respiration. For example, rainwater cannot infiltrate into ridges in a mulched field due to the barrier of plastic mulch which, however, can cause additional soil moisture increase in furrows. Differently, infiltration of irrigation water principally occurs in ridges under drip irrigation method as drip tapes are beneath the plastic mulch. The different impact of PFM on soil moisture distribution induced by precipitation or irrigation may further have different influences on soil respiration. To the best of authors' knowledge, however, such different influences of PFM on soil respiration in terms of irrigation or precipitation have not yet been explored.

The main objective of this study is, therefore, to address the effect of PFM on soil respiration and the confounding influence of irrigation and precipitation. Control experiments under mulched and non-mulched drip irrigation conditions were conducted in a cotton field in the arid area of the Xinjiang Uygur Autonomous Region, Northwest China. The soil respiration from different locations in mulched and non-mulched fields were continuously monitored in the growth periods from 2014 to 2016. With these experimental results, we investigated the following questions specifically: (1) what's the spatiotemporal pattern of soil respiration in a PFM field? (2) how does PFM affect soil respiration through its alteration on soil temperature and moisture? and (3) what's the confounding effect of irrigation/precipitation and PFM on soil respiration?

2. Study Area and Methods

2.1 Study area

The field experimental site (86°12′ E, 41°36′ N; 886 m above sea level) is located in one of the oases scattered on the alluvial plain of the Kaidu-Kongqi River (a tributary of the Tarim River) Basin, north of the Taklamakan Desert in the Xinjiang Uygur Autonomous Region of Northwest China. The region has a temperate continental climate, with a mean annual precipitation of 60 mm, mean annual temperature of 11.48 ℃, and mean annual water surface evaporation of 2,788 mm as measured by Φ20 pan. The annual sunshine duration is 3,036 hours, which is favorable for cotton growth.

The experimental field covers an area of 3.48 ha. The major soil texture in the field is silt loam, and the contents of sand, silt and clay separates are 32.8%, 62.4% and 4.8%, respectively, and its bulk density is from 1.4 g cm^{-3} to 1.64 g cm^{-3} in the 1.5 m soil profile. The soil porosity is 0.42, which was directly determined in the laboratory using the undisturbed soil columns collected in the experimental field.

Cotton (Gossypium hirsutum L.) is usually sown in April and harvested during October and November, i.e. the growth period is from DOY (day of the year) 100 to 300 approximately. The planting style is “one film, one drip pipe beneath the film and four rows of cotton above the film” as depicted in Fig. 1. The plastic film (0.008 mm thick) is white and made of dense and airtight transparent polyethylene film. The width of the film is 1.1 m, and the inter-film zone is 0.4 m. Before sowing, small square holes (2 cm length) are made for germinating at 0.1 m intervals within a row in the plastic film, and then seeds are placed into the holes, and each hole is covered with soil. The planting density is approximately 160,000 plants per ha. The annual basic fertilizer before sowing includes 173 kg ha^{-1} of compound fertilizers (14% N, 16% P_2O_5, and 15% K_2O), 518 kg ha^{-1} of calcium superphosphate (18% N, 40% P_2O_5) and 288 kg ha^{-1} of diammonium phosphate (P_2O_5>16%). Supplemental fertilizers during the growth period contain approximately 292 kg ha^{-1} of urea (46% N) and 586 kg ha^{-1} of drip compound fertilizer (13% N, 18% P_2O_5, and 16% K_2O) and foliar fertilizer (P_2O_5>52%, and K_2O>34%). Drip irrigation usually begins on June 12 in the bud stage with an approximate amount of 20-50 mm each time and 9-12 times per growth season. The annual irrigation amount is 500-600 mm.

2.2 Experimental set-up

This study focuses on the growth season as soil respiration in non-growth season is extremely low. The mulched and non-mulched treatments were arranged in a randomized block design with three replicates in the same field with the same fertilization and irrigation scheme from the year 2014 to 2016. The plastic mulch had been covered until the seed germination in the non-mulched treatment to protect seed germinating. The experiments roughly started from the bud stages when cotton began to grow faster. The beginning experimental dates are DOY 184, 175,167 and the length of measured periods are 95, 60, 100 days, respectively. Soil respiration measurements were carried out with an LI-8100A (LI-COR, Inc., Lincoln, Nebraska) on one day between two irrigation events. Therefore, soil respiration was approximately measured every one weeks during the cotton-growth season. The automated soil CO_2 flux measurement system consists of two parts, PVC collars (10 cm in diameter and 5 cm in height) and a measuring chamber. The PVC collars were inserted 2-3 cm into the soil by removing living plants and litter inside the soil collars at least 1 day before the measurements. Data were recorded by the data logger in the LI-8100A.

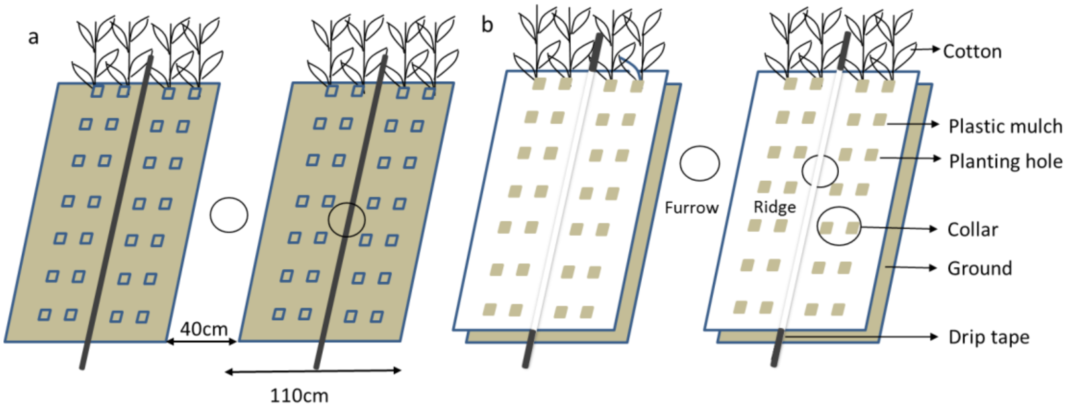

Fig. 1. Schematic drawing of the experimental configuration for: (a) a non-mulched field, and (b) a mulched field.

The soil respiration was measured in the following parts, i.e., the furrow and ridge of the non-mulched treatment, and the furrow, planting hole, and plastic mulch of the mulched treatment in 2016 (see Fig. 1 for the experimental configuration). Soil respiration was measured in the furrow for the mulched treatment and the ridge for the non-mulched treatment in 2014 and it was measured the furrow for the mulched treatment and in both furrow and ridge for the non-mulched treatment in 2015. The measurements were performed every 2 hours during the experimental day from 8:00 to 24:00. To measure the soil respiration on the soil surface without film covering (i.e., the furrows in the mulched and non-mulched fields and the non-mulched ridge), the PVC collars were inserted directly into the soil. Before measuring the CO_2 emission through the plastic mulch and in the plant holes, the plastic mulch was accomplished by cutting holes of the size of the collar in the plastic mulch and around plant holes, installing the collars and then placing the plastic mulch in the collars. Scotch tape was used to seal the interspaces between the plastic mulch and collar to prevent air leakage.

The soil temperature and soil moisture at a depth of 5 cm were monitored adjacent to each PVC collar using the auxiliary sensors of the LI-8100A, and concurrent with the soil CO_2 flux measurements. The drip irrigation amount was obtained by water meters installed on the branch pipes of the drip irrigation system. The precipitation was measured by a tipping bucket rain gauge (model TE525MM, Campbell Scientific Inc., Logan, UT, USA), which was mounted 0.7 m above the ground.

2.3 Data analysis method

The soil respiration from different parts at a particular time of a day was calculated as the average of three replicates. The daily mean R_s was calculated as average of R_s measured at various times in a day. The R_s in the mulched ridges was calculated with the area ratio of R_s through the plant holes and the plastic mulch：

$$R_{r-m} = R_{h-m} * A_{h-m} + R_{p-m} * A_{p-m} \tag{1}$$

where, the symbols of $R_{h\text{-}m}$ and $R_{p\text{-}m}$ are the soil respiration from the planting hole and plastic mulch, which constitute the soil respiration in the ridge ($R_{r\text{-}m}$). The term A means the area ratio of the different parts. The accumulative R_s in the ridges and furrows during the growth season was estimated by summing the products of soil CO_2 flux and the number of days between sampling times. Hypothetical *t*-test was used to test the significance of differences among R_s from furrows and ridges of the mulched and non-mulched fields.

The regression of R_s with soil temperature and soil moisture were analyzed using SPSS (Statistical Package for the Social Sciences) software. The Van't Hoff equation was used to represent the relationship of R_s with soil temperature (Hoff, 1898):

$$R_s = Ae^{bT} \tag{2}$$

where, R_s is soil respiration, T is soil temperature, A is the intercept of soil respiration when soil temperature is 0 °C (i.e., reference soil respiration). Moreover, b represents the temperature sensitivity of soil respiration. The Q_{10} value, which describes the change in soil respiration over a 10 °C increase in soil temperature, is calculated as

$$Q_{10} = e^{10b} \tag{3}$$

Considering lower and higher values of soil water content both restrain the soil respiration, we adopt a quadratic equation to simulate the effect of soil moisture on soil respiration according to Davidson et al. (1998):

$$R_s = aV^2 + bV + c \tag{4}$$

where, V is the soil water content and a, b, and c are regressed parameters.

3. Results

3.1 Environmental factors and crop growth

Fig. 2 shows the dynamics of albedo, soil moisture, soil temperature, and cotton leaf area index (LAI), which suggests that these environmental factors and crop growth conditions are modified by PFM and other cultivation practices. Other than two snowfall events occurring in January 2015 and January 2016 that elevated albedo beyond 0.4, the albedo was altered by cultivations as shown in Fig. 2(b). In early March, it was increased by the spring irrigation applied one month before sowing. Then it was decreased by plough several days before mulching on April 20 or so. After plastic mulching in April, the surface albedo had a sudden rise, and then slowly decreased with crop canopy development. Generally, the albedo reached the minimum value with the highest value of LAI during the bud stage in August, and then, increased very slowly with leaf fall.

Spatial distributions of soil moisture and soil temperature were both affected by plastic mulching. As shown in Fig. 2(a), soil moisture in ridges was mostly higher than furrows with the effect of frequent drip irrigation. Fig. 2(c) shows that soil temperature in the mulched ridge was higher than the open furrow. However, in the later growth stages, soil temperature in the furrow became coincident with or even exceeded that in the ridge due to canopy development.

PFM can also affect plant phenology. As shown in Fig. 2(d), LAI started increasing with seed germination, reached its maximum value at the bud stage during August, and then decreased with leaf falling. The LAI in the mulched field was higher than the non-mulched field during the comparative experiment year of 2016, particularly in the vigorous growth stages.

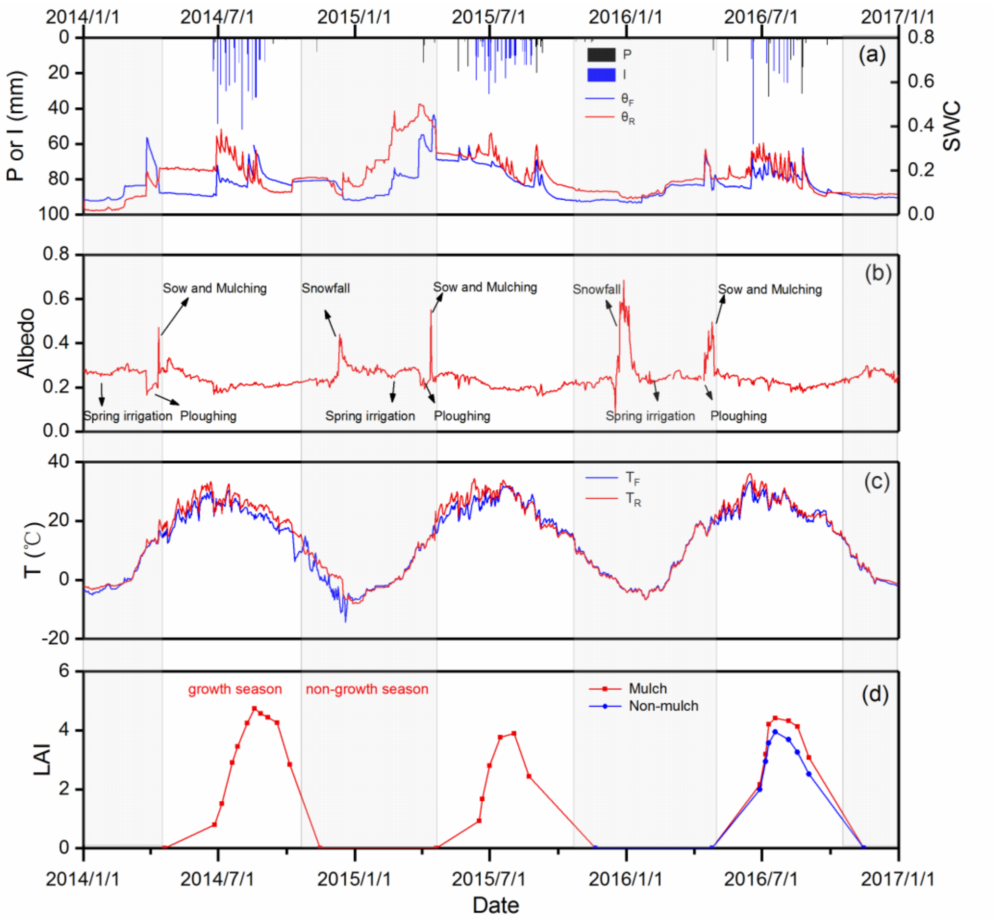

Fig. 2. Environmental factors and crop growth in the PFM field under drip irrigation; (a) SWC (soil water content) in the ridge (θ_R) and furrow (θ_F) affected by irrigation and precipitation; (b) Albedo affected by cultivation practices and snowfall in the mulched field; (c) T (soil temperature) in the furrow (T_F) and ridge (T_R) in the mulched field; (d) LAI (leaf area index) in the mulched and non-mulched fields (LAI comparative measurements were only conducted in 2016). The shadow part indicates the non-growth season.

3.2 Seasonal and spatial variations in soil respiration

As shown in Fig. 3, the magnitude and amplitude of R_s are rather different in different years. For example, soil respiration fluxes in non-mulched ridges were 1-6 μmol m^{-2} s^{-1}, 4-7 μmol m^{-2} s^{-1} and 3-11 μmol m^{-2} s^{-1}, respectively, in the three years. Seasonal R_s variation was generally dominated by soil temperature dynamics (their correlation will be further analyzed in Section 3.4) although some anomalies occurred. For example, on the DOY 180 of 2016, R_s rates in the non-mulched ridge and planting hole obtained peak values, while those from furrows in both mulched and non-mulched fields were pretty low. On the following DOY 192, however, the situation was reverse and on DOY 235 all R_s fluxes experienced an abnormal declining and then rising cycle. These anomalies may be related to the SWC dynamics caused by irrigation and precipitation, which will be further explained in Sections 3.5 and 3.6.

R_s shows a significant spatial variability at field scale. As shown in Fig. 3, the results in 2015 and 2016 indicated a consistent higher soil CO_2 emission rate from the ridge than the furrow in the non-mulched field. In the mulched field as indicated by Fig. 3(c), R_s from the plastic film was very low, while the rate from the planting hole was higher than that from the furrow most of the time. For R_s from the furrow, its rate in the mulched field generally exceeded that in the non-mulched field in 2015 and 2016 except DOY 222 of 2016, which was just after a 12.8-mm rainfall event as shown in Fig. 8.

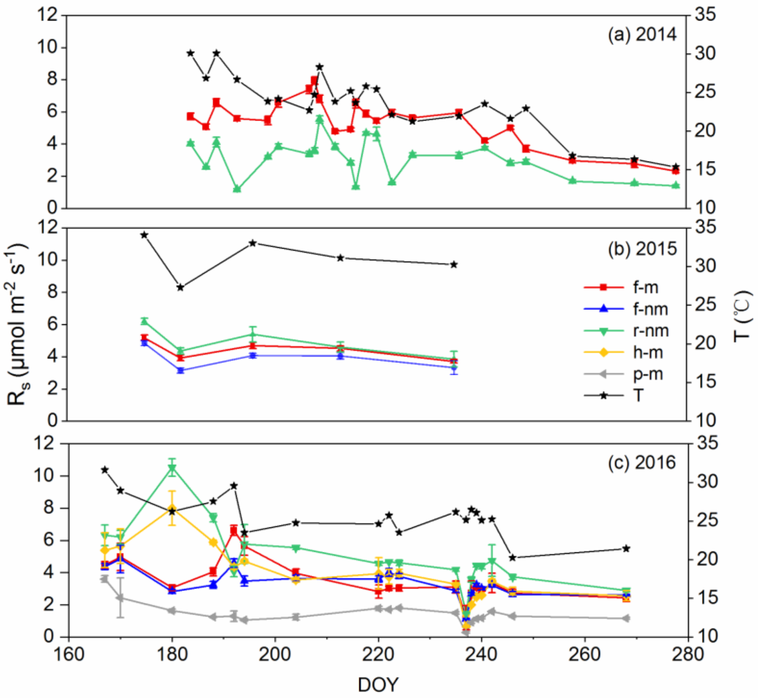

Fig. 3. Spatiotemporal variations of soil respiration in mulched and non-mulched fields over the three years. The whiskers represent the standard deviation of three replicate R_s measurements (f-m, h-m and p-m represent furrow, planting hole, and plastic mulch in the mulched field; f-nm and r-nm represent furrow and ridge in the non-mulched field; T represent soil temperature).

3.3 Comparison of soil respiration in mulched and non-mulched fields

Fig. 4 depicts seasonal accumulative R_s and precipitation over the three experimental years. To be noted, R_s from the mulched ridge is the area weighted summation of the terms from the plastic mulch and planting holes. A prominent feature indicated in the figure is that R_s fluxes over the ridge and furrow in the mulched field are consistently larger than the corresponding terms in the non-mulched field. Although, this magnitude relation was not significant at the furrow in 2015 and 2016 or at the ridge in 2016 at a significance level of 0.05 (Table 1). Totally, seasonal average R_s was 444.69 g C m^{-2} in the mulched field and 359.9 g C m^{-2} in the non-mulched field during the growth period over three years. The accumulative R_s in the mulched field was indeed significantly larger than that in the non-mulched field in the years of 2014 and 2015.

However, for the year of 2016 with substantial precipitation amount of 130 mm, the positive deviation of mulched field R_s was not at a significance level.

Also, the furrow R_s difference between the mulched and non-mulched field was smaller than the difference at the ridge over all the three years and the magnitude of such differences decreased from the year 2014 to 2016. To be noted, seasonal precipitation amount presented an increase trend from the year of 2014 to 2016. This means that more precipitation tends to eliminate R_s differences between mulched and non-mulched fields.

Table 1 *t*-test of significance for soil respiration in furrows, ridges and the total soil respiration between mulched and non-mulched fields (R_m and R_{nm} are the total soil respiration in mulched and non-mulched field, respectively. *df* is the degree freedom, $t_{0.05}(4)$ is the *t* value at the significant value of 0.05 at the *df* of 4).

Year	R_{f-m}/R_{f-nm}	R_{r-m}/R_{r-nm}	R_m/R_{nm}	***df***	$t_{0.05}(4)$
2014	4.92	9.27	7.87	4	2.776
2015	2.25	4.59	4.04		
2016	0.40	1.91	1.52		

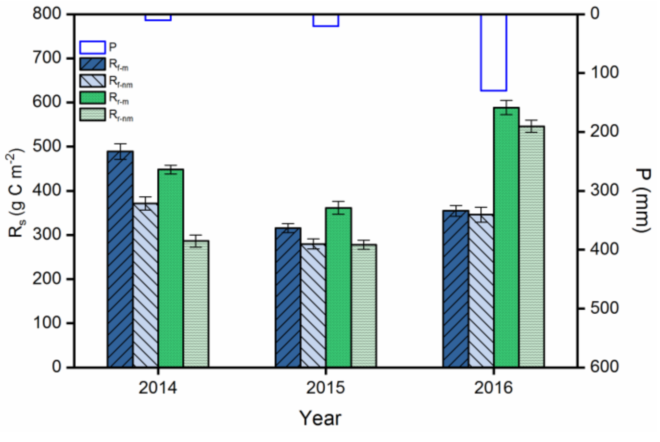

Fig. 4 Seasonal accumulative soil respiration and precipitation over three experimental years. The whiskers represent standard deviations (f-m, r-m represent furrow and ridge in the mulched field; f-nm and r-nm represent furrow and ridge in the non-mulched field).

3.4 Functional relations between soil respiration and soil temperature

All R_s fluxes in different locations of the mulched and non-mulched fields showed increasing trends with temperature (Fig. 5), which were fitted using exponential equation as described in Section 2.3. However, their correlation is very poor and vary with location and time. The furrow possesses higher R^2 than the ridge for relatively stable soil moisture in the furrow. Also, the Q_{10} values in the furrows are much lower than in the ridges.

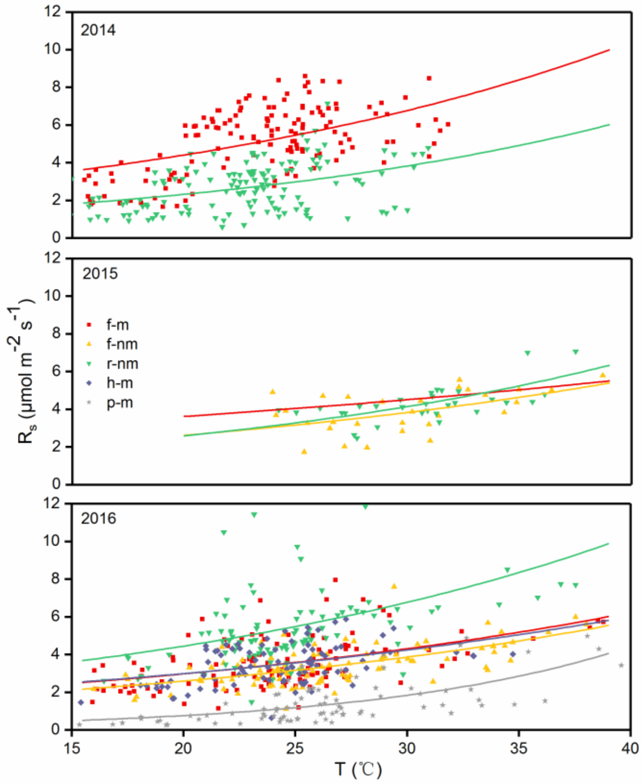

Fig. 5. Relations between soil respiration and soil temperature at different locations in mulched and non-mulched fields. The data represent means ± standard deviation (SD) of three replicates. The regression lines for different locations were fitted with Equation 2 and the regression equations are shown in Table 2 (f-m, h-m, p-m represent furrow, planting hole, plastic mulch; f-nm and r-nm represent furrow and ridge in non-mulched fields).

Table 2 Parameters for fitted exponential equations of soil respiration with soil temperature for different locations in mulched and non-mulched fields (refer to Equations (2) and (3))

Year	**Parameters**	**f-m**	**f-nm**	**r-nm**	**h-m**	**p-m**
2014	a	1.87		0.86		
	b	0.04		0.05		
	Q_{10}	1.54		1.65		
	R^2	0.29		0.18		
2015	a	2.33	1.23	1.01		
	b	0.02	0.04	0.05		
	Q_{10}	1.25	1.46	1.60		
	R^2	0.18	0.27	0.43		
2016	a	1.42	1.16	1.92	1.48	0.13
	b	0.04	0.04	0.04	0.04	0.09
	Q_{10}	1.45	1.49	1.52	1.42	2.41
	R^2	0.23	0.39	0.20	0.18	0.44

3.5 Irrigation and soil respiration

The year 2014 was chosen to investigate the response of R_s to irrigation for very few precipitation events occurring in this year and the results are shown in Fig. 6. It is clear that soil moisture in the non-mulched ridge was always lower than the furrow in the mulched field except for some days immediately after irrigation. Reasonably higher soil moisture favors soil respiration and consequently R_s from the furrow in the mulched field was always higher than from the non-mulched ridge. Another dominant feature shown in Fig. 6 is the quick response of soil moisture and R_s to irrigation. Soil moisture experienced a quick rising, while R_s witnessed a diving after irrigation, which means that too much water in soil may conversely restrain its respiration. Due to the configuration of drip tape and plastic mulch, soil moisture and respiration in the ridges of mulched and non-mulched fields experienced similar but more drastic variations than the furrow.

To investigate the response of R_s to irrigation in more detail, the R_s dynamics within an irrigation cycle was explored. As R_s measurements were conducted randomly between two irrigation events, data on different days after irrigation were collected to analyze the R_s variation. The irrigation effect is presented by plotting R_s versus the number of days after irrigation with an irrigation cycle of approximately 6 days. The results in Fig. 7(a) shows again that R_s rate in the non-mulched ridge was extremely low immediately after irrigation, and then recovered slowly. While in the furrow of the mulched field, irrigation had almost no influence on soil respiration. Both R_s rates from the furrow and ridge reached the maximum values on the fourth day after irrigation and then began to decrease with soil drying process. The relation between R_s and soil moisture can be expressed in the form of a binomial equation as shown in Fig. 7(b), which indicates that R_s is very low with dry soil and increases with soil moisture. However, R_s shows a declining trend when soil moisture exceeds a certain threshold. The threshold is approximately 0.25 in the furrow of the mulched field and approximately 0.2 in the non-mulched ridge. The above thresholds are approximately 60% and 50% of the water-filled pore space (WFP), respectively.

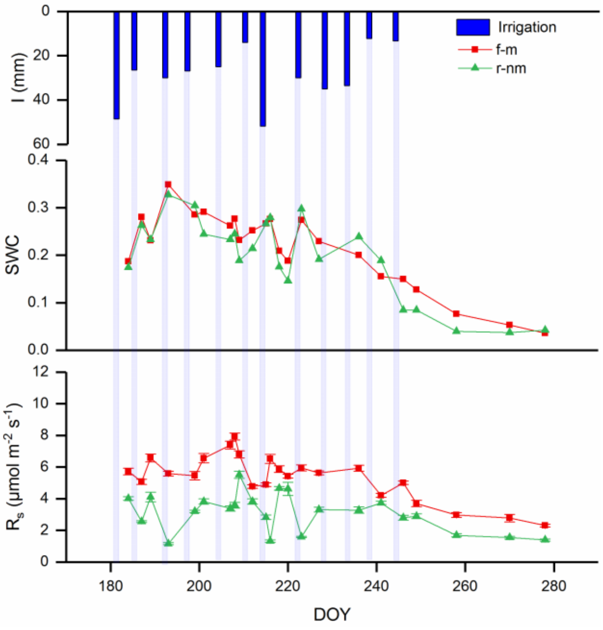

Fig. 6. The responses of soil moisture and respiration to irrigation at different locations in the mulched and non-

mulched fields in 2014 (f-m and r-nm represent furrow in the mulched field and ridge in the non-mulched field).

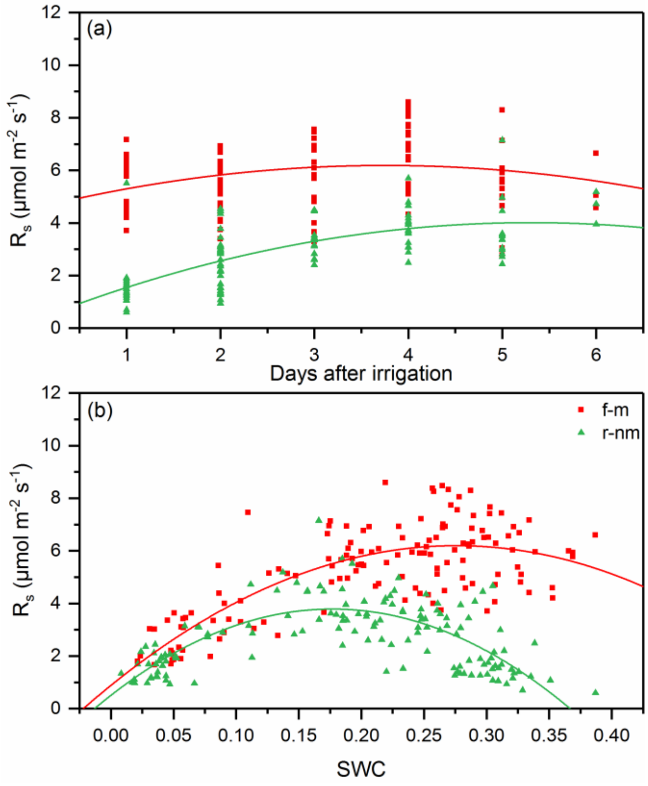

Fig. 7. Influence of irrigation on soil respiration. (a) Variation of soil respiration with number of day after irrigation. (b) Relation between soil respiration and soil moisture (regression lines are fitted with the binomial equation as shown in Equation (4)). (f-m and r-nm represent furrow in the mulched field and ridge in the non-mulched field)

3.6 Precipitation and soil respiration

The year 2016 was chosen to investigate the response of soil respiration to precipitation because significant amount of rainfall occurred in this year. As shown in Fig. 8, R_s exhibited similar response behavior to irrigation in the planting hole, plastic mulch, and non-mulched, while it presented similar response behavior to precipitation in the furrows of mulched and non-mulched fields. Particularly, three large rainfall events with the amount of 12.8 mm, 36.8 mm, and 48 mm occurred on the DOY 222, 192, and 235 of 2016, respectively. As we can see from the Fig. 8, the light event (12.8 mm) had little effect on soil moisture and R_s, the moderate event (36.8 mm) restrained R_s in the non-mulched ridge and planting hole but motivated R_s in the furrows of the mulched and non-mulched fields, while the heavy event (48 mm) restrained R_s in all parts of the mulched and non-mulched fields.

Taken the heavy event as an example, the effect of precipitation on R_s in a wetting-drying cycle was more closely investigated before and after the event. As shown in Fig. 9, R_s rates at all locations were restrained by substantially high soil water content. It was even substantially restrained in the mulched ridge where soil water content was only 0.15. This finding means that soil moisture threshold to restrain R_s under precipitation is less than that under irrigation. It is noteworthy that it took roughly one day for R_s to return back to a normal rate after precipitation. This is much shorter than that associated with irrigation.

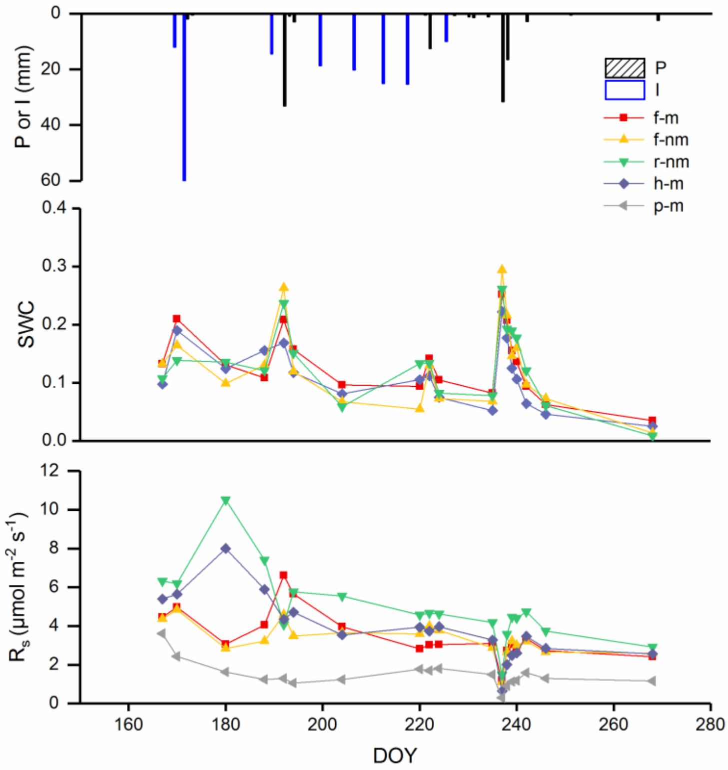

Fig. 8. Response of soil moisture and soil respiration to precipitation and irrigation during 2016. (f-m, h-m and p-m represent furrow, planting hole, and plastic mulch in the mulched field; f-nm and r-nm represent furrow and ridge in the non-mulched field)

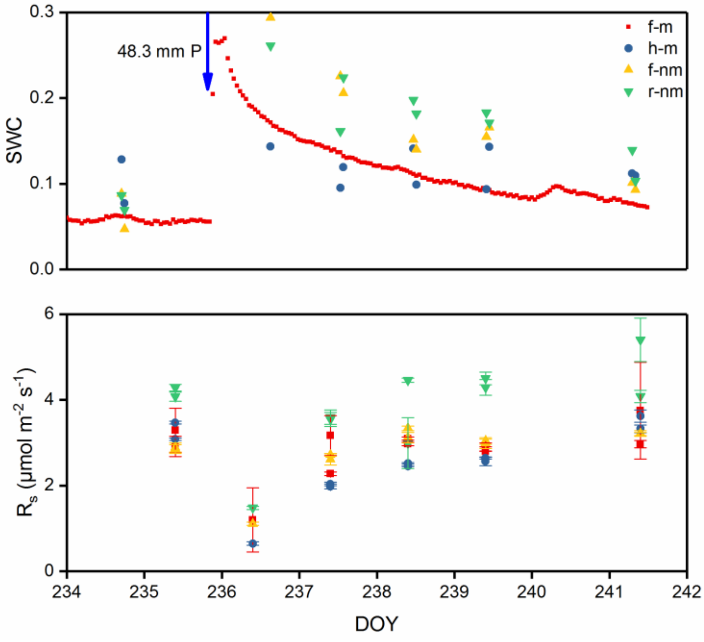

Fig. 9. Variations in soil moisture and soil respiration in a wetting-drying cycle after a heavy rainfall.

4. Discussion

4.1 Effect of plastic mulch on soil respiration

Our experiment indicates that the planting hole emitted more CO_2 than the furrow (Fig. 3), and the plastic mulch itself can also emit CO_2 at a rate of 3.6 μmol m^{-2} s^{-1}. Considering that the plastic mulch occupies most of the ridge area, it is also an important pathway for CO_2 emission in the mulched field. In fact, the soil CO_2 emission rate of the plastic mulch depends on film features including thickness, texture and color. For example, according to Berger et al. (2013) thick black PE mulch has an extraordinarily low N_2O emission, while high N_2O can be emitted from a polyethylene film only 0.02 mm thick (Nishimura et al., 2012). Liu et al. (2016b) also reported that the transparent plastic film emits more CO_2 than the black plastic mulch. Local farmers in our study area often use clear polyvinyl chloride (PVC) film with a thickness of only 0.008 mm for its low price. This film has a relatively high diffusion capacity for CO_2 as indicated by our results. In a word, the planting hole, furrow, and plastic mulch are primary pathways that are responsible for CO_2 emissions in a mulched field. A comprehensive measurement scheme at different locations is, therefore, necessary to detect R_s in a mulched field. Our results can be potentially used to correct the reported CO_2 emissions conducted only at the furrow in a mulched field (Qian-Bing et al., 2012;Liu et al., 2016b).

Our experiment also indicates higher soil CO_2 emission rates from furrows and ridges in the mulched field compared to the corresponding terms in the non-mulched field. Therefore, PFM can indeed promote soil respiration in our study area. This is principally due to the improved soil temperature, soil moisture and crop growth by plastic mulching (see Fig. 2). Improved crop growth condition produces more root biomass and litter fall, which will promote root respiration and litter fall decomposition. Moreover, improved soil temperature and soil moisture can promote the activities of roots and microorganisms to increase mineralization of soil organic carbon, for example, by stimulating the decomposition of buried crop straw (Wang et al., 2016). This result can be partly confirmed by Yu *et al.* (2016) who reported that furrow R_s in the mulched field is greater than the non-mulched field. However, they also reported that R_s rates from mulched and non-mulched ridges are similar, which is different from our results. Furthermore, some other studies obtained the contrary conclusion (i.e., PFM decreases R_s) in northern Xinjiang Uygur Autonomous Region of China (Li et al., 2011), the Loess Plateau of China (Xiang et al., 2014), the Southwest of China (Lei, 2016) and central Japan (Okuda et al., 2007). Also, Berger *et al.* (2013) found that PFM significantly decreases N_2O emission in South Korea. Therefore, the effect of plastic mulch on R_s presents different features in different areas. Our work reveals that R_s difference between mulched and non-mulched fields depends on the precipitation amount. This could be the reason leading to the opposite results, which will be discussed in more detail in the following section.

4.2 Effect of irrigation and precipitation on soil respiration

Our results indicate that a substantially high SWC right after irrigation and precipitation restrained R_s, and this effect decreased as soil moisture returned to the normal level (Fig.7a, Fig. 9). In contrast, in natural ecosystems precipitation always increases R_s immediately, such as the water addition after long-drought in a tallgrass prairie ecosystem in Oklahoma, USA (Liu et al., 2002), and the 12-mm precipitation in an oak/grass savanna ecosystem in California (Xu and Baldocchi, 2004). This is due to the so called soil degassing effect, which is the non-steady-state CO_2 efflux at the soil surface occurring mostly during rainfall or irrigation after long periods of drought (Luo and Zhou, 2006). In agricultural systems, however, frequent irrigation is applied to satisfy crop water requirements which maintains favorable soil moisture. This further renders higher R_s than natural ecosystems particularly in the arid areas. Our results further indicate that both too low and too high SWC can restrain R_s, which can be expressed by a quadratic equation (Fig. 7b). This is because that lower water content affects the diffusion of soluble substrates, while higher water content affects the diffusion and availability of oxygen (Davidson et al., 2006;Linn and Doran, 1984). Our result confirms Wang et al. (2010) who reported that irrigation stimulates R_s but too much water reduces it especially shortly after the irrigation. Compared to our quadratic functional relation between SWC and R_s, the effect of SWC on R_s has also be described by linear, logarithmic or parabolic functions in different ecosystems around the world (Davidson et al., 2000). For example, in a mountain oasis of Oman, soil respiration is described to linearly correlate with SWC (Wichern et al., 2004). To be noted, the range of SWC in Wichern et al. (2004) is from 0.14 to 0.25, which is smaller than soil moisture threshold to restrain R_s obtained in our study. More theoretical efforts should be made to reconcile different experimental results and obtain a general relationship between SWC and R_s.

Our results indicated that the correlation between R_s and temperature, and the temperature sensitivity (i.e. Q_{10}) are rather low in our PFM field equipped with drip irrigation (Table 2). The obtained R^2 values of 0.18-0.44 are much smaller than the reported values in natural ecosystems, such as in a tall grass prairie in central Oklahoma, USA with R^2 of 0.77-0.97 (Luo et al., 2001), and in the Harvard Forest in central Massachusetts, USA with R^2 of 0.8 (Davidson et al., 1998). The obtained Q_{10} values of

1.25-1.65 (Table 2, expect for the planting hole) are below the median of 2.4 reported in a literature review of global soil respiration (Raich and Schlesinger, 1992). Also, they are much smaller than the Q_{10} of 3.8 in a rain-fed maize cropland in the Loess Plateau of China (Xiang et al., 2012). Comparatively, higher correlations between R_s and SWC indicate that SWC may be the main factor affecting R_s in the PFM field under drip irrigation. Lower Q_{10} values indicate that the sensitivity of R_s to temperature has been weakened by higher variation of soil moisture induced by irrigation and precipitation.

Our results clearly reveal the confounded influence of PFM and precipitation on soil respiration. The hydrological responses to precipitation in the field are changed by the impermeable plastic mulch, which is the reason that the effect of precipitation on R_s is different in the mulched and non-mulched fields. For example, the R_s rate in the non-mulched ridge was higher than in the furrow of mulched fields and planting holes during 2016 with more precipitation. However, the result was contrary in 2014 and 2015 with less rainfall. Also, although soil respiration rate in the mulched field was always higher than in the non-mulched field during all the three years, the significance of such magnitude relation decreased with increased precipitation. Therefore, we can speculate that the magnitude at which the mulch accelerating soil respiration should be related to the precipitation amount.

To verify the above speculation, a meta-analysis was carried out. The relationship of the amount of annual precipitation P with the differences of annual R_s (noted as dF, i.e., R_s in the non-mulched field minus that in the mulched field) was analyzed (Fig. 10). The relevant studies include an arid area (P=45.7 mm) in southern Xinjiang (Yu et al., 2016), a semiarid area (P=160 mm) in northern Xinjiang (Li et al., 2011), a semi-humid area (P=566.8 mm) on the Loess Plateau of China (Xiang et al., 2014), a subtropical monsoon area (P=1,105mm) in Southwest of China (Lei, 2016) and a temperate monsoon climate area (P=1,954 mm) in Japan (Okuda et al., 2007). The dF was found to have a linear relationship with the amount of precipitation. Under 200-mm annual precipitation condition, R_s rates in the mulched and non-mulched fields are roughly identical. For the fields with annual precipitation greater than 200 mm, R_s was lower in the mulched field than the non-mulched field. This is reason why some studies obtained the contrary conclusion with our results that PFM decreases R_s.

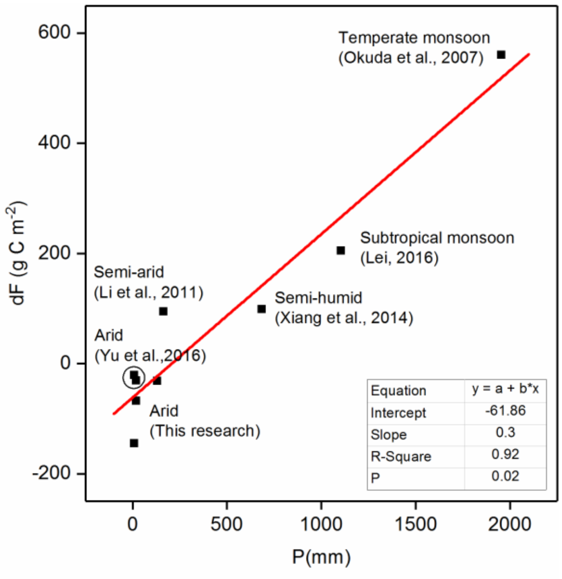

Fig. 10 The relationship of the difference in soil respiration between the mulched and non-mulched fields with precipitation, *dF* means the soil respiration in non-mulched field minus that in mulched field. In the five points of arid areas, the data from (Yu et al., 2016) is in the circle, while our research is out of the circle.

5. Summary

PFM is now widely used in agriculture around the world due to the continuous fall in the prices of plastic products, particularly in developing countries such as China. The changing land cover with a mass of PFM fields and the changing climate will affect the energy, water and carbon cycle regionally or globally. From the comprehensive analysis and discussion about the effect of plastic mulch, irrigation and precipitation on soil respiration with our controlled experimental results, some new findings were discovered in this study. First, PFM can enhance spatial heterogeneity of soil respiration under drip irrigation, and the planting hole, furrow, and plastic mulch (sort by the emission rate) are three important pathways for surface soil CO_2 emission. Second, PFM can increase soil respiration at field scale in arid areas, while this enhancement depends on precipitation amount. The linear relationship has been found between soil respiration difference (between non-mulched and mulched fields) and precipitation amount at annual scale. PFM is, therefore, benefit for carbon sequestration in wet areas, while it is harmful in arid areas. Third, frequent water supplies elevate soil moisture and soil respiration as well as enhance their variations. The resultant higher variation of soil moisture further alleviates the sensitivity of soil respiration to soil temperature leading to poor correlation and lower Q_{10} values.

Our results suggest that the rapid expansion of PFM fields in arid areas brings new challenges for controlling greenhouse gas emissions. PFM and irrigation should be better depicted in future soil carbon models. Linking the hydrologic and carbon cycles via the conservation of water resources is crucial for improving agronomic yields and soil carbon sequestration in dryland.

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