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ORIGINAL PAPER

Partial root-zone drying (PRD) leads to lower carbon retention in the soil-plant systems of alfalfa

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Abstract

Pastures play vital roles in carbon (C) sequestration and the global C balance. Partial root-zone drying (PRD) is widely known to reduce water consumption with a minimum impact on alfalfa productivity in the field. A 2-year field experiment was used to investigate the effects of PRD on C retention in the soil-plant systems of alfalfa. This field experiment consisted of two factors (irrigation modes and irrigation volumes) in a split-plot design. The two irrigation modes were PRD and conventional furrow irrigation, and the four irrigation levels were 70%, 85%, 100%, and 115% alfalfa potential evapotranspiration. This study showed that PRD increased the C in alfalfa plants due to higher C in alfalfa roots. PRD led to higher soil organic C storage, whereas it led to lower soil total C and soil inorganic C storage. PRD was found to decrease the C retention in the soil-plant systems of alfalfa. The findings of this study display a pattern of PRD influencing C retention in the soil-plant systems of perennial crops, and imply that PRD reduces the C sequestration potential of alfalfa pastures.

Introduction

Perennial pasture is an agricultural system with significant potential for carbon (C) sequestration (Silveira et al. 2020). Increasing perennial pastures throughout the world (Cavero et al. 2017; Pozo et al. 2017; Djaman et al. 2020) can sequester more CO_2 from the atmosphere (Liu et al. 2011; Guan et al. 2016) and further mitigate global warming (Chan et al. 2010; Liu et al. 2011; Carmona et al. 2020a). Agronomic measures, such as irrigation, fertilization and tillage (Bhattacharyya et al. 2013; Guan et al. 2016), are usually used to increase the crop productions, which often encourages more atmospheric C dioxide to be stored in plant biomass (Cavero et al. 2017; Zhang et al. 2021b), however, these agronomic measures inevitably influence the C sequestration potential in the soil-plant systems (Wang et al. 2010; Sun et al. 2013). The C retention in the soil-plant systems is often considered an effective agent to estimate the C sequestration potential (Reeder and Schuman 2002; Koteen et al. 2011; Carmona et al. 2020b). Generally, the C retention in the soil-plant systems is assessed by the C in plants and the changes of soil C storage (Olson 2013). Previous studies have shown that three-years strip-tillage (Al-Kaisi et al. 2005) and irrigation within a year (Chandel et al. 2021) lead to higher soil organic C (SOC). These demonstrate that agronomic measures possibly influence the C retention in the soil-plant systems through changing plant biomass (Xiao et al. 2015;

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Djaman et al. 2020; Wang et al. 2021) and soil C storage in a short term (Al-Kaisi et al. 2005; Wang et al. 2010; Chandel et al. 2021).

Partial root-zone drying (PRD) is a water-saving irrigation technique and it can save irrigation water with a minimum impact on crop productivity (Shahnazari et al. 2008; Abboud et al. 2019; Mehrabi and Sepaskhah 2019; Zhang et al. 2021a). This water-saving technique has been widely applied to the production of many densely planted crops in arid and semiarid regions, such as potato (*Solanum tuberosum*) (Shahnazari et al. 2008), alfalfa (*Medicago sativa*) (Xiao et al. 2015; Zhang et al. 2021b; Wang et al. 2021), tomato (*Lycopersicon esculentum*) (Mingo et al. 2004) and winter wheat (*Triticum aestivum*) (Mehrabi and Sepaskhah 2019). PRD has been found to improve the total root length of rice (*Oryza sativa*) (Fang et al. 2018), the quality and productivity (Xiao et al. 2015; Wang et al. 2021), root biomass and branches of alfalfa (Li et al. 2020), and reduce the stomatal conductance of winter wheat (*Triticum aestivum*) (Mehrabi and Sepaskhah 2019). In addition, a few studies have used pot experiment to examine the effect of PRD on C retention in the soil-plant systems of annual crops, such as potato (Wang et al. 2010) and tomato (Sun et al. 2013), and these studies have found that PRD can decrease the C retention in the soil-plant systems of annual crops (Wang et al. 2010; Sun et al. 2013). Plant roots are important parts to sequester C, in which the root systems of perennial crops survive for many years, while the roots growth of annual crops are usually observed in one growth season. Thus, the potential of sequester C may be different between perennial crops and annual crops. The perennial crops have been found to have more sustainability and greater potential to sequester C than annual crops (Chan et al. 2010; Pozo et al. 2017) because the root system of perennial crops survive for many years. However, whether PRD influences C retention in soil-plant systems of perennial crops is not well documented.

Alfalfa is a perennial crop with high yield and good quality for livestock (Deng et al. 2014; Djaman et al. 2020), and this crop also improves soil nitrogen content because of its nitrogen-fixing effect (Guan et al. 2016; Pozo et al. 2017). Alfalfa is widely grown in North America (Picasso et al. 2019), South America (Pozo et al. 2017), Asia (Xiao et al. 2015), Europe (Cavero et al. 2017), Africa (Li et al. 2020), and Oceania (Greenwood et al. 2009) and covers approximately 2.380 × 10^7 ha worldwide (Xie et al. 2021). These large alfalfa pastures are vital to sequester CO_2 from the atmosphere (Guan et al. 2016). Irrigation is often required to maintain high alfalfa yield because alfalfa commonly suffers from water stress in arid and semiarid regions (Djaman et al. 2020; Wang et al. 2021; Pozo et al. 2017). PRD has been found to improve the water use efficiency of alfalfa plants (Xiao et al. 2015; Li et al. 2020; Wang et al. 2021), and increase the C concentration in alfalfa roots and decrease the soil bulk density (Zhang et al. 2021a), while it has no effect on the C concentration in alfalfa leaves and stems (Zhang et al. 2021b). Therefore, more studies are needed to verify whether PRD influences the C retention in the soil-plant systems of alfalfa, which can provide more information for extension of PRD in alfalfa production, and present a pattern of PRD influencing the C retention in the soil-plant systems of perennial crops.

This study considers alfalfa as a focal crop to investigate the effects of PRD on the C in alfalfa plants and soil C storage, and further examine the PRD in relation to the C retention in the soil-plant systems of perennial crops through a 2-year field experiment. Here, this study hypothesizes that (1) PRD increases the C in alfalfa plants because PRD can increase alfalfa root biomass and C concentration (Zhang et al. 2021b); (2) PRD decreases the soil C storage of alfalfa pasture because PRD can decrease soil bulk density in alfalfa pasture (Zhang et al. 2021a); and (3) PRD decreases the C retention in the soil-plant systems of alfalfa because PRD can decrease the C retention in the soil-plant systems of annual crops (Wang et al. 2010; Sun et al. 2013).

Materials and methods

Experimental site description

The field experiment was conducted at Huangyang Farmland Station (37°42′ N, 102°48′ E, elevation 1710 m) during the period of 2017–2019, and this station was located in Wuwei city of Gansu Province, China. The climate at this station is typical continental temperate, similar to Dwa with the characteristics of snow, winter dry and hot summer in Köppen-Geiger Climate Classification. Based on meteorological data from 1996 to 2015, the average annual temperature and annual precipitation were 9 °C and 175 mm, respectively, and the mean annual evaporation was 2000 mm. 80% of the precipitation occurred from June to September. According to the Chinese soil classification system (Gong 2001), the soil type was medium loam, similar to irragric anthrosols in the World Reference Base for soil resources. This soil type is characterized by soil bulk density with 1.49 ± 0.05 g cm^{-3}, and field capacity with 1.49 ± 0.05 g cm^{-3}. In addition, the wilting point by weight was 0.0805 ± 0.0003 g g^{-1}. The basic soil chemical properties in the experimental field were measured as follows: pH was 8.20, and total N, P, K were 0.86, 1.34, 11.92 (g kg^{-1}), respectively; soil organic carbon was 12.90 (g kg^{-1}), and hydrolysable N, Olsen-P and exchangeable K were 33.50, 28.39, 253.18 (mg kg^{-1}), respectively (Zhang et al. 2021a, b).

During the experiment, the maximum temperature, minimum temperature, average temperature and average monthly precipitation in 2018 and 2019 were collected from the

Wuwei meteorological station and are shown in Table S1. The Wuwei meteorological station is 36 km away from the Huangyang Farmland Station. The maximum temperatures were 40.7 °C and 35.0 °C, average temperatures were 7.7 °C and 8.5 °C, and annual precipitations were 263.4 mm and 206.6 mm in 2018 and 2019, respectively. The total precipitation during the growing seasons was 133.5 mm in 2018 and 172.5 mm in 2019, most of which primarily occurred from April to August.

Experimental design

The field experiment included two factors (two irrigation modes and four irrigation volumes) in a split-plot design. Irrigation modes were regarded as main factors, and irrigation volumes were regarded as subfactors. The two irrigation modes were PRD and conventional furrow irrigation (CFI).

Determination of irrigation volumes

The irrigation volumes were determined by alfalfa potential evapotranspiration (ETc), and they were 70% ETc (I_1), 85% ETc (I_2), 100% ETc (I_3) and 115% ETc (I_4). Because PRD treatment received 50% of the irrigation water volume of CFI at each irrigation event, this study designed the lowest irrigation volume as 70% ETc (Zhang et al. 2021b), which can prevent the effects of excessive drought on alfalfa in plots with PRD. ETc was quantified by the Penman-Monteith formula as $\mathrm{ETc} = \mathrm{Kc} \times \mathrm{ET}_0$ (Allen et al. 1998), where Kc was crop coefficient and ET_0 was the average value of potential evapotranspiration over 20-years. The potential evapotranspiration for each year was calculated with climatic data from 1996 to 2015, which were collected from the local meteorological station. The Kc was 0.88 for alfalfa (Xiao et al. 2015). The ETc was estimated to be 943 mm at the experimental site during the whole alfalfa growing season.

Construction of furrows and ridges

This field experiment included 8 treatments: PRD-I_1, PRD-I_2, PRD-I_3, PRD-I_4, CFI-I_1, CFI-I_2, CFI-I_3, and CFI-I_4. The irrigation volumes during 2018–2019 are shown in Table S2, in which total water volumes of 1525 mm and 3051 mm were irrigated in PRD and CFI conditions in 2018, and total water volumes of 1744 mm and 3488 mm 2019 were applied to PRD and CFI conditions during 2019. PRD is usually practiced by alternate furrow irrigation in the field referring to previous studies (Xiao et al. 2015; Zhang et al. 2021a). The flat experimental field in alternate furrow irrigation was converted into many furrows and ridges, in which furrows were used to irrigate water and ridges were used to grow crops. All furrows were classified into an odd number group and an even number group. In PRD conditions, irrigation was conducted in odd number furrows at the first irrigation time, and it was conducted in even number furrows at the subsequent irrigation time (Zhang et al. 2021b). In contrast, irrigation was conducted in each furrow at each irrigation time in CFI condition.

Since the household contrast responsibility system was implemented in the 1980s in China, the area size of alfalfa pasture parcels has ranged from 1000 to 5000 m^2 in Wuwei city of Gansu Province, China (Qu et al. 1995; Zhang et al. 2021a). The household survey showed that most alfalfa pasture parcels were 1000–4000 m^2. Thus, this study selected a about 3500 m^2 (89 m × 39 m) cropland to establish the experimental field. The experimental field was divided by two buffer zones with a width of 1 m into three blocks as three replications. Each block with a size of 89 m × 13 m was divided into 8 subplots, and a 1 m wide isolation belt was set up among the subplots to avoid lateral water transmission (Wei et al. 2016). Each subplot had a length of 11 m and a width of 10 m, and it was equipped with 13 ridges and 14 furrows. The ridges were approximately 0.5 m apart which was determined in previous study (Zhang et al. 2021a), and carried out a pre-experiment to ensure the soil dry-wet cycle in PRD truly occurred. The length, width and height of each ridge were 10, 0.5 and 0.2 m, respectively. The length of each furrow was 10 m, and its top width, bottom width and depth were 0.3, 0.25 and 0.2 m, respectively. Each subplot was surrounded by high ridges that were 30 cm wide and 30 cm tall to avoid surface runoff. There were 24 subplots in total.

Establishment of alfalfa pasture

On March 25th, 2017, the field was plowed, harrowed, and rolled, in which the trash and roots were cleared to ensure the uniformity of the experimental field. According to the experimental design, 24 subplots were established. On April 7th, 2017, the same amount of water (40 mm) was irrigated, and 75 kg ha^{-1} urea (N 46%) and 650 kg ha^{-1} calcium superphosphate (P_2O_5, 15.5%) were applied in each subplot. On April 8th, 2017, the furrows and ridges were manually established in each subplot, and a hole-sowing machine was used to sow alfalfa seeds in two rows at each ridge. The distance between two rows was 30 cm, and the distance between two holes was 15 cm, in which the 8–10 alfalfa seeds were sown in each hole and the sowing depth of seeds was 3 cm. Alfalfa variety was "8920-FM" from Canada, which had been widely planted in the experimental region with good quality and high yield.

Conduction of partial root-zone drying

Irrigation water was delivered from the well with an electrical pump and was stocked in a water tank. An 80 mm diameter flexible hose with a flow meter and switch at the end of this flexible hose was used to move water to each subplot, which ensured the approximate consistency of water at each subplot. This flexible hose was moved to the next subplot when one subplot was irrigated according to the experimental design.

The irrigation times were determined by the critical water requirement stage of alfalfa and the experience of local farmers. The irrigation times during the period of 2018–2019 were shown in Table S3, in which irrigation times were 8 times at each experimental year. In 2018 and 2019, alfalfa pastures were irrigated at the re-greening stage after winter, and the next irrigation events were conducted after each harvest and the next branch stage, which can ensure the occurrence of the dry-wet cycle of soils in PRD and healthy growth of alfalfa in CFI. The harvest time was performed when approximately 10% of alfalfa branches were blooming in most subplots (Djaman et al. 2020). If extreme precipitation occurred during the experiment, the irrigation schedule was delayed by one week to ensure that PRD truly occurred (Wang et al. 2021). The alfalfa pastures were treated with pesticides to control weeds and aphids, and fungal diseases, and these treatments were performed in accordance with the local farmers from 2017 to 2019.

Method of measuring soil water content

The main effect of PRD of crops is the alternated spatially and temporally to produce wet-dry cycles in the root systems of plants (Shahnazari et al. 2008), and the changes of soil water content is the basic way to judge the PRD truly occurred. The soil water content was monitored at 10-day intervals, with 20-cm depth increments of the vertical soil layer to a depth of 200 cm because the perennial alfalfa roots in the study regions were found to be over 100 cm (Clément et al. 2022). In each subplot, a soil auger with a diameter of 4 cm and height of 20 cm was used to randomly collect soil samples in odd and even furrows, respectively, with three replicates in odd and even furrows in each subplot. Each hole created by soil auger was filled quickly with experimental field soil to avoid water infiltration. The three soil samples from the same soil layer were mixed as a fresh composite soil, and this fresh composite soil was weighed immediately and then put into an aluminum box with known weight, carried back to the laboratory, and dried at 105 °C to reach a constant weight. The aluminum boxes with dry composite soil were weighed again. The soil water content was determined by dividing the decrement of dry composite soil with the fresh composite soil. The soil water content was calculated by averaging the odd and even furrows and is shown in Fig. 1 in PRD and CFI.

Plant and soil sampling

Since alfalfa is a perennial crop, the sampled roots impacted the next root sampling and the accuracy of shoot biomass. Zhang et al. (2021a) proposed a framework to collect plant root and soil samples in alfalfa pastures in field (Fig. 2), which can avoid the effect of first root and soil sampling on the next sampling. In this framework, three quadrats of 1 m × 1 m were placed along the diagonal of each subplot for sampling alfalfa shoots, and these quadrats were 0.5 m away from the boundary of the subplot. For each quadrat to sample alfalfa shoots, 6 paired areas were correspondingly placed to sample roots and soils, in which two areas along

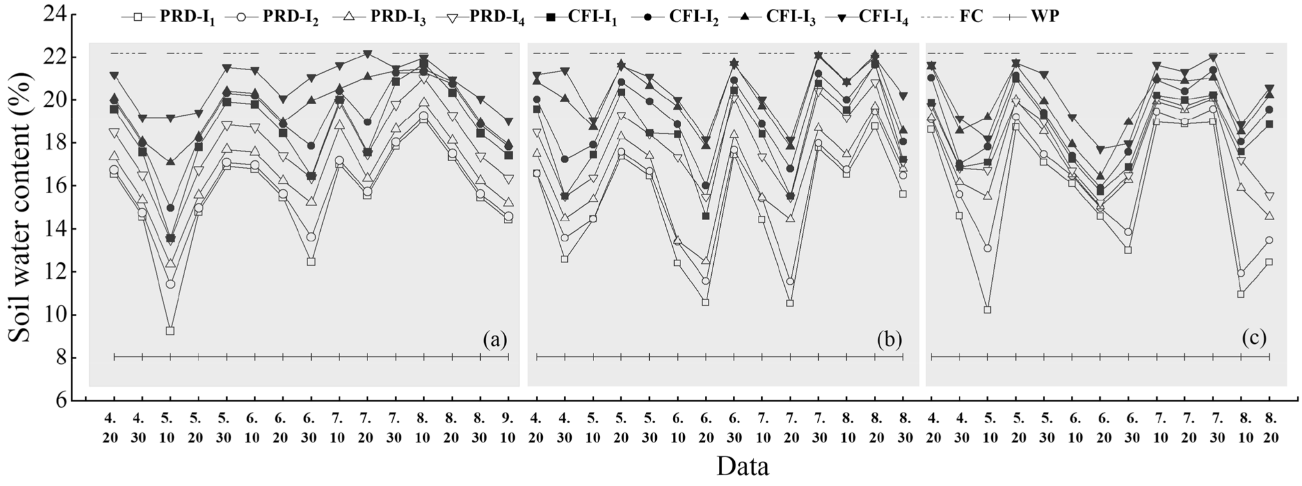


Fig. 1 Seasonal variations in soil water content as affected by irrigation modes and irrigation volumes in 2017 (**a**), 2018 (**b**) and 2019 (**c**). *PRD* partial root-zone drying, *CFI* conventional furrow irrigation, I_1 70% of alfalfa evapotranspiration, I_2 85% of alfalfa evapotranspiration, I_3 100% of alfalfa evapotranspiration, I_4 115% of alfalfa evapotranspiration, *FC* field capacity, *WP* wilting point

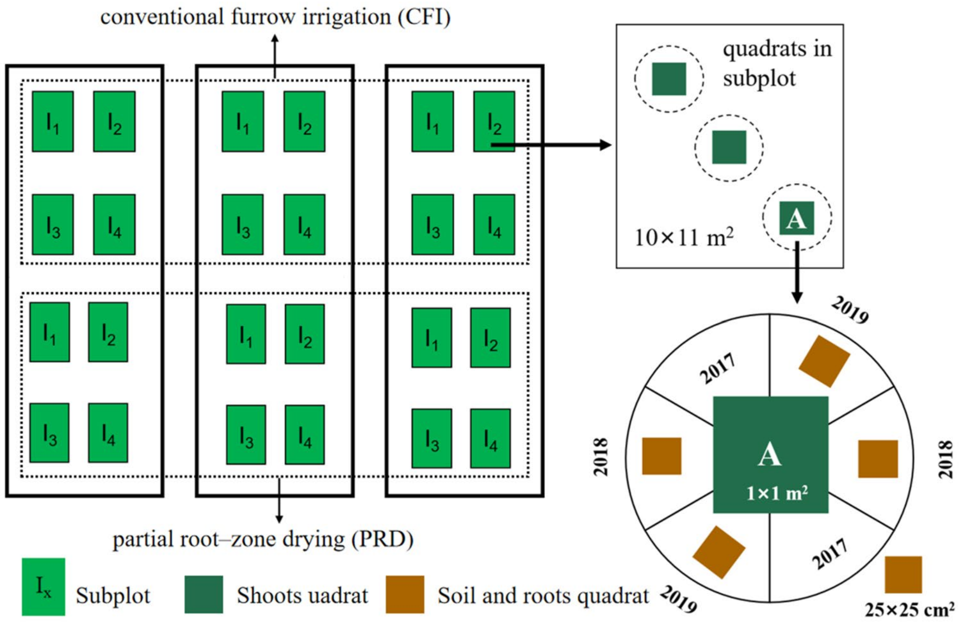


Fig. 2 Split-plot design and framework of first root and soil sampling, and the next sampling at each subplot during 2018 and 2019

the diagonal were used in each year. A quadrat with a size of 25 × 25 cm^2 was used to collect root and soil samples.

More root biomass contributes to C stabilization in perennial pasture (Rasse et al. 2005) and the 2-year alfalfa pasture has a relatively steady yield (Guo et al. 2005; Xiao et al. 2015). Thus, this study sampled the plants and soils from 2018 to 2019 to quantify the C retention in the soil-plant systems of alfalfa. The shoots were harvested 4 times in 2018–2019 (Table S4), while roots and soils were sampled at the last shoot harvested in a growing season. Root and soil samples were collected intermittently by a cube soil column (25 × 25 × 20 cm^3) at 20 cm intervals, which ranged from 0 to 100 cm. First, the cube soil column was screened out garbage and stones and then divided into root samples and soil samples by a 2 mm sieve; second, all root samples from two soil cube columns were mixed as the root composite samples, and soil samples at the same layer from two cube columns were mixed as the soil composite samples at different soil layers. The shoots, roots and soil samples were stored at 4 °C until analysis. In addition, the soil profile produced by cube soil columns were used to collect soils for analyzing soil bulk density.

Sample analysis

The alfalfa shoots were divided into leaves and stems, in which the titbit was classified as leaves. Root samples were carefully washed with tap water three times and then washed with deionized water once. Leaf, stem and root samples were dried at 65 °C to reach a constant weight. Dried samples were ground into a pounder and sieved with a 1 mm sieve, and then they were used to measure the C concentrations by the Dumas dry combustion method (Zhang et al. 2021b) in a Flash-II EA112 Elemental Analyzer (Thermo Fisher Scientific, Waltham, MA, USA). Soil samples for measuring soil bulk density were dried at 105 °C to a constant weight for weighing, and other soil samples were air-dried at room temperature to measure the soil total carbon (STC) and SOC concentrations. The STC concentration of the soil was determined by the same method as that used for the plants. The SOC concentrations were determined by dichromate heating-oxidation (Pang et al. 2019).

Calculations of C in plants and soil

The C in one plant organ was calculated by multiplying the C concentrations in one organ by the dry biomass of the corresponding organ (Zhang et al. 2021b). For example, the C in leaves was calculated according to the following equation:

$$C_{SL} = \sum_{i=1}^{n} C_{CLi} \times LDB_i \quad (1)$$

where C_{SL} is the C in leaves (kg m^{-2}), C_{CLi} is the C concentrations in leaves (g kg^{-1}) in the i harvesting time, LDB_i is the dry biomass of leaves (g m^{-2}) in the i harvesting time, and i is the number of harvesting times each year, n is the total harvesting time each year (n = 4). The C in alfalfa shoots consisted of the C in alfalfa leaves and alfalfa stems, and the C in alfalfa plants consisted of C in alfalfa shoots and C in alfalfa roots.

Calculation methods of soil C storage were different (Chan et al. 2010; Wendt and Hauser 2013). Some studies used the fixed depth to quantify the soil C storage (Ellert and

Bettany 1995; Puget and Lal 2005; Chan et al. 2010; Deng et al. 2014; Paramesh et al. 2022), other studies used equivalent soil mass to calculate the soil C storage (Wendt and Hauser 2013; Bhattacharyya et al. 2013). This study used the fixed depth method to calculate soil C storage, either STC or SOC storage, because soil C storage is usually considered to be over-estimated with equivalent soil mass method (Wendt and Hauser 2013). Here, STC was considered as an example to present a calculated process of soil C storage.

$$STC_s = \sum_{j=1}^{n} BD_j \times STC_{cj} \times D_j \times 0.01 \tag{2}$$

where STC_s is the STC storage (kg m^{-2}), j represents the number of soil layers (0–20, 20–40, 40–60, 60–80, 80–100), n represents the total number of soil layers ($n = 5$), BD_j is the soil bulk density (g cm^{-3}), which was calculated by dividing the weight of the dry soil by the volume of each core occupied by soil at depth j, $STC_{c\,j}$ is the STC concentration (g kg^{-1}) at depth j, D_j is the thickness of the soil layers (20 cm), and 0.1 represents the unit conversion factor. The soil inorganic C (SIC) fractions were calculated as the difference between STC and SOC, either for C storage or C concentration calculations.

The changes of soil C storage is considered to estimate the soil C retention (Olson 2013). Thus, the difference in soil C storage and C in alfalfa plants between CFI and PRD conditions can be used to estimate the effect of PRD on the C retention in the soil-plant systems of alfalfa (Wang et al. 2010; Sun et al. 2013).

Statistical analyses

Data were checked for normal distribution and homogeneity in 2018–2019, respectively. If necessary, the data were transformed to comply with the normality and homogeneity.

A two-way analysis of variance (ANOVA) was used to determine whether the irrigation modes, irrigation volumes, and their interactions affected the C in alfalfa shoots, C in alfalfa roots, C in alfalfa plants, soil bulk density, STC, SOC and SIC concentrations and storage, and the C retention in the soil-plant systems of alfalfa. In the model, the above-mentioned variables acted as the response variables, irrigation modes and irrigation volumes were regarded as the fixed factors, and the subplots were treated as random factors. When ANOVA indicated a significant difference, multiple comparisons among treatments were performed using Tukey's test at $p = 0.05$, which is usually used to compare the mean between groups with the same sample size. Two-way analysis of variance and multiple comparisons were conducted using IBM statistics SPSS 24.0. The graphs were created in Origin 2021.

Results

Effect of PRD on the C in alfalfa plants

The responses of C in alfalfa shoots, C in alfalfa roots, and C in alfalfa plants to irrigation modes and irrigation volumes and their interaction were consistent between 2018 and 2019. PRD had no effect on C in alfalfa shoots, but it significantly increased the C in alfalfa roots by 0.49% and 0.16% in 2018 and 2019, and significantly increased C in alfalfa plants by 0.41% and 0.93% in 2018 and 2019, respectively ($p < 0.05$). With the increase of irrigation volume, C in alfalfa shoots firstly increased from the I_1 condition to I_2 condition and then remained stable. Irrigation volume had no effect on C in alfalfa roots and C in alfalfa plants. The interaction between irrigation modes and irrigation volumes also had no effect on the C in alfalfa shoots, C in alfalfa roots and C in alfalfa plants (Fig. 3).

Effect of PRD on the C in soils

Effect of PRD on the soil bulk density

The soil bulk density in PRD conditions were 17.87% and 14.50% lower than that in CFI conditions during 2018 and 2019, respectively ($p < 0.05$). Irrigation volumes did not significantly influence the soil bulk density in 2018 and 2019 (Fig. 4).

The soil bulk density was the highest in combination of CFI and I_4, and was the lowest in combination of PRD and I_1 in 2018, PRD and I_2 in 2019.

Effect of PRD on the soil C concentration

The responses of the STC, SOC and SIC concentrations to irrigation modes, irrigation volumes and their interaction were consistent in 2018–2019 (Fig. 5). PRD significantly increased the STC and SOC, and significantly decreased SIC concentrations ($p < 0.05$). Irrigation volumes and the interaction between irrigation modes and irrigation volumes had no effect on STC, SOC and SIC concentrations.

Effect of PRD on the soil C storage

The influences of irrigation modes, irrigation volumes, and their interaction on the STC, SOC and SIC storages were consistent between 2018 and 2019 (Fig. 6). PRD was found to significantly decreased the STC and SIC storages, whereas it significantly increased SOC storage during 2018 and 2019 ($p < 0.05$). Irrigation volumes were found to have

Fig. 3 Effect of irrigation modes, and irrigation volumes and their interaction on C in alfalfa shoots, C in alfalfa roots, and C in alfalfa plants in 2018–2019. *IM* irrigation modes, *IV* irrigation volumes, *IM* × *IV* interaction of irrigation modes and irrigation volumes. All the values are represented as the mean of three replicates with standard error. Lowercase letters indicate significant differences among the four irrigation volumes based on Tukey's tests, and capital letters above the bars show significant differences between PRD and CFI ($p < 0.05$)

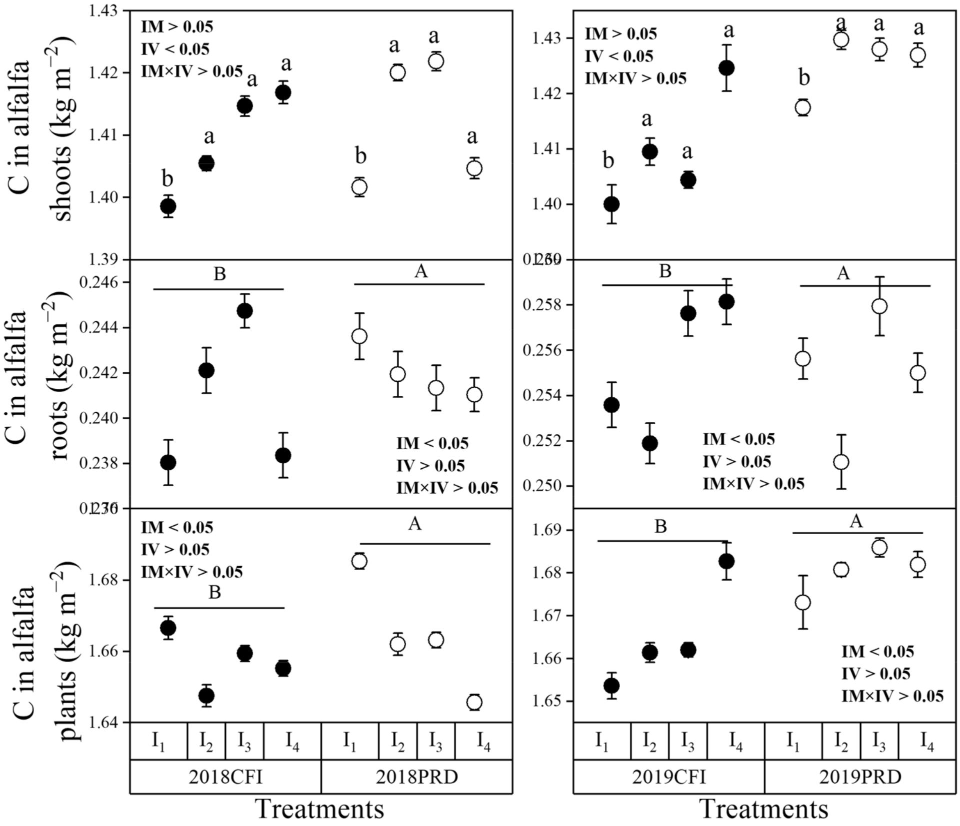
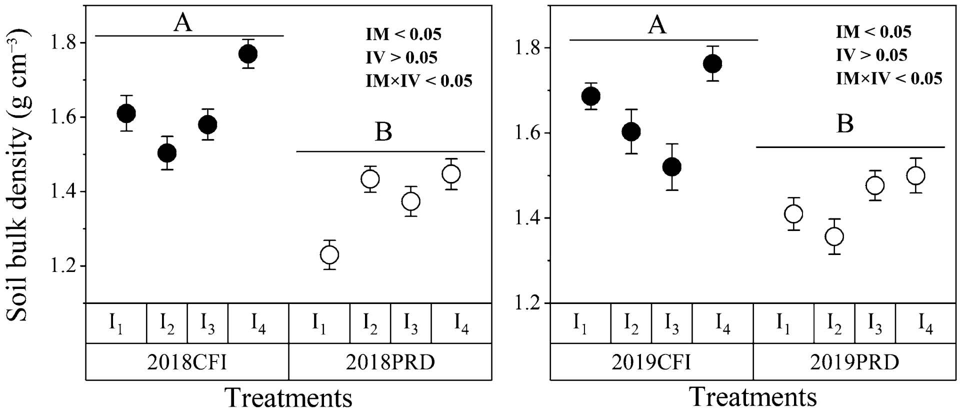


Fig. 4 Effect of irrigation modes, and irrigation volumes and their interaction on soil bulk density during 2018-2019. *IM* irrigation modes, *IV* irrigation volumes, *IM* × *IV* interaction of irrigation modes and irrigation volumes. Capital letters above the bars show significant differences between PRD and CFI ($p < 0.05$)



no impact on the STC, SOC and SIC storages. The interactions between irrigation modes and irrigation volumes were found to affect only SOC storage.

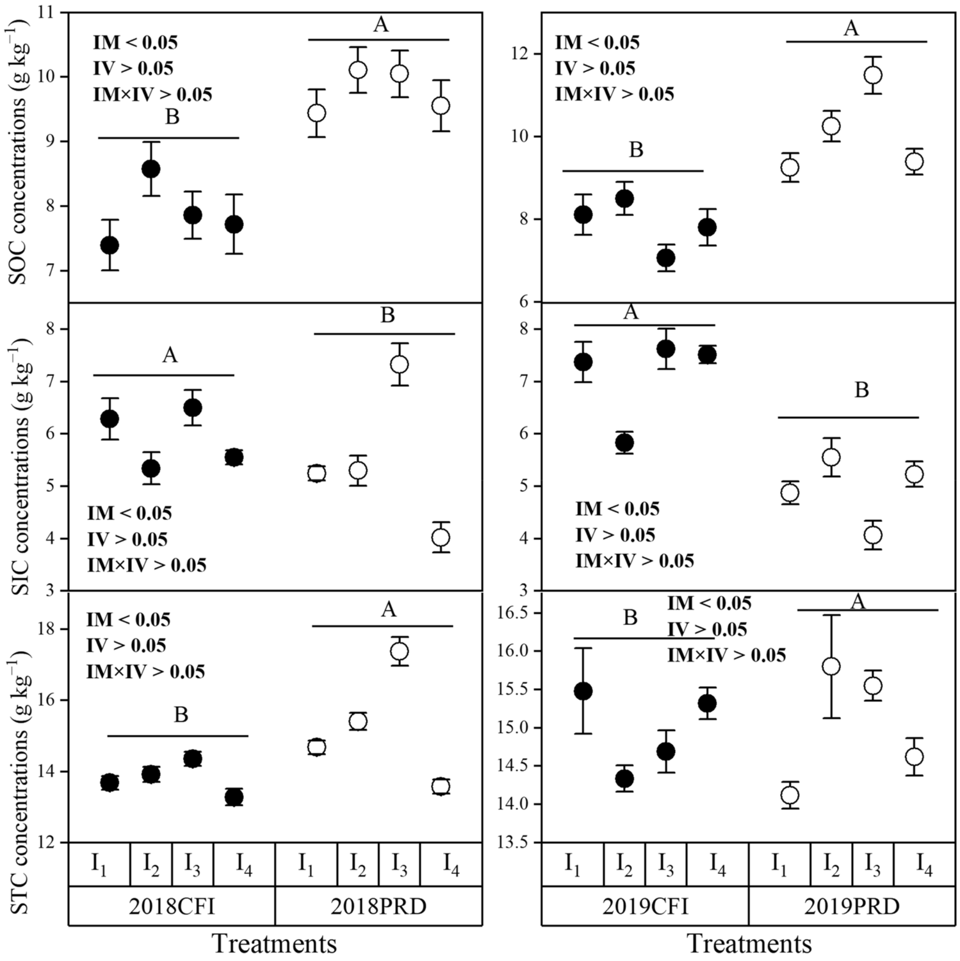
Effect of PRD on the C retention in the soil-plant systems of alfalfa

The C retention in the soil-plant systems of alfalfa in relation to irrigation modes, irrigation volumes and their interaction was consistent between 2 years (Fig. 7). PRD significantly decreased the C retention in the soil-plant systems of alfalfa by 6.01% in 2018 and 12.95% in 2019 ($p < 0.05$), while irrigation volumes and the interaction between irrigation modes and irrigation volumes had no effect on the C retention in the soil-plant systems of alfalfa.

Discussion

Previous studies have found that PRD can decrease C retention in the soil-plant systems of annual crops (Wang et al. 2010; Sun et al. 2013), and this study takes alfalfa as an example perennial plant to examine the effect of PRD on C retention in the soil-plant systems of perennial crops in the

Fig. 5 Effect of irrigation modes, and irrigation volumes and their interaction on SOC concentrations, SIC concentrations and STC concentrations during 2018–2019. *IM* irrigation modes, *IV* irrigation volumes, *IM* × *IV* interaction of irrigation modes and irrigation volumes. Capital letters above the bars show significant differences between PRD and CFI ($p < 0.05$)



field, and finds that PRD leads to lower C retention in the soil-plant systems of alfalfa.

This study shows that PRD increases the C in alfalfa plants, supporting the first hypothesis, and this is also reported in the effect of PRD on C in tomato (Wang et al. 2010), and these indicates that PRD can increase the C in plant of perennial and annual crops. Higher C in alfalfa plants is ascribed to higher alfalfa root biomass. Furrows and ridges can develop different soil surface configurations, in which PRD can greatly induce the initiation of secondary roots (Abrisqueta et al. 2008; Shahnazari et al. 2008; Wang et al. 2010), and enables alfalfa to produce more root systems, resulting in higher alfalfa root biomass (Wang et al. 2010; Sun et al. 2013; McNally et al. 2015). Low irrigation volumes cannot meet the requirement of alfalfa for water (Xiao et al. 2015; Zhang et al. 2021b), which causes the relatively lower C in alfalfa shoots when the irrigation volume is below 85% of ETc. However, alfalfa shoot biomass remains relatively stable when irrigation volumes are over 85% of ETc (Xiao et al. 2015). Correspondingly, the C in alfalfa shoots remains stable when the irrigation volumes are over 85% of ETc.

This study also shows that PRD leads to lower STC storage, which is consistent with the second hypothesis and similar to previous studies (Wang et al. 2010; Sun et al. 2013). The STC storage consists of SOC and SIC storage (Pang et al. 2019) and is dependent on the trade-off between SOC storage and SIC storage. SOC and SIC storage rely on their concentrations and soil bulk density (Pang et al. 2019). In this study, PRD leads to lower soil bulk density, which might be caused by three mechanisms: first, the repeated cycling of soil wetting and drying in PRD is beneficial to increase the number of soil microorganisms and their activities (Shahnazari et al. 2008; Sun et al. 2013), which contributes to better aeration and relatively higher soil porosity (Wang et al. 2010); second, the developed root system in PRD (Zhang et al. 2021b) often produces many macropores, which often encourages soil to become loose (Fang et al. 2018; Zhang et al. 2021a); third, constant water application in the CFI condition develop higher mechanical constraint on the soils when compared to PRD conditions, which can decrease the soil porosity and impede the root elongation in CFI, leading to a higher soil bulk density in CFI conditions than

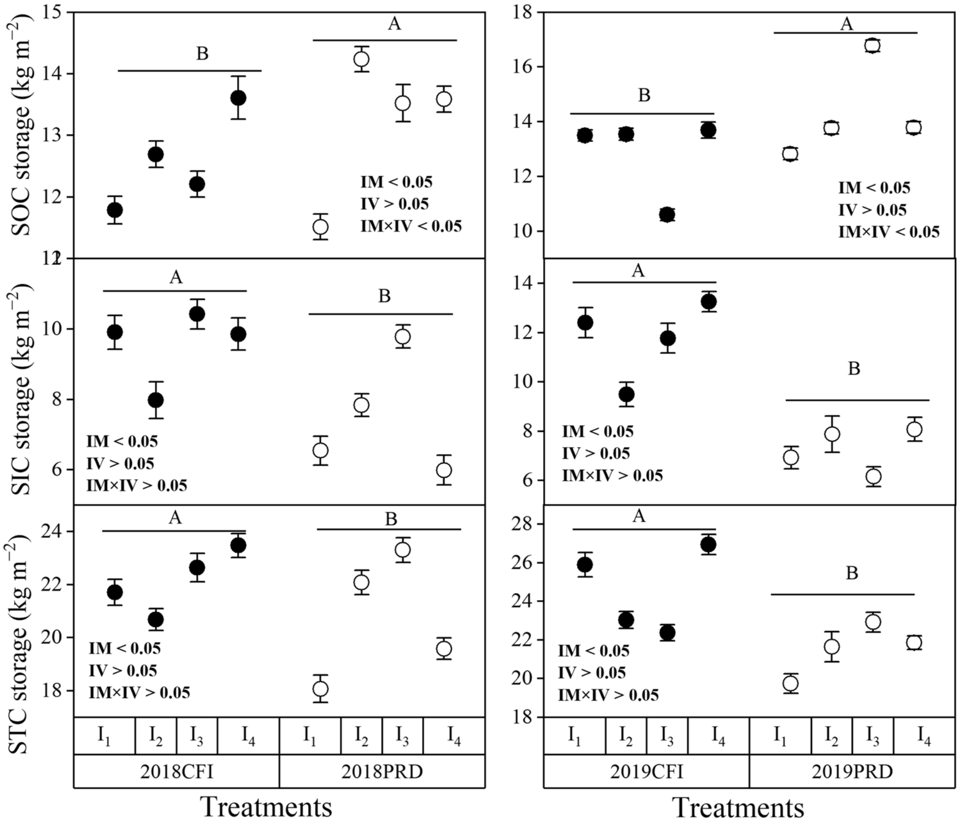


Fig. 6 Effect of irrigation modes, and irrigation volumes and their interaction on SOC storage, SIC storage and STC storage during 2018–2019. *IM* irrigation modes, *IV* irrigation volumes, *IM* × *IV* interaction of irrigation modes and irrigation volumes. Capital letters above the bars show significant differences between PRD and CFI ($p < 0.05$)

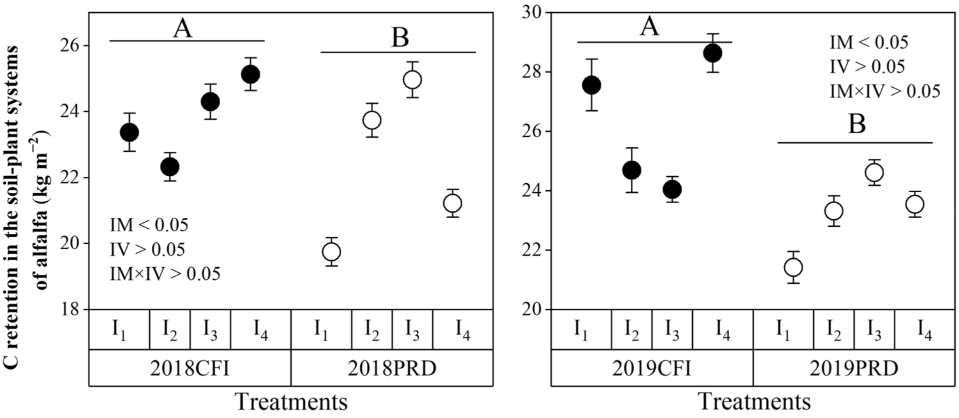


Fig. 7 Effect of irrigation modes, and irrigation volumes and their interactio on the C retention in the soil-plant systems of alfalfa 2018–2019. *IM* irrigation modes, *IV* irrigation volumes, *IM* × *IV* interaction of irrigation modes and irrigation volumes. Capital letters above the bars show significant differences between PRD and CFI ($p < 0.05$)

in PRD conditions (Veen and Boone 1990). The higher SOC storage in PRD is a consequence of the balanced increase in organic matter input and the simultaneous decrease in soil bulk density. The higher input of organic matter in PRD can be explained in two ways. First, PRD increases the alfalfa root biomass (Zhang et al. 2021b) and further increases the input of organic matter to the soil through root turnover and rhizodeposition (Bai and Li 2003; McNally et al. 2015). Second, a higher frequency of the dry-wet cycle can lead more roots to slough (Bai et al. 2020), which contributes to an increase in organic matter in the soil by accelerating root decomposition (Wang et al. 2010). In this case, the decrease in SOC storage caused by lower soil bulk density is weaker than the increase in SOC storage induced by higher soil organic matter, leading to higher SOC storage in PRD than in CFI. Wendt and Hauser (2013) have proposed that SOC storage is always over-estimated in soil with greater bulk density when SOC is estimated by equivalent soil mass method. In this study, the soil bulk density is higher in CFI than PRD, indicating that SOC storage might be over-estimated in CFI, which in turn verify that higher SOC in PRD is valid and robust. Lower SIC storage in PRD is ascribed to soil bulk density and SIC concentration. SIC is more stable than SOC (Pang et al. 2019), and it mainly accumulates as primary carbonates and secondary carbonates. In PRD, the lower SIC concentrations may be related to higher SOC concentrations. Previous studies have shown that higher SOC concentrations produce more organic acids, mainly fulvic acid and humic acid, and these organic acids accelerate SIC decomposition into atmospheric CO_2 (Yang et al. 2021). In this study, the trade-off between SOC storage and SIC storage led to PRD decreasing STC storage.

This study further shows that PRD results in lower C retention in the soil-plant systems of alfalfa, which is in accordance with the third hypothesis and is also reported in soil-plant systems of annual crops (Wang et al. 2010; Sun et al. 2013). These indicate that PRD can decrease the C retention in the soil-plant systems of annual crops or perennial crops. The C in alfalfa plants in PRD were 0.41% and 0.93% more than that in CFI in 2018 and 2019, respectively; however, the STC storage in PRD were 6.59% and 14.03% (Fig. 6) lower than that in CFI in 2018 and 2019, respectively. In this case, the decrease in STC storage in PRD is larger than the increase in the C in alfalfa plants of the C retention in the soil-plant systems of alfalfa, implying that PRD is disadvantageous to C retention in the soil-plant systems of alfalfa.

Many previous studies have verified that PRD can be applied to alfalfa production because it can save irrigation water and maintain aboveground biomass in arid and semiarid regions (Xiao et al. 2015; Zhang et al. 2021b), whereas the findings of this study indicate that PRD is not a sustainable agricultural practice for alfalfa production in terms of C sequestration.

Although PRD leads to higher C in alfalfa plants, it leads to lower C retention in the soil-plant systems of alfalfa. The microbial and enzyme activities are important to soil C turnover. Thus, how PRD affects the microbial and enzyme activities in alfalfa pasture are needed to examine for disclosing the mechanism of PRD leading to lower soil C storage.

Conclusions

This study used a 2-year field experiment to investigate the effect of PRD on C retention in the soil-plant systems of alfalfa, and have found that PRD increased C in alfalfa plants, while it decreased STC storage. The trade-off between C in alfalfa plants and STC storage leads to a decrease in C retention in the soil-plant systems of alfalfa in PRD, which indicates that PRD can encourage more soil C to be lost in field, in contrast to CFI. These results presented a pattern of PRD influencing C retention in the soil-plant systems of perennial plants, and suggested that PRD was disadvantageous to C retention in the soil-plant systems of perennial plants in the field.

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Availability of data and materials Data and materials are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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