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Machine learning methods, particularly ridge regression, were employed to analyze the impact of environmental factors on water use efficiency of summer maize in the Loess Plateau region of China. The ridge regression model effectively mitigated multicollinearity issues among predictors, thereby e···

Authors: CHEN Pengpeng, Gu Xiaobo, LI Yuannong, QIAO Linran, Machine learning [?] and deep learning [?] have emerged as pivotal methodologies in contemporary artificial intelligence research. These techniques have demonstrated remarkable efficacy across diverse domains, including computer vision [?], natural language processing [?], and reinforcement learning [?]. The fundamental principle underlying these approaches involves learning hierarchical representations from data through optimization of loss functions (??).

Despite their empirical success, conventional neural network architectures encounter substantial challenges when handling structured data with inherent symmetries. Graph neural networks [?] have been proposed to address relational reasoning tasks, yet they exhibit limitations in capturing long-range dependencies [?]. The attention mechanism [?] partially mitigates this issue, though its computational complexity scales quadratically with sequence length, as evidenced by $\mathcal{O}(n^2)$ complexity in (??).

Recent advances in transformer-based models [?] have revolutionized sequence modeling paradigms. However, the self-attention operation' s quadratic complexity constrains applicability to long sequences. Alternative approaches such as linear attention [?] and sparse attention patterns [?] endeavor to reduce computational overhead while preserving expressive capacity. Empirical evaluations demonstrate that these methods achieve comparable performance with significantly reduced memory footprint, as illustrated in Table~??.

Future research directions should prioritize development of theoretically-grounded architectures that simultaneously ensure computational efficiency and representation power. Investigating the interplay between inductive biases [?] and learned representations constitutes another promising avenue. Furthermore, establishing rigorous evaluation protocols across standardized

benchmarks remains imperative for meaningful progress in the field., FANG Heng, YIN Minhua, ZHOU Changming, GU Xiaobo, LI Yuannong

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Abstract

Ridge-furrow film mulching has been proven to be an effective water-saving and yield-improving planting pattern in arid and semi-arid regions. Drought is the main factor limiting the local agricultural production in the Loess Plateau of China. In this study, we tried to select a suitable ridge-furrow mulching system to improve this situation. A two-year field experiment of summer maize (Zea mays L.) during the growing seasons of 2017 and 2018 was conducted to systematically analyze the effects of flat planting with no film mulching (CK), ridge-furrow with ridges mulching and furrows bare (RFM), and double ridges and furrows full mulching (DRFFM) on soil temperature, soil water storage (SWS), root growth, aboveground dry matter, water use efficiency (WUE), and grain yield. Both RFM and DRFFM significantly increased soil temperature in ridges, while soil temperature in furrows for RFM and DRFFM was similar to that for CK. The largest SWS was observed in DRFFM, followed by RFM and CK, with significant differences among them. SWS was lower in ridges than in furrows for RFM. DRFFM treatment kept soil water in ridges, resulting in higher SWS in ridges than in furrows after a period of no water input. Across the two growing seasons, compared with CK, RFM increased root mass by 10.2% and 19.3% at the jointing and filling stages, respectively, and DRFFM increased root mass by 7.9% at the jointing stage but decreased root mass by 6.0% at the filling stage. Over the two growing seasons, root length at the jointing and filling stages was respectively increased by 75.4% and 58.7% in DRFFM, and 20.6% and 30.2% in RFM. Relative to the jointing stage, the increased proportions of root mass and length at the filling stage were respectively 42.8% and 94.9% in DRFFM, 63.2% and 115.1% in CK, and 76.7% and 132.1% in RFM, over the two growing seasons, showing that DRFFM slowed down root growth while RFM promoted root growth at the later growth stages. DRFFM treatment increased root mass and root length in ridges and decreased them in 0–30 cm soil layer, while RFM increased them in 0–30 cm soil layer. Compared with CK, DRFFM decreased aboveground dry matter while RFM increased it. Evapotranspiration was reduced by 9.8% and 7.1% in DRFFM and RFM, respectively, across the two growing seasons. Grain yield was decreased by 14.3% in DRFFM and increased by 13.6% in RFM compared with CK over the two growing seasons. WUE in CK was non-significantly 6.8% higher than that in DRFFM and significantly 22.5% lower than that in RFM across the two growing seasons. Thus, RFM planting pattern is recommended as a viable water-saving option for summer maize in the Loess Plateau of China.

Full Text

Preamble

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Abstract

Ridge-furrow film mulching has proven to be an effective water-saving and yield-improving planting pattern in arid and semi-arid regions. Drought is the main factor limiting agricultural production in the Loess Plateau of China, and this study aimed to identify a suitable ridge-furrow mulching system to address this challenge. A two-year field experiment with summer maize (Zea mays L.) was conducted during the 2017 and 2018 growing seasons to systematically analyze the effects of three treatments: flat planting with no film mulching (CK), ridge-furrow with ridges mulched and furrows bare (RFM), and double ridges and furrows full mulching (DRFFM) on soil temperature, soil water storage (SWS), root growth, aboveground dry matter, water use efficiency (WUE), and grain yield. Both RFM and DRFFM significantly increased soil temperature in ridges, while soil temperature in furrows remained similar to CK. The largest SWS was observed in DRFFM, followed by RFM and CK, with significant differences among them. SWS was lower in ridges than in furrows for RFM, whereas DRFFM retained soil water in ridges, resulting in higher SWS in ridges than in furrows after periods without water input. Across both growing seasons, RFM increased root mass by 10.2% and 19.3% at the jointing and filling stages, respectively, while DRFFM increased root mass by 7.9% at jointing but decreased it by 6.0% at filling. Root length at jointing and filling stages increased by 75.4% and 58.7% in DRFFM, and by 20.6% and 30.2% in RFM, respectively. The relative increases in root mass and length from jointing to filling stage were 42.8% and 94.9% in DRFFM, 63.2% and 115.1% in CK, and 76.7% and 132.1% in RFM, indicating that DRFFM slowed root growth while RFM promoted it at later stages. DRFFM increased root mass and length in ridges but decreased them in the 0–30 cm soil layer, whereas RFM increased them in the 0–30 cm layer. Compared with CK, DRFFM decreased aboveground dry matter while RFM increased it. Evapotranspiration was reduced by 9.8% in DRFFM and 7.1% in RFM across both seasons. Grain yield decreased by 14.3% in DRFFM and increased by 13.6% in RFM compared with CK. WUE in CK was non-significantly 6.8% higher than in DRFFM and significantly 22.5% lower than in RFM. Thus, the RFM planting pattern is recommended as a viable water-saving option for summer maize in the Loess Plateau of China.

Keywords: ridge-furrow mulching; summer maize; soil water storage; soil temperature; root mass; root length

1 Introduction

Dryland agriculture in the Loess Plateau represents an important component of China' s agricultural system. However, influenced by temperate monsoon and continental climates, precipitation in this region is low and concentrated primarily in July–September, consisting mainly of multiple light rain events and infrequent heavy rains that cannot be effectively utilized by widely grown summer maize. This precipitation pattern, combined with drought and soil erosion, has seriously hindered sustainable agricultural development. The primary causes of drought in local summer maize production are the unavailability of precipitation to crops and the mismatch between precipitation distribution and critical crop water demand periods. Additionally, population growth and industrial development have exacerbated excessive use of surface and groundwater, widening the gap between agricultural water supply and demand. Improving precipitation use efficiency represents an effective approach to addressing agricultural drought in this region.

Ridge-furrow film mulching is recognized as an effective rainwater harvesting planting pattern in arid and semi-arid regions. In the ridge-furrow with ridges mulched and furrows bare (RFM) system, mulched ridges serve as rainwater collection areas while bare furrows function as infiltration and planting zones. This pattern can collect light rain, increase water infiltration, improve soil water storage to meet immediate crop water requirements, reduce soil evaporation, extend soil water availability, and enhance temporal and spatial controllability of rainfall resources. Based on these advantages, RFM has proven effective in alleviating crop drought and improving water use efficiency and yield, demonstrating its utility in arid and semi-arid regions. In recent years, an improved system called double ridges and furrows full mulching (DRFFM) has emerged in Gansu Province and Ningxia Hui Autonomous Region. With larger mulching area, DRFFM more effectively collects light rain, increases soil moisture, reduces evaporation, and raises soil temperature. Due to narrower furrows, collected rainwater concentrates in planting rows for crop absorption. DRFFM has significantly improved grain yield and WUE for maize, cotton, and potato, with both RFM and DRFFM showing positive effects primarily in dry, cold regions.

However, climate warming over recent decades has altered the challenges facing dryland farming in the Loess Plateau. Local agriculture now faces not only more severe droughts from rising temperatures but also earlier crop phenology, shorter growing seasons, and CO_2 emissions. Studies have found that yield benefits from ridge-furrow mulching diminish with increasing precipitation and air temperature, suggesting that mulch selection should consider local climatic conditions. Whether these ridge-furrow mulching systems remain suitable for Loess Plateau dryland farming and which performs better requires clarification. These systems substantially alter topsoil structure and aeration, differentially impacting soil water and temperature conditions in ridges versus furrows. Previous research has focused primarily on furrow hydrothermal effects on yield and WUE while neglecting ridge moisture and temperature changes, providing an incomplete understanding of these systems' impacts on agricultural production.

Therefore, this study aimed to: (1) assess effects of different ridge-furrow mulching systems on soil temperature, SWS, root growth, aboveground dry matter, grain yield, and WUE; and (2) determine the suitability of RFM and DRFFM for summer maize production in Loess Plateau dryland regions under current climate conditions.

2.1 Study Area

The experimental site was located at the irrigation station of Northwest A&F University in Yangling (34°18 N, 108°24 E), Northwest China. The region has a mean annual air temperature of 12.9°C, mean annual precipitation of 632 mm (approximately 70% occurring during July–September), mean annual pan evaporation of 1500 mm, mean sunshine duration of 2164 h, and a frost-free period exceeding 210 days. The topsoil (0.0–0.2 m) is loam with field capacity of 24.0%, permanent wilting point of 8.5%, dry bulk density of 1.40 g/cm^3, organic matter content of 13.36 g/kg, total nitrogen of 0.96 g/kg, nitrate nitrogen of 73.01 mg/kg, available phosphorus of 24.07 mg/kg, available potassium of 135.73 mg/kg, and pH of 8.13.

Precipitation and average air temperature during the 2017 and 2018 summer maize growing seasons are shown in Figure 1 [Figure 1: see original paper]. Total growing season precipitation was 294.3 mm in 2017 and 398.6 mm in 2018. Precipitation distribution across growth stages (seedling, jointing, tasseling, filling, and maturity) was 7.1%, 9.6%, 18.0%, 27.6%, and 37.6% in 2017, respectively, and 25.9%, 15.9%, 12.4%, 42.8%, and 3.0% in 2018, respectively. Precipitation concentrated at filling and maturity stages in 2017 and at seedling and tasseling stages in 2018. Air temperature during the growing season ranged from 11.4°C to 33.4°C in 2017 and 13.8°C to 31.4°C in 2018, with averages of 24.1°C and 24.3°C, respectively.

2.2 Experimental Design and Field Management

The field experiment comprised three treatments: conventional flat planting with no mulching (CK; Fig. 2a [Figure 2: see original paper]), RFM (ridge-furrow with ridges mulched and furrows bare; Fig. 2b), and DRFFM (double ridges and furrows full mulching; Fig. 2c). Each treatment had three replicates arranged in a completely randomized design. Before the experiment, basal fertilizers were applied at rates of 160 kg/hm^2 nitrogen, 120 kg/hm^2 P_2O_5, and

60 kg/hm^2 K_2O. The field was plowed and divided into 4.0 m × 4.5 m plots separated by 1 m-wide pathways.

Ridges were 0.1 m high and 0.5 m wide for both RFM and DRFFM, with furrows 0.5 m wide for RFM. Ridges were covered with 0.008 mm thick, 0.9 m wide transparent polyethylene film. In DRFFM furrows, where plastic films from adjacent ridges met, a narrow gap served as the sowing row (Fig. 2c). Summer maize ('Zhengdan 958') was sown at 66,667 plants/hm^2 with 0.5 m row spacing and 0.3 m plant spacing on June 23, 2017 and June 20, 2018, and harvested on October 8, 2017 and October 4, 2018, respectively. At the three-leaf stage, weak seedlings were removed to ensure uniform growth. Due to early-season drought in 2017, plots received 20 mm irrigation at seedling stage (June 29) and 30 mm at jointing stage (July 20) to ensure normal crop growth (Fig. 1). Weed control and pesticide application were conducted throughout both growing seasons to maintain healthy crops.

2.3.1 Soil Temperature

Mercury-in-glass geothermometers with bent stems (Hongxing Thermal Instruments, Wuqiang County, China) were placed in ridge and furrow centers at 5, 10, 15, 20, and 25 cm depths in each plot. Soil temperature was recorded every 2 h from 08:00 to 18:00 (LST) at 15-day intervals after sowing during both growing seasons. Mean daily temperature was calculated using all readings across depths and times.

2.3.2 Soil Moisture

Soil moisture for the 0–200 cm profile was determined before sowing and after harvesting to calculate SWS changes throughout each growing season. Soil moisture for 0–100 cm depth was measured every 15 days from sowing to harvesting to observe seasonal dynamics. Soil samples were collected at 10 cm intervals using a soil auger between two adjacent plants in row centers, with three replicates per sample. Since jointing and filling stages are critical for rapid growth and yield formation, soil water distribution was measured in ridges and furrows on the first and seventh day after rainfall events at these stages. Sampling times were 36, 42, 87, and 94 days after seedling (DAS) in 2017, and 24, 31, 65, and 72 DAS in 2018. All samples were oven-dried at 105°C to constant weight for gravimetric water content calculation.

Soil water storage (SWS, mm) was calculated as: $\times\times\times$ where ωi is gravimetric water content (%) at different soil layers; γ is soil dry bulk density (g/cm^3); h is soil thickness (cm); and n is the number of soil layers.

2.3.3 Root Parameters and Aboveground Dry Matter

Three representative plants per treatment were sampled using the soil monolith excavation method (Böhm, 2012; Thidar et al., 2020) at jointing and filling stages in 2017 and 2018 (Fig. 2d). Since over half of maize root biomass concentrates in topsoil (Schenk and Jackson, 2002; Fan et al., 2016), sampling depth was set at 40 cm (30 cm below flat ground plus 10 cm ridge height) to balance research needs and labor constraints. Centered on each plant, the sampling range was 50 cm (perpendicular to row) × 20 cm (parallel to row) × 40 cm (from ridge top). Soil was excavated in 10 cm layers (Fig. 2d). Roots from each depth were extracted, washed, and imaged using an EPSON V900 scanner (Epson, Nagano, Japan). Root length at different depths was analyzed using WinRHIZO software (Regent Instruments Inc., Quebec, Canada), then roots were oven-dried at 75°C to constant weight for root mass calculation. Total root mass and length per plant were calculated by doubling measured biomass in all soil monoliths for CK, DRFFM, and RFM.

Three representative plants per treatment were randomly selected at different growth stages; aboveground parts were separated into stem, leaf, and ear, cut into small pieces, oven-dried at 105°C for 30 minutes, then at 75°C to constant weight before weighing.

2.3.4 Yield, Evapotranspiration (ET), and Water Use Efficiency (WUE)

Three rows of summer maize were manually harvested from each plot center to determine grain yield (at 14% water content) and yield components including spike length, ear diameter, grains per ear, and 100-grain weight.

With groundwater depth below 5 m and plot boundaries preventing lateral flow, recharge, permeation, and runoff were assumed negligible. ET (mm) was calculated as:

$$ET = P + I + W_0 - W_1 \qquad (2)$$

where P is precipitation (mm); I is irrigation amount (mm); and W_0 and W_1 are SWS (0–200 cm depth) before sowing and after harvesting (mm), respectively.

WUE (kg/(hm^2 · mm)) was defined as:

$$WUE = Y/ET$$

where Y is summer maize yield (kg/hm^2).

2.4 Data Analysis

All data represent averages of three replicates. Analysis of variance (ANOVA) was conducted using SPSS 19.0 (SPSS Inc., Chicago, USA), with treatment differences determined by Duncan' s multiple range test at $P < 0.05$. Figures were created using Origin 8.0 (OriginLab, Northampton, USA) and AutoCAD 2007 (Autodesk Inc., San Rafael, USA).

3.1.1 Dynamics of Soil Temperature

Soil temperature changes in all treatments followed air temperature patterns (Figs. 1 and 3). Soil temperature in ridges for DRFFM and RFM did not differ significantly from each other but was significantly ($P < 0.05$) higher than CK (Fig. 3 [Figure 3: see original paper]), while furrow temperatures for both treatments were similar to CK. Compared with CK, average ridge soil temperature was 3.9°C and 4.3°C higher in DRFFM, and 2.7°C and 3.0°C higher in RFM, in 2017 and 2018, respectively.

3.1.2 Diurnal Variations of Soil Temperature

From 08:00 to 18:00, average soil temperature at 5–25 cm depth in ridges exceeded CK values, with differences increasing after 12:00 (Fig. 4 [Figure 4: see original paper]), indicating that plastic mulching significantly increased soil temperature, particularly in the afternoon. Except during the 2017 filling stage, ridge soil temperature greatly exceeded the 30.0°C threshold suitable for maize growth (Lobell et al., 2013). Daily average ridge temperatures for DRFFM and RFM were 44.5°C and 43.5°C at jointing stage, and 25.2°C and 24.2°C at filling stage in 2017; corresponding values in 2018 were 34.8°C and 33.5°C at jointing, and 33.8°C and 32.7°C at filling.

3.2.1 SWS at Different Growth Stages

SWS in the 0–100 cm layer for CK, RFM, and DRFFM fluctuated with precipitation distribution during both growing seasons. Significant differences among treatments occurred at seedling (15 DAS), tasseling (60 DAS), filling (75 and 90 DAS), and maturity (105 DAS) stages in both years (Fig. 5 [Figure 5: see original paper]). At jointing stage, SWS in DRFFM exceeded RFM but not significantly. DRFFM maintained the highest SWS, followed by RFM and CK, being 14.7% and 14.2% higher than CK in 2017 and 2018, respectively. Correspondingly, RFM SWS was 8.1% and 8.2% higher than CK in 2017 and 2018.

3.2.2 SWS in Furrows and Ridges

In the absence of rainfall and irrigation, SWS in both ridges and furrows decreased over time, though differences between them varied primarily in the 0–50 cm layer (Fig. 6 [Figure 6: see original paper]). On the first day after rainfall, SWS to 50 cm depth in furrows exceeded ridges by 7.7, 5.0, 9.8, and 4.8 mm for DRFFM at jointing 2017, filling 2017, jointing 2018, and filling 2018, respectively; corresponding differences for RFM were 13.9, 8.4, 11.3, and 8.2 mm. On the seventh day after rainfall, SWS in furrows was 9.5, 5.6, 15.9, and 4.9 mm lower than ridges for DRFFM at these four stages, respectively, while furrow SWS remained 9.8, 8.0, 11.4, and 7.2 mm higher than ridges for RFM.

3.3.1 Roots in Different Planting Patterns

Root mass and length varied significantly among planting patterns, growth stages, and years (Table 1). Compared with CK, root mass at jointing stage increased non-significantly by 1.5% and 10.4% in DRFFM and RFM, respectively, in 2017, and significantly by 14.3% and 9.9% in 2018. At filling stage, DRFFM decreased root mass by 4.6% and 7.4% in 2017 and 2018, respectively, while RFM increased it by 21.1% and 17.4% (significantly different from CK). Both DRFFM and RFM significantly increased root length compared with CK, with DRFFM showing more pronounced effects. Across both seasons, root length at jointing and filling increased by 75.4% and 58.7% in DRFFM, and 20.6% and 30.2% in RFM, relative to CK. While root mass and length for all treatments increased from jointing to filling, the magnitude differed: relative increases were 42.8% and 94.9% in DRFFM, 63.2% and 115.1% in CK, and 76.7% and 132.1% in RFM.

3.3.2 Vertical Root Distribution

Root mass in ridges was 538.4% and 422.4% significantly higher in DRFFM than RFM at jointing and filling stages, respectively, across both seasons (Fig. 7 [Figure 7: see original paper]). Compared with CK, root mass in 0–10, 10–20, and 20–30 cm layers was higher in RFM and lower in DRFFM (except 0–10 cm at jointing 2018). RFM increased root mass by 6.6%, 19.1%, and 32.6% at jointing, and by 15.0%, 21.1%, and 31.7% at filling in these three layers, respectively. DRFFM decreased root mass by 5.2%, 33.8%, and 31.8% at jointing, and by 22.0%, 38.2%, and 33.7% at filling, respectively.

Root length in ridges was 619.6% and 514.2% significantly higher in DRFFM than RFM at jointing and filling stages, respectively (Fig. 8 [Figure 8: see original paper]). Root length in 0–10, 10–20, and 20–30 cm layers for DRFFM was significantly lower than CK (except 0–10 cm at filling 2017). RFM root length in 0–10 cm was non-significantly larger than CK (except at filling 2018). In 2017, RFM root length in 10–20 and 20–30 cm layers was significantly higher than CK (except 20–30 cm at jointing). Across both seasons, DRFFM decreased root length by 9.9%, 9.1%, and 14.7% at jointing, and by 19.1%, 20.5%, and 18.2% at filling in these layers, respectively, while RFM increased root length by 0.6%, 51.5%, and 19.6% at jointing, and by 11.2%, 46.9%, and 30.0% at filling, respectively.

Although DRFFM had greater root mass at jointing and longer root length at both stages within the sampling depth, considerable root mass and length were located in ridge soil. After removing ridge soil roots, root mass and length in the 0–30 cm layer for CK were lower than RFM but higher than DRFFM at both stages in both years.

3.4 Aboveground Dry Matter

Stem and leaf dry matter increased then decreased during growth, peaking at the filling stage in both seasons, while aboveground dry matter peaked at maturity (Fig. 9 [Figure 9: see original paper]). Treatment differences varied between seasons. In 2017, DRFFM decreased stem, leaf, ear, and total aboveground dry matter by 8.6%-19.2%, 5.2%-16.6%, 15.7%-25.6%, and 6.6%-18.8%, respectively, compared with CK, with significant differences at most stages. In 2018, DRFFM significantly increased stem, leaf, ear, and aboveground dry matter from seedling to tasseling (except leaves at tasseling) but decreased them significantly at filling and maturity relative to CK. DRFFM increased aboveground dry matter by 13.6%-53.5% from seedling to tasseling but decreased it by 13.0%-14.5% from filling to maturity in 2018. RFM increased stem, leaf, ear, and aboveground dry matter by 2.1%-16.3%, 2.5%-15.8%, 10.6%-15.4%, and 2.4%-12.7% in 2017, respectively, and by 6.5%-37.1%, 4.7%-30.1%, 13.0%-79.9%, and 10.6%-32.5% in 2018, respectively, with significant differences at most stages in both years.

3.5 Grain Yield and WUE

All yield component factors (spike length, diameter, kernel rows number, grains per row and per spike, and 100-grain weight) were lower in DRFFM and higher in RFM compared with CK. CK-DRFFM differences were only significant for 100-grain weight in 2018, while CK-RFM differences were significant for grains per row and per spike in 2018 and spike length in both years (Table 2). Grain yield was non-significantly 12.5% lower in DRFFM in 2017 and significantly 16.1% lower in 2018, while RFM yield was non-significantly 10.4% higher in 2017 and significantly 16.8% higher in 2018, compared with CK. ET values for both DRFFM and RFM were significantly lower than CK, with mean ET for CK being 9.8% and 7.1% higher than DRFFM and RFM, respectively, across both seasons. WUE for CK was non-significantly 6.8% higher than DRFFM and significantly 22.5% lower than RFM across both seasons.

4 Discussion

Ridge-furrow mulching systems substantially impact soil water and thermal conditions, thereby affecting root morphology, distribution, and crop yield.

4.1 Soil Temperature

The warming effect of plastic film mulching on soil is well established, and our experiment confirmed increased ridge soil temperatures under mulching (Fig. 3). However, excessive soil warming is not always beneficial in regions with sufficient accumulated temperature. Within reasonable limits, elevated soil temperature can increase effective accumulated temperature (Chen et al., 2012), accelerate crop growth (Mo et al., 2016), and increase yield (Wang et al., 2018). When temperature exceeds optimal ranges, it becomes detrimental. Lobell et al. (2013) reported negative maize yield responses when temperatures exceeded 30.0°C, and Yu et al. (2018) found no positive plastic film effects in Chinese drylands above 24.0°C. In this study, ridge soil temperatures significantly exceeding 30.0°C in DRFFM and RFM (Figs. 3 and 4) likely impaired crop health (Morales et al., 2003; Yin et al., 2019).

4.2 SWS

SWS is affected by precipitation (Han et al., 2014), planting pattern (Zhou et al., 2009), and crop consumption (Zhang et al., 2019a). DRFFM and RFM significantly increased furrow SWS through rainwater collection and enhanced infiltration compared with CK (Figs. 5 and 6), consistent with previous research (Wu et al., 2017; Gu et al., 2018; Gao et al., 2019). Unlike traditional flat farming, ridge-furrow mulching alters soil surface shape and aeration, changing horizontal water distribution and redistribution. Previous studies focused on increased furrow SWS while neglecting ridge moisture changes (Wang et al., 2016; Wang et al., 2018). We found that shortly after rainfall, ridge SWS was lower than furrow SWS for both systems because furrows served as infiltration zones for collected water (Yin et al., 2015). After prolonged dry periods, ridge SWS exceeded furrow SWS in DRFFM but remained lower in RFM (Fig. 6), attributable to structural differences (Wu et al., 2017). DRFFM' s narrower furrows (Ren et al., 2016) concentrated collected rainwater near ridges, where solar radiation drove upward movement and accumulation under plastic film (He et al., 2018; Zhang et al., 2019b), while furrow water decreased through evaporation and crop uptake. Although DRFFM reduced evaporation through greater mulching area (Zhao et al., 2014), some water transferred to ridges (Fig. 6). Since maize roots tend to grow where soil moisture is abundant (Qi et al., 2015; Yin et al., 2015), higher ridge SWS in DRFFM likely induced greater root proliferation in ridges.

4.3 Root Distribution

Root biomass and its distribution are crucial for crop growth. While ridge-furrow mulching effects on root mass and length are documented (Yin et al., 2015; Gu et al., 2016; Thidar et al., 2020), vertical distribution under different systems remains poorly understood. RFM and DRFFM increased root mass at jointing and filling across both seasons (except DRFFM at filling), partially contradicting previous findings. Some studies reported that high soil temperature reduces root enzyme activity and accelerates aging (Bu et al., 2013; Qin et al., 2018). DRFFM' s reduced root mass at filling may result from accelerated senescence caused by high ridge temperatures (Gao et al., 2014). A healthy root system at filling is essential for nutrient absorption and maintaining high plant activity for high yield (Gao et al., 2014; Zhao et al., 2017). RFM showed the largest relative increases in root mass and length from jointing to filling, followed by CK and DRFFM, indicating DRFFM lacked capacity to promote root growth and even hindered it during filling.

Due to abundant water and heat in ridge soil, DRFFM increased root mass and length in ridges but decreased them in the 0–30 cm layer beneath flat ground compared with CK. This may benefit early growth, but closed soil spaces, nutrient deficiencies, and high temperatures in ridges likely damaged roots at later stages. Reduced deep rooting may limit utilization of deep soil moisture and nutrients and decrease lodging resistance (Morales et al., 2003). In contrast, RFM increased root mass and length in both ridges and the 0–30 cm layer compared with CK at jointing and filling, potentially benefiting early dry matter accumulation and later grain formation.

4.4 Aboveground Dry Matter, Grain Yield, and WUE

Many studies have shown that ridge-furrow plastic mulching improves soil hydrothermal conditions and increases aboveground dry matter, grain yield, and WUE for maize (Liu et al., 2014), potato (Zhao et al., 2014), and oat (Qi et al., 2015). However, DRFFM decreased summer maize aboveground dry matter in both seasons except at seedling and jointing stages in 2018, contrasting with previous findings (Liu et al., 2014; Ren et al., 2016). In 2017, nearly complete DRFFM coverage aggravated drought and heat stress, reducing early aboveground dry matter. More uniform rainfall in 2018 highlighted DRFFM' s rain collection effect, increasing early aboveground dry matter. At later stages, limited ridge nutrients and poor aeration in DRFFM accelerated root senescence and impeded dry matter accumulation (Bu et al., 2013; Qin et al., 2018). RFM increased stem, leaf, and ear dry matter in both seasons. Although RFM also excessively increased ridge soil temperature, relatively few roots grew in ridges, avoiding adverse effects of high temperature, nutrient shortage, and poor aeration on root growth (Zhang et al., 2015). Additionally, RFM significantly increased furrow soil moisture, promoting crop growth. Overall, RFM' s advantages outweighed its disadvantages, ultimately increasing aboveground dry matter.

DRFFM reduced ET, grain yield, and WUE, while RFM reduced ET but increased grain yield and WUE. This contrasts with previous conclusions that DRFFM increased yield and WUE in arid, cold regions (Wang et al., 2018), possibly because water deficit and insufficient accumulated temperature historically limited crop growth in those regions, whereas climate warming has now provided relatively sufficient accumulated temperature in Loess Plateau regions (Gao et al., 2014; Zhang et al., 2018).

5 Conclusions

Both DRFFM and RFM increased ridge soil temperature and furrow SWS. DRFFM prevented soil water evaporation in ridges, resulting in higher ridge than furrow water content after dry periods. Both systems increased root mass and length at jointing and filling except DRFFM decreased root mass at filling. DRFFM slowed root growth at later stages. RFM increased root mass and length in the 0–30 cm soil layer, while DRFFM decreased them in this layer but increased them in ridges. DRFFM decreased aboveground dry matter, grain yield, and WUE, while RFM increased these parameters. Therefore, RFM is recommended as a viable option for summer maize in regions with water shortage and sufficient accumulated temperature.

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