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Effects of Ridge and Furrow Rain Harvesting Cultivation with Supplemental Irrigation on Root, Yield and Water Use Efficiency of Winter Oilseed Rape (*Brassica napus* L.)

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Abstract: Two-year (2012—2013 and 2013—2014) field experiments were conducted to determine the appropriate supplemental irrigation amount of winter oilseed rape (*Brassica napus* L.) at stem elongation stage with the ridge and furrow rain harvesting cultivation. Four treatments, including T_1, T_2, T_3 (with supplemental irrigation amounts of 0, 60, 120 mm under ridge and furrow rain harvesting cultivation, respectively) and CK (with supplemental irrigation amount of 120 mm under flat planting cultivation) were set up to evaluate the effects of different supplemental irrigation amounts on soil moisture content at 0 ~ 30 cm and 30 ~ 100 cm soil depths, aboveground dry matter, taproot growth parameters, lateral root density, yield components and water use efficiency (WUE) of winter oilseed rape. The results showed that soil moisture contents at 0 ~ 30 cm soil depth of T_2 and T_3 at different periods were obviously higher than those of T_1 and CK. Aboveground dry matter at flowering stage and pod stage, taproot diameter and dry weight, lateral root density at 0 ~ 10 cm and 10 ~ 20 cm soil depths at pod stage of T_2 and T_3 were significantly higher than those of T_1 and CK, and no significant differences were found between T_2 and T_3. Compared with T_1 and CK, seed yields of T_2 and T_3 in two years were increased by 50. 99%, 58. 15% and 53. 89%, 61. 19%, respectively, and WUE of T_2 and T_3 in two years were improved by 37. 28%, 25. 98% and 92. 77%, 76. 90%, respectively. T_3 achieved the highest yield in both years, the average yield, crop evapotranspiration (ET) and WUE of which were 3 235 kg/hm^2, 368 mm, 0. 89 kg/m^3, respectively. While the highest WUE with average value of 0. 96 kg/m^3 was determined in T_2, with average yield of 3 089 kg/hm^2 and average ET of 322 mm. Therefore, compared with T_3, T_2 could save irrigation amount by 60 mm, increase WUE by 8. 97%, and the yield was just reduced by 4. 74%. From the perspective of saving water and increasing yield, T_2 was recommended as an appropriate irrigation schedule and cultivation pattern for winter oilseed rape at stem elongation stage.

Key words: winter oilseed rape; ridge and furrow rain harvesting; supplemental irrigation; root characteristics; yield; water use efficiency

0 Introduction

Water scarcity has always been the most critical restriction to the sustainable development of agriculture in arid and semiarid areas of Northwest China. In recent years, phenomena of climate warmer and persistent drought were happened in most regions of northern China, and precipitation was decreased significantly. Average annual precipitation in Northwest China was reduced by 5%[1]. The Guanzhong region of Shaanxi Province was an important irrigated agricultural area in China, however, crop yield was not improved with local extensive plant and irrigation methods, which caused a serious waste of water resources. In recent years, the amount of water resources allocated to agriculture in this region was 2. 52 billion m^3 per year, and the degree of water shortage was 25. 8% in moderate drought year[2]. Therefore, it is of practical significance to sustainable development of local agriculture and improve the utilization efficiency of precipitation and irrigation, reduce irrigation amount and enlarge irrigation area. The ridge and furrow rain harvesting (RFRH) cultivation technique through building ditches in the

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field, mulching ridges with plastic film and planting crops in the furrows, could collect rainwater falling onto the ridges to flow along the slope and then infiltrate into the furrow soils. Many researches showed that RFRH cultivation technique could obviously improve crop yield and water use efficiency (WUE)[3-5], effectively regulate soil water deficit, reduce invalid soil evaporation, increase soil water content[6-7] and surface runoff collecting efficiency, reduce soil and water erosion[8], and it could also effectively improve the crop absorption and utilization efficiency of nutrients[9-10], increase soil temperature[11], activate soil nutrients[12], suppress the occurrence of soil salinization[13], optimize the crop demand for light, improve the chlorophyll content and photosynthetic efficiency of crops[14]. So far, domestic and international researchers mainly focused on the effects of RFRH planting pattern on wheat[15], maize[16], potato[17], bromm corn millet[18], oat[19] and alfalfa[20]. However, few studies were reported about the effects of appropriate supplemental irrigation at critical growth stages under RFRH planting pattern on crop yield and WUE, especially the crop of winter oilseed rape under RFRH planting pattern.

In order to determine the appropriate supplemental irrigation amount and provide theoretical basis for reasonable irrigation of winter oilseed rape under RFRH planting pattern, based on two-year field experiment, the effects of different supplemental irrigation amounts applied at stem elongation stage on soil water content, aboveground dry matter, root characteristics, seed yield and WUE of winter oilseed rape under RFRH planting pattern were analyzed and compared.

1 Materials and methods

1.1 Experimental site

Two-year (2012 – 2013 and 2013 – 2014) field experiments were conducted in the Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Areas of the Ministry of Education (34°18′N, 108°24′E, and altitude 521 m), Northwest A&F University, Yangling, Shaanxi, China. The mean annual sunshine duration of study area is about 2 163.8 h, with mean annual frost-free period of more than 210 d. The soil of the experimental field is medium loam with field capacity of 24.0% and dry bulk density of 1.40 g/cm^3. The ground water table is deeper than 8 m, and its upward supplementary amount can be neglected. The basic physical and chemical properties of the top soil layer (0 ~ 20 cm) at the start of 2012 – 2013 experiment were: organic matter content of 13.36 g/kg, total nitrogen (N) content of 0.96 g/kg, nitrate N content of 73.01 mg/kg, rapidly available phosphorus content of 24.07 mg/kg, rapidly available potassium content of 135.73 mg/kg, and pH value of 8.13; and the basic physical and chemical properties of the top soil layer (0 ~ 20 cm) at the start of 2013 – 2014 experiment were: organic matter content of 12.87 g/kg, total nitrogen (N) content of 0.98 g/kg, nitrate N content of 72.54 mg/kg, rapidly available phosphorus content of 24.26 mg/kg, rapidly available potassium content of 135.32 mg/kg and pH value of 8.14.

1.2 Experimental materials and design

The plastic film used was 80 cm width and 0.008 mm thickness. The variety of winter oilseed rape was ‘Shaanyou No. 107’, which was provided by College of Agriculture in Northwest A&F University. Fertilizers were urea (N mass fraction was more than 46%), calcium superphosphate (P_2O_5 mass fraction was more than 16%), potassium sulphate (K_2O mass fraction was more than 51%), and borax (B mass fraction was more than 11.5%).

Supplemental irrigation was applied at stem elongation stage (March 1). Four treatments were arranged in a completely randomized design with three replicates: supplemental irrigation amounts of 0 mm (T_1), 60 mm (T_2) and 120 mm (T_3) under RFRH cultivation and supplemental irrigation amount of 120 mm under flat planting cultivation (CK). There were totally twelve plots with area of 13.5 m^2 (4 m × 3.5 m) and 1 m buffer area was set between plots. Plastic film was mulched on ridges of 50 cm width and 20 cm height, and winter oilseed rape was planted in furrows of 50 cm width. Supplemental irrigation was applied in the furrows under RFRH planting pattern and flat planting pattern was not mulched by plastic film. Schematic diagrams of the RFRH and flat planting patterns were presented in Fig. 1. Basal fertilizers of N, P_2O_5, K_2O and B at rates of 100 kg/hm^2, 90 kg/hm^2, 120 kg/hm^2 and 15 kg/hm^2 were applied before sowing, and additional N of 80 kg/hm^2 was applied before supplemental irrigation. Seeds were manually sown in each plot with row spacing of 50 cm and on-row plant spacing of 13 cm on September 15 and 12 in 2012 and 2013, respectively. Seedlings were thinned artificially at the third-leaf stage (September 30 and 27 in 2012 and 2013, respectively), and the plant density was determined as 120 000 plants/hm^2. 30 mm of irrigation water was applied to each plot due to a severe drought after sowing in September 2013 to ensure seedling emergence. Other field managements were consistent with the local high-yield field. All plants were harvested on May 20, 2013 and May 22, 2014.

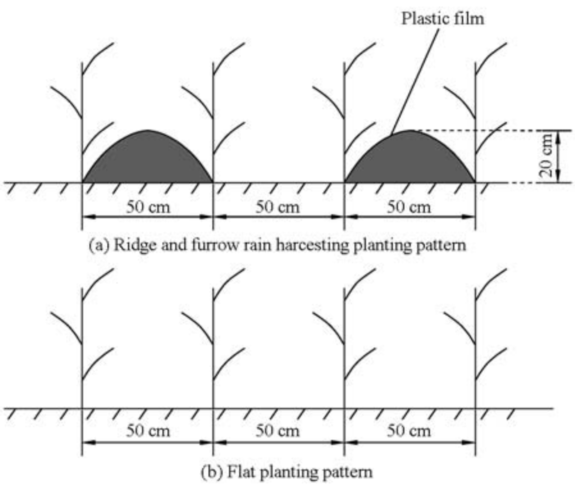

Fig. 1 Sketches of ridge and furrow rain harvesting cultivation and flat plantings

1.3 Measurements and methods

Soil water content of 0 ~ 200 cm depth was determined before sowing and after harvesting in different treatments on the basis of oven-dried method. Soil water content to a depth of 100 cm was also measured every 15 d from the day of supplemental irrigation. The soil was sampled at 10 cm intervals in depth between adjacent plants within the furrows under RFRH planting pattern and the rows under flat planting pattern.

Soil water storage was calculated as

$$W = 10\gamma h\theta \tag{1}$$

where W is soil water storage (mm); γ is soil dry bulk density (g/cm^3); h is soil thickness (cm); θ is gravimetric water content (%).

Evapotranspiration was calculated as

$$ET = P + I - \Delta W \tag{2}$$

where ET is evapotranspiration (mm); P is precipitation (mm); I is irrigation amount (mm); ΔW is variation of soil water storage before sowing and after harvesting (mm).

Irrigation, precipitation and water use efficiency were calculated as

$$I_{WUE} = Y/(10I) \tag{3}$$

$$P_{WUE} = Y/(10P) \tag{4}$$

$$W_{UE} = Y/(10ET) \tag{5}$$

where I_{WUE} is irrigation water use efficiency (kg/m^3); P_{WUE} is precipitation water use efficiency (kg/m^3); W_{UE} is water use efficiency (kg/m^3); Y is seed yield of winter oilseed rape (kg/hm^2).

Aboveground dry matter: five representative plants were sampled per plot at stem elongation stage (before supplemental irrigation, 166 DAS in 2013, 169 DAS in 2014, DAS denoted days after sowing), initial flowering stage (192 DAS in 2013, 194 DAS in 2014), full-bloom stage (206 DAS in 2013, 209 DAS in 2014) and pod stage (237 DAS in 2013, 242 DAS in 2014) to determine shoot dry matter. The plants were separated into stem, leaf and pod, and the dry weight of each part was measured on the basis of oven-dried method. The aboveground dry matter was the sum of dry weights of each part.

Taproot characteristics and lateral root distribution of winter oilseed rape were measured at stem elongation stage and pod stage. Five representative whole root systems were dug out per plot and the lateral roots were removed with scissors. The length and diameter of taproot were measured using rulers and calipers, respectively. Lateral roots in depths of 0 ~ 10 cm, 10 ~ 20 cm and 20 ~ 30 cm were sampled between adjacent plants using soil cores (7 cm diameter). Roots in the cores were separated from the soil on a thin mesh with tap water. The taproots and lateral roots were dried in an oven at 70℃ to constant weight, and then weighed.

Yield was measured from 1 m^2 selected area in each plot in advance, and the rapeseed plants in this area were harvested separately to measure seed yield after dried and shelled. Ten plants in the 1 m^2 area were randomly selected to measure branch and pod numbers per plant, seed numbers per pod, and 1000-seed weight.

1.4 Data analysis

Experimental data were handled by Excel 2010.

PASW Statistics 18.0 was used to conduct analysis of variance, and significant differences between the treatments were compared by the Duncan's new multiple range method at 5% probability level. Graphics were made using the Origin 8.5 software program.

2 Results

2.1 Rainfall and temperature during growth periods of winter oilseed rape

Monthly total rainfall and monthly mean temperature during the growth periods of winter oilseed rape in 2012 – 2013, 2013 – 2014 and 2006 – 2011 were shown in Fig. 2. Mean temperature in January for 2013 and 2014 (0.1℃ and 1.1℃) were significantly higher than mean temperature in January of 2006 – 2011 (–1.8℃). Total rainfall during the growing periods was 119.6 mm and 335.8 mm for 2012 – 2013 and 2013 – 2014, and mean rainfall during the growing period of 2006 – 2011 was 371.6 mm. Rainfall during critical growth stages (from March to April) of winter oilseed rape for 2012 – 2013 was 156.4 mm, which was lower than that for 2013 – 2014. Therefore, 2012 – 2013 belonged to dry year.

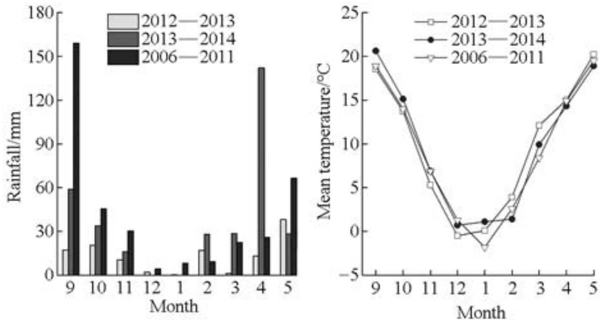

Fig. 2 Monthly total rainfall and mean temperature during winter oilseed rape growth seasons at experimental site

2.2 Dynamics of soil water content under RFRH planting pattern

Dynamics of soil water contents in 0 ~ 30 cm and 30 ~ 100 cm soil layers after supplemental irrigation at stem elongation stage of winter oilseed rape under different treatments were shown in Fig. 3. It can be known that the effect of rainfall and irrigation on soil water content was more significant in 0 ~ 30 cm soil layer than that in 30 ~ 100 cm soil layer. The variation trends of soil water contents in 0 ~ 30 cm and 30 ~ 100 cm soil layers from 15 d to 75 d after supplemental irrigation were obviously different in two growing seasons because of the differences of rainfall amount and its distribution in two seasons. Soil water contents in 0 ~ 30 cm and 30 ~ 100 cm soil layers under RFRH planting pattern before supplemental irrigation were obviously higher than that in CK, and mean soil water contents in 0 ~ 30 cm and 30 ~ 100 cm soil layers under RFRH planting pattern before supplemental irrigation across the two seasons were 11.33% and 6.61% higher than that in CK.

Soil water contents in 0 ~ 30 cm in T_2, T_3 and CK were sharply increased after 15 d of supplemental irrigation. Soil water content in 0 ~ 30 cm soil layer presented a downward trend from 15 d to 75 d after supplemental irrigation in 2012 – 2013 due to drought. Soil water contents in 0 ~ 30 cm soil layer in T_2 and T_3

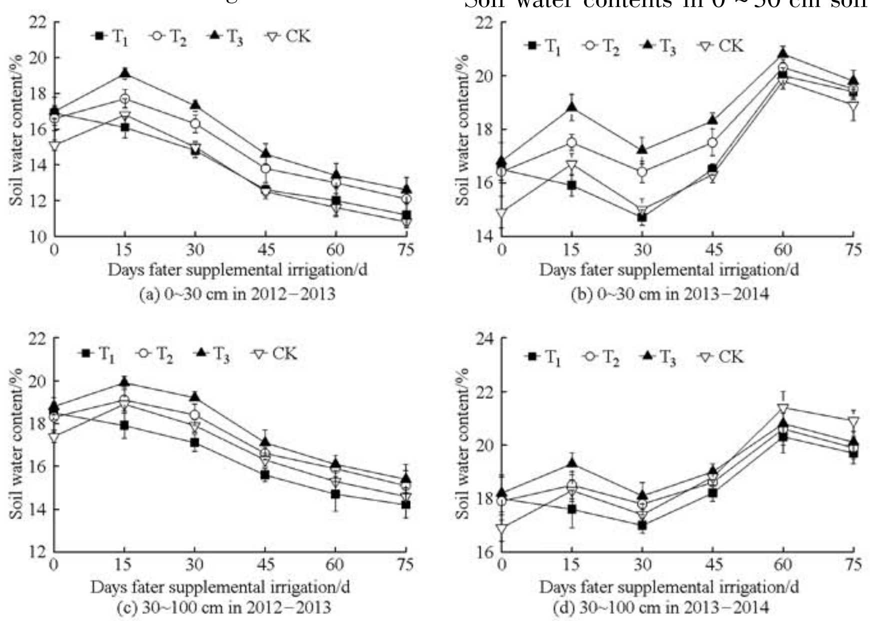

Fig. 3 Dynamics of soil moisture content at different soil layers after supplemental irrigation

from 30 d to 45 d after supplemental irrigation, which was full-bloom stage and winter oilseed rape grew vigorously, were 9.52% ~ 10.14% and 15.87% ~ 16.89% higher than that in T_1, and 8.67% ~ 10.40% and 15.33% ~ 16.80% higher than that in CK. Winter oilseed rape was mature and senescent, and the soil water content had little effect on winter oilseed rape. Soil water contents in 0 ~ 30 cm soil layer in T_2 and T_3 at 75 d after supplemental irrigation were 8.04% and 12.50% higher than that in T_1, and 12.04% and 16.67% higher than that in CK. Soil water content in 0 ~ 30 cm soil layer from 15 d to 75 d after supplemental irrigation in 2013 – 2014 presented a fluctuated trend due to much rainfall. Soil water content in 0 ~ 30 cm soil layer from 30 d to 60 d after supplemental irrigation under each treatment was increased sharply because of rich rainfall during this period. Soil water contents in 0 ~ 30 cm soil layer in T_2 and T_3 from 30 d to 45 d after supplemental irrigation were 6.06% ~ 11.56% and 10.91% ~ 17.00% higher than that in T_1, and 7.36% ~ 9.33% and 12.27% ~ 14.67% higher than that in CK. Soil water content in 0 ~ 30 cm soil layer at 75 d after supplemental irrigation was almost the same among treatments, and soil water contents in T_2 and T_3 were increased by 0.52% and 2.06% compared with T_1, and 3.17% and 4.76% compared with CK.

Soil water content in 30 ~ 100 cm soil layer after supplemental irrigation had small variation amplitude. Soil water content in 30 ~ 100 cm soil layer at 15 d after supplemental irrigation obtained the maximum increasing amplitude in CK, with increase of 8.62% and 8.28% in two seasons, respectively. Soil water content in 30 ~ 100 cm soil layer in 2012 – 2013 had similar trend with soil water content in 0 ~ 30 cm soil layer, which presented a downward trend over time. Soil water content in 30 ~ 100 cm soil layer in 2013 – 2014 presented a fluctuated trend over time, but the soil water content of CK had different variation trend in 30 ~ 100 cm and 0 ~ 30 cm soil layers. Soil water content in 30 ~ 100 cm soil layer from 30 d to 60 d after supplemental irrigation in CK was rapidly increased with the sharp increase of rainfall amount, and soil water content in 30 ~ 100 cm soil layer at 50 d after supplemental irrigation in CK was higher than those in RFRH treatments. Soil water content in 30 ~ 100 cm soil layer at 75 d after supplemental irrigation in CK was 3.98% ~ 6.09% higher than those in RFRH treatments.

Based on above analysis, RFRH treatments increased soil water content in 0 ~ 30 cm soil layer, and prevented the infiltration of water to deep soil layer after heavy rain or irrigation, thus the water use efficiency of winter oilseed rape was improved. Supplemental irrigation at stem elongation stage was beneficial to RFRH treatments to improve soil water content in surface layers, however, heavy rain or irrigation mainly increased soil water content in deep layer in flat planting treatments, and it was unbeneficial to winter oilseed rape to make use of water efficiently.

2.3 Effects of supplemental irrigation under RFRH planting pattern on aboveground dry matter of winter oilseed rape

Aboveground dry matter of winter oilseed rape was significantly affected by different treatments (Tab. 1). The aboveground dry matter under RFRH planting treatments (T_1, T_2 and T_3) at stem elongation stage (before supplemental irrigation) was increased by 22.97% and 20.44% compared with CK in two seasons, respectively. Therefore, RFRH planting pattern could significantly increase the aboveground dry matter of winter oilseed rape. After supplemental irrigation, the aboveground dry matters at initial flowering stage, full-bloom stage and pod stage in T_2 and T_3 (no significant differences were found between the two treatments) were significantly higher than those in T_1 and CK (no significant differences were found between the two treatments). Average aboveground dry matters at pod stage in the two seasons in T_2 and T_3 were 24.42% and 35.45% higher than that in T_1, and 29.78% and 41.30% higher than that in CK. It was obvious that application of appropriate supplemental irrigation at stem elongation stage could significantly increase the accumulation of aboveground dry matter of winter oilseed rape, however, the enhancement would not be significantly promoted when excessive supplemental irrigation was applied.

Tab. 1 Aboveground dry biomass of winter oilseed rape under different treatments kg/hm^2

Growing seasons	Treatments	Aboveground dry matter			
		Stem elongation stage	Initial flowering stage	Full-bloom stage	Pod stage
2012 – 2013	T_1	1 284^{a}	2 215^{b}	3 533^{b}	7 072^{b}
	T_2	1 302^{a}	2 869^{a}	4 980^{a}	9 271^{a}
	T_3	1 269^{a}	3 016^{a}	5 672^{a}	10 301^{a}
	CK	1 045^{b}	2 437^{b}	3 859^{b}	7 286^{b}
2013 – 2014	T_1	1 568^{a}	3 040^{b}	5 104^{b}	10 216^{b}
	T_2	1 605^{a}	3 518^{a}	6 528^{a}	12 238^{a}
	T_3	1 582^{a}	3 769^{a}	7 177^{a}	13 116^{a}
	CK	1 316^{b}	3 162^{b}	4 872^{b}	9 287^{b}

Note: different letters within a column indicated significant differences among treatments within a season at $P < 0.05$. The same as below.

Obvious differences in aboveground dry matter of winter oilseed rape were found between the two seasons due to the differences of rainfall during the two seasons. The aboveground dry matters of winter oilseed rape from initial flowering stage to pod stage in 2013 – 2014 were obviously higher than that in 2012 – 2013 because more precipitation was occurred in 2013 – 2014. The mean aboveground dry matter at pod stage in 2013 – 2014 was 32.20% higher than that in 2012 – 2013.

2.4 Effects of supplemental irrigation under RFRH planting pattern on taproot characteristics and lateral root distribution of winter oilseed rape

2.4.1 Taproot characteristics

Well-developed root system was good for winter oilseed rape to absorb water and nutrients, it could also increase the lodging-resistance capability of winter oilseed rape, and lowered the probability of yield reduction due to lodging of winter oilseed rape. The depth of taproot dug down to the soil and taproot dry weight was significantly correlated with the lodging-resistance coefficient[21-22]. The effects of different treatments on taproot characteristics of winter oilseed rape reached the significance level of $P < 0.05$ (Tab. 2). Taproot lengths in T_1, T_2 and T_3 at stem elongation stage (before supplemental irrigation) in two seasons were significantly lower than that in CK at $P < 0.05$ level, but the taproot diameters at top, top-5 cm and top-10 cm and taproot dry weight in T_1, T_2 and T_3 were significantly higher than that in CK at $P < 0.05$ level.

Tab. 2 Taproot growth parameters of winter oilseed rape under different treatments

Growing seasons	Treat-ments	Stem elongation stage					Pod stage				
		Taproot length/cm	Taproot diameter/mm			Taproot dry weight/(g·plant^{-1})	Taproot length/cm	Taproot diameter/mm			Taproot dry weight/(g·plant^{-1})
			Top	Top-5 cm	Top-10 cm			Top	Top-5 cm	Top-10 cm	
2012 – 2013	T_1	12.1^{b}	13.6^{a}	7.3^{a}	3.2^{a}	4.0^{a}	20.7^{a}	14.1^{b}	9.5^{b}	4.5^{b}	5.1^{b}
	T_2	11.7^{b}	13.1^{a}	7.0^{a}	2.9^{a}	3.8^{a}	18.1^{b}	15.3^{a}	11.4^{a}	5.7^{a}	6.3^{a}
	T_3	12.3^{b}	12.9^{a}	7.7^{a}	3.0^{a}	4.1^{a}	17.9^{b}	15.9^{a}	11.8^{a}	6.1^{a}	6.7^{a}
	CK	14.9^{a}	10.3^{b}	5.2^{b}	1.6^{b}	3.0^{b}	21.3^{a}	13.5^{b}	9.3^{b}	4.0^{b}	4.5^{b}
2013 – 2014	T_1	12.5^{b}	12.8^{a}	6.1^{a}	3.0^{a}	3.6^{a}	20.3^{a}	14.9^{b}	10.3^{b}	5.1^{b}	5.3^{b}
	T_2	12.8^{b}	12.5^{a}	6.7^{a}	2.8^{a}	3.4^{a}	16.9^{b}	16.3^{a}	11.6^{a}	6.4^{a}	6.4^{a}
	T_3	13.0^{b}	12.9^{a}	6.5^{a}	2.7^{a}	3.9^{a}	17.6^{b}	16.5^{a}	12.9^{a}	6.7^{a}	6.9^{a}
	CK	15.7^{a}	9.7^{b}	5.0^{b}	1.5^{b}	2.3^{b}	20.8^{a}	14.2^{b}	9.4^{b}	4.6^{b}	5.0^{b}

Taproot lengths at pod stage in T_2 and T_3 were significantly lower than those in T_1 and CK in two seasons ($P < 0.05$), and the taproot diameters at top, top-5 cm and top-10 cm and taproot dry weights in T_2 and T_3 were significantly higher than those in T_1 and CK ($P < 0.05$). No significant differences were found among the taproot characteristics in T_2 and T_3, and T_1 and CK in two seasons ($P > 0.05$). It was obvious that application of appropriate supplemental irrigation at stem elongation stage could significantly increase taproot diameter and dry weight, but the taproot length was decreased a little. And excessive supplemental irrigation would not further improve the taproot characteristics of winter oilseed rape.

2.4.2 Lateral root distribution

Different treatments significantly affected lateral root density of winter oilseed rape in 0 ~ 10 cm, 10 ~ 20 cm and 20 ~ 30 cm soil layers at $P < 0.05$ level (Fig. 4, different letters indicated significant differences among treatments within a season at $P < 0.05$ level, the same as below). The maximum lateral root density at stem elongation and pod stage in two seasons were all observed in 0 ~ 10 cm soil layer, and the lateral root density was sharply decreased with increase of soil depth. The lateral root density at stem elongation and pod stage across the seasons in 0 ~ 10 cm soil layer accounted for 63.75% ~ 71.07% and 71.14% ~ 75.90% of the total lateral root density in 0 ~ 30 cm soil layer, respectively.

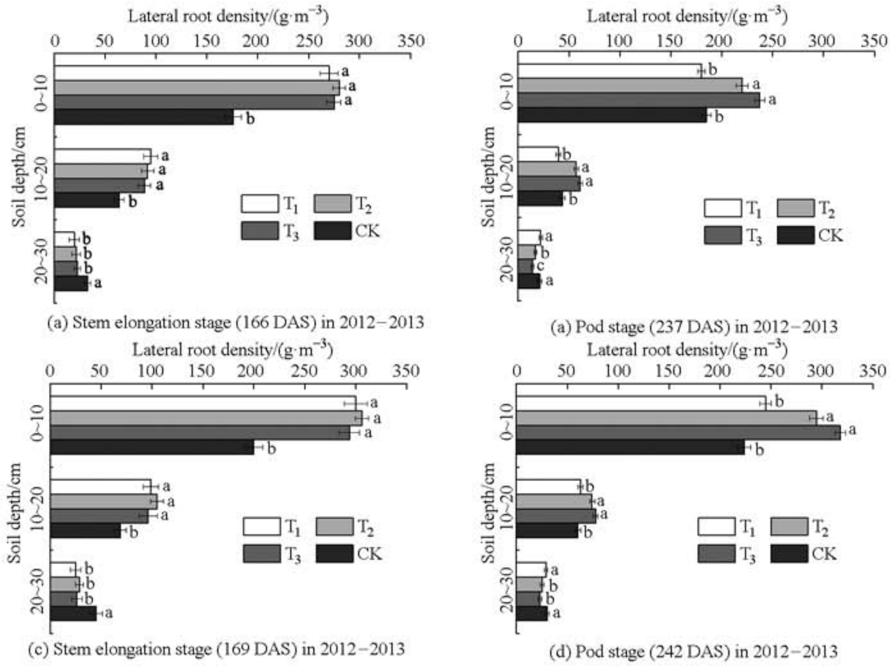

Fig. 4 Distribution of lateral root density of winter oilseed rape under different treatments

Lateral root densities in 0 ~ 10 cm and 10 ~ 20 cm soil layers in T_1, T_2 and T_3 at stem elongation stage (before supplemental irrigation) were significantly higher than those in CK ($P < 0.05$), and lateral root density in 20 ~ 30 cm soil layer was significantly lower than that in CK ($P < 0.05$). It was clear that high soil water content under RFRH planting could significantly increase the lateral root density in 0 ~ 10 cm and 10 ~ 20 cm soil layers.

Lateral root densities in 0 ~ 10 cm and 10 ~ 20 cm soil layers in T_2 and T_3 at pod stage were significantly higher than those in T_1 and CK ($P < 0.05$), and no significant differences were found between T_2 and T_3, and between T_1 and CK. In 2012 – 2013, lateral root densities in 20 ~ 30 cm soil layer in T_1 and CK were significantly higher than that in T_2 ($P < 0.05$), and it was significantly higher in T_2 than that in T_3. In 2013 – 2014, lateral root densities in 20 ~ 30 cm soil layer in T_1 and CK were significantly higher than those in T_2 and T_3 ($P < 0.05$), however, no significant differences were found between T_2 and T_3. This might be caused by the differences of rainfall amount in two seasons.

2.5 Effects of supplemental irrigation under RFRH planting pattern on yield and water use efficiency of winter oilseed rape

2.5.1 Yield and yield components

Different treatments significantly affected seed yield and yield components of winter oilseed rape ($P < 0.05$) (Fig. 5). It can be seen that branch numbers per plant, pod numbers per plant, seed numbers per square meter, and seed yields in T_2 and T_3 were all significantly higher than those in T_1 and CK in two seasons ($P < 0.05$), except for seed numbers per pod and 1000-seed weight in 2013 – 2014, with no significant differences between T_2 and T_3, and between T_1 and CK. Average seed yields across the two seasons in T_2 and T_3 were increased by 50.99% and 58.15% compared with that in T_1, and increased by 53.89% and 61.19% compared with that in CK, respectively. It was obvious that application of appropriate supplemental irrigation at stem elongation stage of winter oilseed rape under RFRH planting could increase branch numbers, pod numbers, seed numbers and 1000-seed weight, and significantly increase seed yield ($P < 0.05$). However, the effect of excessive supplemental irrigation on improving seed yield was not significant.

Yield and yield components in 2013 – 2014 were obviously higher than those in 2012 – 2013, because more precipitation was occurred during the growth period of winter oilseed rape in 2013 – 2014. Seed yield in 2013 – 2014 was increased by 28.98% compared with that in 2012 – 2013. Seed numbers per pod and 1000-seed weight did not differ significantly among T_1, T_2 and T_3 in 2013 – 2014, but they were all significantly higher than those in CK ($P < 0.05$).

2.5.2 Evapotranspiration and water use efficiency

Evapotranspiration (ET), irrigation water use efficiency (IUE), precipitation utilization efficiency (PUE) and water use efficiency (WUE) of winter oilseed rape under different treatments were shown in Tab. 3. It can be seen that ET in T_1, T_2 and T_3 treatments were significantly higher than that in CK ($P < 0.05$), and ET in T_3 was significantly higher than those in T_1 and T_2. Compared with CK, average ET across the two seasons in T_1, T_2 and T_3 were reduced by 27.72%, 20.17% and 8.91%, respectively.

IUE in T_2 and T_3 were significantly higher than that in CK in two seasons ($P < 0.05$), and IUE in T_2 was significantly higher than in T_3 ($P < 0.05$). Average IUE across the two seasons in T_2 and T_3 were improved by 182.40% and 61.65% compared with that in CK. PUE in T_2 and T_3 were significantly higher than those in T_1 and CK in two seasons ($P < 0.05$), with no significant differences between T_2 and T_3, and between T_1 and CK. Average PUE across the two seasons in T_2 and T_3 were improved by 58.04% and 66.87% compared with that in T_1, and improved by 54.61% and 63.25% compared with that in CK, respectively.

Tab. 3 Crop evapotranspiration (ET), irrigation water use efficiency (IUE), precipitation utilization efficiency (PUE) and water use efficiency (WUE) of winter oilseed rape under different treatments

Growing seasons	Treatments	ET/mm	IUE/(kg·m^{-3})	PUE/(kg·m^{-3})	WUE/(kg·m^{-3})
2012 – 2013	T_1	232^d		1.37^b	0.71^b
	T_2	274^c	4.57^a	2.29^a	1.00^a
	T_3	319^b	2.44^b	2.44^a	0.92^a
	CK	341^a	1.47^c	1.47^b	0.52^c
2013 – 2014	T_1	352^c		0.73^b	0.70^b
	T_2	371^c	3.82^a	1.02^a	0.93^a
	T_3	417^b	2.36^b	1.06^a	0.85^a
	CK	467^a	1.50^c	0.67^b	0.48^c

WUE were significantly higher in T_2 and T_3 than those in T_1 and CK in two seasons ($P < 0.05$), and it was significantly higher in T_1 than that in CK ($P < 0.05$). Average WUE across the two seasons in T_2 and T_3 were improved by 37.28% and 25.98% compared with that in T_1, and improved by 92.77% and 76.90% compared with that in CK. Average WUE across the two seasons in T_1 was improved by 40.42% compared with that in CK.

Across the two seasons, compared with T_3, average ET in T_2 was reduced by 45.5 mm, and average IWUE and WUE were increased by 74.70% and 8.97%,

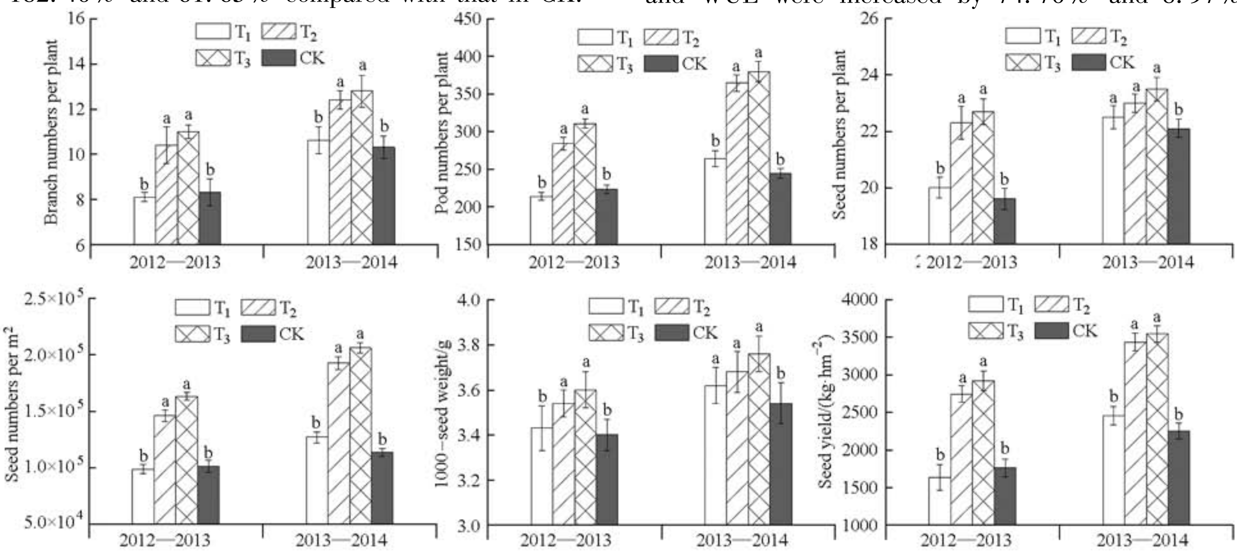

Fig. 5 Effects of supplement irrigation under ridge and furrow rain harvesting cultivation on yield and yield components of winter oilseed rape

respectively. Therefore, RFRH planting pattern could decrease ET of winter oilseed rape, improve PUE and WUE. Application of supplemental irrigation at stem elongation stage (T_2 and T_3) significantly improved seed yield and WUE, though the ET was also increased to some extent.

3 Discussion

3.1 Effects of supplemental irrigation under RFRH planting pattern onroot system of winter oilseed rape

Root is an important organ for crops to absorb water and nutrients and synthesize physiologically active substances, the functions of which are closely associated with root growth conditions and its distribution in the soil. The crops adapt to the changes of environment is often by changing configuration and spatial distribution of root system[23]. The absorption of nutrients for crops and the formation of final yield were affected by the combination of morphological characteristics and physiological property[24]. RFRH planting technology changed the growth micro-topography of field crops, and consequently changed the spatial framework of roots in the soil[25]. HE et al.[11] found that RFRH cultivation obviously improved the soil water content in the planting furrows, thus causing the underground biomass in 0 ~ 10 cm surface soil layer significantly higher than that with flat planting cultivation, however, the underground biomasses in 10 ~ 20 cm and 20 ~ 30 cm soil layers were significantly lower than that with flat planting cultivation, and the differences of soil water content and underground biomass between RFRH and flat planting cultivations were reduced with the increase of soil depth. LI et al.[26] discovered that the root dry weight, root length, root superficial area and root volume of oats were decreased with the increase of soil depth, and the root dry weights in 0 ~ 10 cm, 10 ~ 20 cm and 20 ~ 30 cm in RFRH planting cultivation accounted for 61%, 25% and 14% of the total root dry weight in 0 ~ 30 cm soil layer, respectively. In the present study, after supplemental irrigation at stem elongation stage, lateral root density of winter oilseed rape at pod stage was decreased with the increase of soil depth, and the lateral root densities in 0 ~ 10 cm, 10 ~ 20 cm and 20 ~ 30 cm soil layers accounted for 71.14% ~ 75.90%, 16.34% ~ 19.49% and 4.63% ~ 9.65% of the total lateral root density in 0 ~ 30 cm soil layer, respectively. Lateral root densities in 0 ~ 10 cm and 10 ~ 20 cm soil layers, taproot dry weight, taproot diameter were all significantly higher in T_2 and T_3 than those in T_1 and CK, and no significant differences of all indices were found between T_2 and T_3. It was shown as $T_2 > T_3$ between the lateral root density in 20 ~ 30 cm soil layer in the two seasons, however, that in T_2 was significantly higher than T_3 in 2012 – 2013 (drought year), and no significant differences were found between T_2 and T_3 in 2013 – 2014 (wet year). This might be caused by the differences of rainfall amount in the two seasons from the start of supplemental irrigation to the pod stage.

3.2 Effects of supplemental irrigation under RFRH planting pattern on soil water content of winter oilseed rape

RFRH planting pattern allowed rainwater falling onto the mulching ridges to flow into the furrows and made water resources richen. Meanwhile, the ridges and furrows in the field could reduce wind speed, inhibit water evaporation, and enhance infiltration depth, and accumulated rainwater and increased soil water content[27]. By means of simulating rainfall, REN et al.[14] found that average soil water content in 0 ~ 120 cm soil layer in the planting furrows under RFRH cultivation was significantly higher than that under flat planting plots, and soil water content in surface soil layer varied largely, however, soil water content below 100 cm soil layer did not change obviously. HAN et al.[28] found that RFRH planting pattern could significantly increase soil water storage of winter wheat in 0 ~ 20 cm and 20 ~ 100 cm soil layers from sowing stage to jointing stage, and from heading stage to filling stage. KOU et al.[20] found that RFRH cultivation with ridges mulched significantly increased soil water content of alfalfa in 0 ~ 20 cm soil layer during early stages (from the mid April to early June), and it significantly increased soil water content in 0 ~ 120 cm soil layer during late stages (from the mid June to late September). In the present research, before the application of supplemental irrigation, the average soil water content in 0 ~ 30 cm soil layer across the two seasons in planting furrows under RFRH cultivation was significantly higher than that in CK, with average increase of 11.33%, and the average soil water content in 30 ~ 100 cm soil layer was slightly higher than that in CK, with average increase of 6.61%. After supplemental irrigation, average soil water content in 0 ~ 30 cm soil layer for different treatments all significantly varied in both seasons. Soil water content in 0 ~ 30 cm soil layer in T_3 at different stages were all significantly higher than those in other treatments, and soil water content in 30 ~ 100 cm soil layer in T_2 was obviously higher than those in T_1 and CK, except for 75 d after supplemental irrigation in 2013 – 2014. Soil water contents in 30 ~ 100 cm soil layer in T_1, T_2 and T_3 did not vary obviously in both seasons, but it varied largely in CK.

ZHANG et al. [2] found that RFRH planting pattern mainly increased soil water content of winter wheat in 0 ~ 40 cm soil layer, and supplemental irrigation at returning green stage was beneficial to the increase of soil water content in surface soil layer under RFRH planting pattern. Irrigation and heavy rain mainly increased soil water content in deep soil layer under flat planting pattern, and it was not good for winter wheat to make use of soil water. The present study obtained the similar result. In the present research, RFRH planting pattern significantly improved soil water content in 0 ~ 30 cm soil layer, and CK remarkably increased soil water content in 30 ~ 100 cm soil layer after supplemental irrigation or heavy rain, which indicated that RFRH planting pattern could effectively promote the use of irrigation water or rain water for winter oilseed rape.

3.3 Effects of supplemental irrigation under RFRH planting pattern on seed yield and water use efficiency of winter oilseed rape

RFRH cultivation technology could effectively regulate soil water deficiency, improve water use efficiency and increase crop yield. HAN et al. [28] found that RFRH planting pattern could significantly increase soil water storage, yield and WUE of winter wheat. KOU et al. [20] observed that the average WUE of alfalfa under RFRH treatments was 34.91 kg/(hm^2 · mm), which was 2.25 times of that under flat planting treatments. ZHANG et al. [2] discovered that yields of winter wheat with supplemental irrigation amount of 0 mm, 37.5 mm and 75.0 mm under RFRH planting pattern were increased by 2.8%, 9.6% and 18.9% compared with supplemental irrigation amount of 75.0 mm under flat planting pattern, respectively, and WUE were improved by 17.9%, 10.4% and 15.4%, respectively. In the present study, compared with CK, average seed yields of winter oilseed rape in T_1, T_2 and T_3 treatments across the two seasons were increased by 1.92%, 53.89% and 61.19%, respectively, and WUE were improved by 40.42%, 92.77% and 76.90%, respectively. Rainfall amount during the critical stage of winter oilseed rape (March to April) in 2013 – 2014 was 156.4 mm more than that in 2012 – 2013, and adequate precipitation increased average seed yield in 2013 – 2014 by 28.98% compared with that in 2012 – 2013.

4 Conclusions

(1) Soil water contents in 0 ~ 30 cm soil layer of treatments with supplemental irrigation amounts of 60 mm (T_2) and 120 mm (T_3) under RFRH cultivation were obviously higher than those in treatments with supplemental irrigation amount of 0 mm (T_1) and supplemental irrigation amount of 120 mm under flat planting cultivation (CK). After supplemental irrigation, aboveground dry matters in T_2 and T_3 at initial flowering stage, full-bloom stage and pod stage were significantly higher than those in T_1 and CK. Taproot diameter and dry weight, and lateral root density in 0 ~ 10 cm and 10 ~ 20 cm soil layers in T_2 and T_3 at pod stage were markedly increased.

(2) RFRH planting pattern could significantly improve seed yield and WUE of winter oilseed rape. Average seed yields across the two seasons in T_2 and T_3 were increased by 50.99% and 58.15% compared with T_1, and increased by 53.89% and 61.19% compared with CK, respectively. Average WUE across the two seasons in T_2 and T_3 were improved by 37.28% and 25.98% compared with that in T_1, and improved by 92.77% and 76.90% compared with that in CK, respectively.

(3) T_3 obtained the highest seed yield in two seasons, however, no significant differences were found between T_2 and T_3. Average seed yield across the two seasons in T_3 was increased by 4.74% compared with that in T_2. But compared with T_3, T_2 saved 60 mm of irrigation water and reduced ET by 45.5 mm, and increased the average WUE by 8.97%.

(4) By comprehensively considering water saving and yield increase, T_2 (with supplemental irrigation amount of 60 mm under RFRH cultivation) was recommended as an appropriate irrigation schedule and cultivation pattern for winter oilseed rape at stem elongation stage.

References

[1] WEI Xiaomei, BA Duoduo. Groundwater resource evolution and agricultural eco-environmental issues in the irrigation areas in North China[J]. Journal of Irrigation and Drainage, 2003, 22(5): 25 – 28. (in Chinese)

[2] ZHANG Yu, HAN Qingfang, CHENG Xuefeng, et al. Effects of ridge and furrow rain harvesting with supplemental irrigation on winter wheat photosynthetic characteristics, yield and water use efficiency in Guanzhong irrigation district [J]. Chinese Journal of Applied Ecology, 2015, 26(5): 1382 – 1390. (in Chinese)

[3] HAN Qingfang, LI Xiangtuo, WANG Junpeng, et al. Simulated study on soil moisture of field under water micro-collecting farming conditions[J]. Transactions of the CSAE, 2004, 20(2): 78 – 82. (in Chinese)

[4] LI X Y, GONG J D. Effects of different ridge, furrow ratios and supplemental irrigation on crop production in ridge and furrow rainfall harvesting system with mulches [J]. Agricultural Water Management, 2002, 54(12): 243 – 254.

[5] WANG Xiaoling, CHEN Mingcan, YI Xianfeng, et al. Effects of ridge width and planting density on corn yields in rainwater-harvesting system with plastic film mulching on ridge[J]. Transactions of the CSAE, 2009, 25(8): 40 – 47. (in Chinese)

[6] KEMPER W D, NOONAN L. Runoff as affected by salt treatments and soil texture[J]. Soil Science Society of America Journal, 1970, 34(1): 126 – 130.

[7] WIYO K A, KASOMEKERA Z M, FEYEN J. Variability in ridge and furrow size and shape and maize population on density on small sunsistence farms in Malawi[J]. Soil and Tillage Research, 1999, 51(1 – 2): 113 – 119.

[8] MYERS L E. Sprayed asphalt pavements for water harvesting[J]. Journal of the Irrigation and Drainage Division, 1967, 93: 79 – 97.

[9] LI F M, GUO A H, WEI H. Effects of clear plastic film mulch on yield of spring wheat [J]. Field Crops Research, 1999, 63(1): 79 – 86.

[10] FISHER P D. An alternative plastic mulching system for improved water management in dryland maize production [J]. Agricultural Water Management, 1995, 27(2): 155 – 166.

[11] HE Feng, WANG Kun, LI Xianglin, et al. Effects of ridge and furrow rainfall harvesting system on soil hydrothermal condition and yields of *Elymus sibiricus* L. in arid and semiarid regions[J]. Transactions of the CSAE, 2012, 28(12): 122 – 126. (in Chinese)

[12] NIU J, GAN Y T, ZHANG J W, et al. Postanthesis dry matter accumulation and redistribution in spring wheat mulched with plastic film[J]. Crops Science, 1998, 38(6): 1562 – 1568.

[13] DONG H Z, LI W J, TANG W, et al. Early plastic mulching increases stand establishment and lint yield of cotton in saline fields[J]. Field Crops Research, 2009, 111(3): 269 – 275.

[14] REN Xiaolong, JIA Zhikuan, CHEN Xiaoli, et al. Effects of ridge and furrow planting for rainfall harvesting on photosynthetic characteristics and yield in corn in semi-arid regions[J]. Acta Agronomica Sinica, 2008, 34(5): 838 – 845. (in Chinese)

[15] WANG Cairong, TIAN Xiaohong, LI Shengxiu. Effects of plastic sheet-mulching on ridge for rainwater-harvesting cultivation on WUE and yield of winter wheat [J]. Scientia Agricultura Sinica, 2004, 37(2): 208 – 214. (in Chinese)

[16] ZHANG S L, LI P R, YANG X Y, et al. Effects of tillage and plastic mulch on soil water, growth and yield of spring-sown maize[J]. Soil Tillage Research, 2011, 112(1): 92 – 97.

[17] WANG X L, LI F M, JIA Y, et al. Increasing potato yields with additional water and increased soil temperature [J]. Agricultural Water Management, 2005, 78(3): 181 – 194.

[18] SU Wang, QU Yang, FENG Baili, et al. Photosynthesis characteristics and yield of broomcorn millet under film mulching on ridge-furrow for harvesting rainwater model in semi-arid region of Northern Shaanxi [J]. Transactions of the CSAE, 2014, 30(13): 137 – 145. (in Chinese)

[19] QIANG Shengcai, ZHANG Hengjia, MO Fei, et al. The effects of micro-rain water harvesting pattern and rain fall variability on water ecological stoichiometry in oat (*Avenasativa* L.) field[J]. Acta Ecologica Sinica, 2011, 37(9): 2365 – 2373. (in Chinese)

[20] KOU Jiangtao, SHI Shangli. Effect of rainwater harvesting via plastic film-covered ridge on soil moisture in *Medicago sativa* grassland and water use efficiency [J]. Chinese Journal of Eco-Agriculture, 2011, 19(1): 47 – 53. (in Chinese)

[21] MA Ni, LI Ling, XU Jun, et al. Researches on the lodging resistance and agronomic traits of winter rape (*Brassica napus* L.)[J]. Crops, 2010(6): 36 – 41. (in Chinese)

[22] CHEN Xinjun, QI Cunkou, PU Huiming, et al. Evaluation of lodging resistance in rapeseed (*Brassica napus* L.) and relationship between plant architecture and lodging resistance[J]. Chinese Journal of Oil Crop Sciences, 2007, 29(1): 54-57. (in Chinese)

[23] WANG Fahong, WANG Xuqing, LIU Suying, et al. Progress on relationship between root distribution and crop yield [J]. Journal of Shandong Agricultural Science, 1997(4): 48-51.

[24] LYNCH J. Root architecture and plant productivity [J]. Plant Physiology, 1995, 109(1): 7-13.

[25] REN Xiaolong, JIA Zhikuan, CHEN Xiaoli, et al. Effect of ridge and furrow planting of rainfall harvesting on soil available nutrient distribution and root growth of summer corn under simulated rainfall conditions [J]. Transactions of the CSAE, 2007, 23(12): 94-99. (in Chinese)

[26] LI Fuchun, REN Xiang, WANG Qi, et al. Effects of rainfall harvesting in ridges and furrows on root distribution patterns of oat in semi-arid area of Gansu, Northwest China [J]. Chinese Journal of Ecology, 2013, 32(11): 2966-2972. (in Chinese)

[27] LI Fengmin, WANG Jing, ZHAO Songling. The rainwater harvesting technology approach for dryland agriculture in semi-arid Loess Plateau of China [J]. Acta Ecologica Sincia, 1999, 19(2): 259-264. (in Chinese)

[28] HAN Juan, LIAO Yuncheng, JIA Zhikuan, et al. Effects of ridging with mulching on yield and water use efficiency in winter wheat in semi-humid drought-prone region in China [J]. Acta Agronomica Sinica, 2014, 40(1): 101-109. (in Chinese)

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垄沟集雨补灌对冬油菜根系、产量与水分利用效率的影响

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摘要：为确定垄沟集雨栽培条件下冬油菜蕾薹期的适宜补灌量，设置垄沟集雨雨养（T_1）、垄沟集雨补灌 60 mm（T_2）和 120 mm（T_3）3 个处理，并设平作补灌 120 mm 作为对照（CK），通过 2 年田间试验，系统地对比分析了不同补灌处理对冬油菜 0～30 cm 和 30～100 cm 土层的平均土壤含水率、地上部干物质量、主根性状和侧根密度、产量构成及水分利用效率的影响。结果表明，T_2 和 T_3 处理不同时期 0～30 cm 土层的平均土壤含水率、花期和角果期地上部干物质量均明显高于 T_1 和 CK 处理，T_2 和 T_3 处理角果期的主根直径和干质量、0～10 cm 和 10～20 cm 侧根密度显著增加，且 T_2 和 T_3 处理间不存在显著差异。T_2 和 T_3 处理能显著增加油菜籽粒产量和水分利用效率，T_2 和 T_3 处理 2 年平均分别比 T_1 增产 50.99% 和 58.15%，比 CK 增产 53.89% 和 61.19%；T_2 和 T_3 处理 2 年平均水分利用效率比 T_1 分别提高 37.28% 和 25.98%，比 CK 分别提高 92.77% 和 76.90%。2 年中 T_3 处理均能获得最高的籽粒产量，但 T_3 与 T_2 处理间产量不存在显著差异，T_3 较 T_2 仅增产 4.74%，但 T_2 比 T_3 能够减少灌水量 60 mm，减少耗水量 45.5 mm，水分利用效率提高 8.97%。从节水和农业可持续发展的角度来看，垄沟集雨种植并在蕾薹期补灌 60 mm（T_2）为较优的冬油菜栽培灌溉措施。

关键词：冬油菜；垄沟集雨；补灌；根系特征；产量；水分利用效率

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Effects of Ridge and Furrow Rain Harvesting Cultivation with Supplemental Irrigation on Root, Yield and Water Use Efficiency of Winter Oilseed Rape (*Brassica napus* L.)

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Abstract: Two-year (2012—2013 and 2013—2014) field experiments were conducted to determine the appropriate supplemental irrigation amount of winter oilseed rape (*Brassica napus* L.) at stem elongation stage with the ridge and furrow rain harvesting cultivation. Four treatments, including T_1, T_2, T_3 (with supplemental irrigation amounts of 0, 60, 120 mm under ridge and furrow rain harvesting cultivation, respectively) and CK (with supplemental irrigation amount of 120 mm under flat planting cultivation) were set up to evaluate the effects of different supplemental irrigation amounts on soil moisture content at 0～30 cm and 30～100 cm soil depths, aboveground dry matter, taproot growth parameters, lateral root density, yield components and water use efficiency (WUE) of winter oilseed rape. The results showed that soil moisture contents at 0～30 cm soil depth of T_2 and T_3 at different periods were obviously higher than those of T_1 and CK. Aboveground dry matter at flowering stage and pod stage, taproot diameter and dry weight, lateral root density at 0～10 cm and 10～20 cm soil depths at pod stage of T_2 and T_3 were significantly higher than those of T_1 and CK, and no significant differences were found between T_2 and

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T_3. Compared with T_1 and CK, seed yields of T_2 and T_3 in two years were increased by 50.99%, 58.15% and 53.89%, 61.19%, respectively, and WUE of T_2 and T_3 in two years were improved by 37.28%, 25.98% and 92.77%, 76.90%, respectively. T_3 achieved the highest yield in both years, the average yield, crop evapotranspiration (ET) and WUE of which were 3 235 kg/hm^2, 368 mm, 0.89 kg/m^3, respectively. While the highest WUE with average value of 0.96 kg/m^3 was determined in T_2, with average yield of 3 089 kg/hm^2 and average ET of 322 mm. Therefore, compared with T_3, T_2 could save irrigation amount by 60 mm, increase WUE by 8.97%, and the yield was just reduced by 4.74%. From the perspective of saving water and increasing yield, T_2 was recommended as an appropriate irrigation schedule and cultivation pattern for winter oilseed rape at stem elongation stage.

Key words: winter oilseed rape; ridge and furrow rain harvesting; supplemental irrigation; root characteristics; yield; water use efficiency

引言

水资源短缺一直是限制我国西北干旱半干旱地区农业发展的巨大难题，加之近年来北方大部分地区出现气候偏暖和持续性干旱现象，降水量明显减少，西北地区平均年降水量减少 5%[1]。陕西关中地区是我国重要的灌溉农业区，当地粗放的种植和灌溉方式不仅没有提高作物产量，还造成水资源的严重浪费，年农业用水总量达 25.2 亿 m^3，在中等干旱年份，缺水程度达 25.8%[2]。因此，研究如何提高自然降水和灌溉水的利用效率，进而降低灌溉量并扩大灌溉面积，对该地区农业的可持续发展具有重要的现实意义。垄沟集雨栽培技术是一种通过在田间修筑垄沟、垄面覆膜、沟内种植作物实现降水由垄面向沟内汇集的田间集水农业技术。大量研究表明，垄沟集雨栽培技术能明显提高作物产量和水分利用效率[3-5]，有效调控土壤水分亏缺，降低土壤无效蒸发，提高土壤含水率[6-7]，增加地表径流的收集效率，减少水土流失[8]，而且还能有效提高作物对养分的吸收利用效率[9-10]，增加土壤温度[11]，活化土壤养分[12]，抑制土壤盐碱化的发生[13]，优化农作物对光照的需求，提高农作物的叶绿素含量和光合效率[14]。目前，国内外学者主要针对小麦[15]、玉米[16]、马铃薯[17]、糜子[18]、燕麦[19]和苜蓿[20]等进行了大量垄沟集雨栽培研究，但在垄沟集雨栽培条件下，在作物生育关键期进行适量补灌对作物产量及水分利用效率的研究鲜有报道，尤其是针对冬油菜的研究报道较少。

本文基于 2 年田间试验，在垄沟集雨栽培条件下，通过分析比较在冬油菜蕾薹期不同补灌量对土壤含水率、地上部干物质量、根系特征、产量和水分利用效率的影响，以期确定在垄沟集雨栽培下冬油菜蕾薹期的适宜补灌量，为冬油菜合理补灌提供理论依据。

1　材料与方法

1.1　试验地概况

2012—2013 年、2013—2014 年 2 年试验于陕西杨凌西北农林科技大学旱区农业水土工程教育部重点实验室试验田进行。该区地处 34°17′N、108°04′E，海拔高度 521 m，属暖湿带季风半湿润气候区，年均日照时数 2 163.8 h，无霜期 210 d。试验田土壤为中壤土，土壤田间持水率为 24%（质量含水率），土壤容重 1.40 g/cm^3。试验站地下水埋深在 8 m 以下，其向上补给量可忽略不计。2012—2013 年播前 0～20 cm 耕层土壤基本理化性状为：有机质13.36 g/kg，全氮 0.96 g/kg，硝态氮 73.01 mg/kg，速效磷 24.07 mg/kg，速效钾 135.73 mg/kg，pH 值为 8.13；2013—2014 年播前 0～20 cm 耕层土壤基本理化性状为：有机质 12.78 g/kg，全氮 0.98 g/kg，硝态氮 72.54 mg/kg，速效磷 24.26 mg/kg，速效钾135.32 mg/kg，pH 值为 8.14。

1.2　试验材料与设计

试验用塑料地膜宽 80 cm、厚 0.008 mm；供试冬油菜品种为“陕油 107 号”，由西北农林科技大学农学院提供。供试氮肥为尿素（含 N 质量分数 46% 以上），磷肥为过磷酸钙（含 P_2O_5 质量分数 16% 以上），钾肥为农业用硫酸钾（含 K_2O 质量分数 51% 以上），硼肥为硼砂（含 B 质量分数 11.5% 以上）。

在蕾薹期（3 月 1 日）进行补灌，垄沟集雨处理的补灌量设 3 个水平：雨养（T_1）、补灌 60 mm（T_2）和补灌 120 mm（T_3），并设平作补灌 120 mm 作为对照（CK）。试验共 4 个处理，每处理重复 3 次，共 12 个小区，完全随机排列，小区面积 14 m^2（4 m×3.5 m），小区间设 1 m 宽的间隔区。集雨种植垄、沟宽均为 50 cm，垄高 20 cm，垄上覆膜，沟内种植冬油菜，在种植沟内进行补灌；平作不起垄不覆膜。垄沟集雨和平作种植方式如图 1 所示。播前基施氮、磷、钾、硼

肥分别为 100、90、120、15 kg/hm^2,在补灌前追施氮肥 80 kg/hm^2。冬油菜按株距 13 cm、行距 50 cm 人工点播,待油菜长出 3 片真叶后(2012 年 9 月30 日、2013 年 9 月 27 日)按密度 12 万株/hm^{2}进行间苗、定苗。2013 年 9 月天气干旱,为保证正常出苗,播种后每小区灌水 30 mm,其它田间生产管理与当地高产田一致。2012 年 9 月 15 日播种,2013 年 5 月 20 日收获;2013 年 9 月 12 日播种,2014 年 5 月 22 日收获。

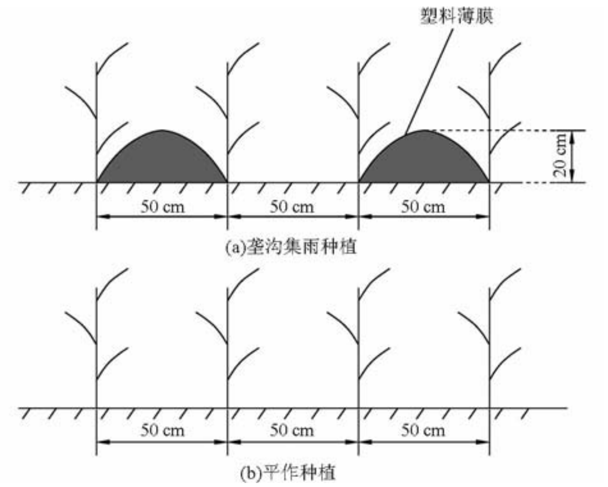

图 1 垄沟集雨种植和平作种植示意图

Fig. 1 Sketches of ridge and furrow rain harvesting cultivation and flat plantings

1.3 测定项目与方法

土壤含水率:采用取土干燥法分别测定不同处理冬油菜播种前和收获后 0 ~200 cm 土层的土壤含水率,并测定从补灌当天起每 15 d 左右的 0 ~100 cm 土层的土壤含水率。于集雨种植处理沟中和平作处理行中取土样,沿土壤深度方向每隔 10 cm 取一个土样。

土壤贮水量计算式为

$$W = 10\gamma h\theta \tag{1}$$

式中 W——土壤贮水量,mm

γ——土壤容重,g/cm^3

h——土层厚度,cm

θ——土壤含水率,%

作物耗水量计算式为

$$ET = P + I - \Delta W \tag{2}$$

式中 ET——作物耗水量,mm

P——油菜生育期降水量,mm

I——灌水量,mm

ΔW——播种前和收获后土壤贮水量的变化量

灌水、降水和水分利用效率计算式为

$$I_{WUE} = Y/(10I) \tag{3}$$

$$P_{WUE} = Y/(10P) \tag{4}$$

$$W_{UE} = Y/(10ET) \tag{5}$$

式中 I_{WUE}——灌水利用效率,kg/m^3

P_{WUE}——降水利用效率,kg/m^3

W_{UE}——水分利用效率,kg/m^3

Y——油菜籽粒产量,kg/hm^2

地上部干物质量:分别于蕾薹期(补灌前,2013 年 166 DAS、2014 年 169 DAS,DAS 为播种后天数)、初花期(2013 年 192 DAS、2014 年 194 DAS)、盛花期(2013 年 206 DAS、2014 年 209 DAS)和角果期(2013 年 237 DAS、2014 年 242 DAS)在各小区选取 5 株具有代表性的植株,将茎、叶和角果分开,用干燥法测定地上部各器官的干物质量,地上部干物质量为各器官干物质量之和。

主根性状和侧根分布:在蕾薹期(补灌前,2013 年 166 DAS、2014 年 169 DAS)和角果期(2013 年 237 DAS、2014 年 242 DAS)测定冬油菜主根性状和侧根分布。每小区挖取 5 个有代表性的整根,剪去侧根后,分别用尺子和游标卡尺测定主根长和根颈粗;用直径 7 cm 的根钻在植株行间(垄沟种植取沟内)分别取出 0 ~10 cm、10 ~20 cm 和 20 ~30 cm 根样,放在细纱网上,用水将土冲净,拣出侧根。将主根和侧根分别放入 70℃ 干燥箱干燥至质量恒定。

产量:提前在各小区中央划定 1 m^{2}的测产区,成熟后单独收获,晒干去壳后测定籽粒产量,在各小区划定的 1 m^{2}测产区内随机选取 10 株分别测定其分枝数、单株角果数、每角籽粒数和千粒质量。

1.4 数据处理与分析

利用 Excel 2010 软件处理试验数据;利用 PASW Statistics 18.0 软件进行方差分析,多重比较采用 Duncan 新复极差法,显著性水平为 $\alpha = 0.05$;利用 OriginPro 8.5 软件作图。

2 结果分析

2.1 冬油菜生育期内降水与气温分布

2012—2013 年、2013—2014 年和 2006—2011 年冬油菜生育期各月的降水量和平均温度见图 2。2013、2014 年 1 月平均气温(0.1℃和 1.1℃)均显著大于 2006—2011 年 1 月平均气温(-1.8℃),2012—2013 年和 2013—2014 年冬油菜生育期总降水量分别为 119.6 mm 和 335.8 mm,2006—2011 年冬油菜生育期平均总降水量为 371.6 mm。在冬油菜关键生育期(3—4 月份)的降水量,2012—2013 年比 2013—2014 年少 156.4 mm,2012—2013 年属于干旱年。

2.2 集雨补灌下土壤含水率的动态变化

冬油菜蕾薹期补灌后不同处理 0 ~30 cm 和 30 ~

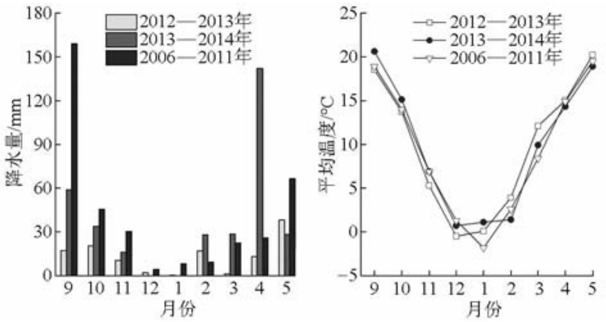

图 2　试验站冬油菜生育期各月降水量和平均温度

Fig. 2　Monthly total rainfall and mean temperature during winter oilseed rape growth seasons at experimental site

100 cm 土层平均含水率的动态变化见图 3。由图 3 分析可知，0 ~ 30 cm 土层的含水率受降水和灌水的影响较大，由于 2 年降水量和降水分布的不同，使得 2 年补灌后 15 ~ 75 d 各处理 0 ~ 30 cm 和 30 ~ 100 cm 土层平均含水率的变化趋势明显不同。补灌前，集雨种植处理 0 ~ 30 cm 和 30 ~ 100 cm 土层的含水率明显高于 CK，2 年集雨种植 0 ~ 30 cm 和 30 ~ 100 cm 土层的平均含水率分别比 CK 提高 11.33% 和 6.61%。

补灌后 15 d，T_2、T_3 和 CK 处理 0 ~ 30 cm 土层的平均含水率大幅提高。2012—2013 年天气干旱，补灌后 15 ~ 75 d 各处理 0 ~ 30 cm 土层的含水率均呈下降趋势；补灌后 30 ~ 45 d 是冬油菜的盛花期，生长旺盛，该阶段 T_2 和 T_3 处理 0 ~ 30 cm 土层的含水率比 T_1 分别增加 9.52% ~ 10.14% 和 15.87% ~ 16.89%，比 CK 分别增加 8.67% ~ 10.40% 和 15.33% ~ 16.80%；补灌后 75 d（5 月 14 号），冬油菜进入成熟期，已经衰老，土壤含水率对冬油菜生长影响不大，T_2 和 T_3 处理 0 ~ 30 cm 土层的含水率分别比 T_1 提高 8.04% 和 12.50%，比 CK 提高 12.04% 和 16.67%。2013—2014 年降水较多，补灌后 15 ~ 75 d 各处理 0 ~ 30 cm 土层的含水率随时间推移呈上下波动趋势，补灌后 30 ~ 60 d，降水丰富，该阶段各处理 0 ~ 30 cm 土层的含水率大幅升高，补灌后 30 ~ 45 d，T_2 和 T_3 处理 0 ~ 30 cm 土层的含水率比 T_1 分别增加 6.06% ~ 11.56% 和 10.91% ~ 17.00%，比 CK 分别增加 7.36% ~ 9.33% 和 12.27% ~ 14.67%；补灌后 75 d，各处理 0 ~ 30 cm 土层的含水率相差不大，T_2 和 T_3 处理分别比 T_1 提高 0.52% 和 2.06%，比 CK 提高 3.17% 和 4.76%。

补灌后，30 ~ 100 cm 土层的平均含水率变动幅度较小。补灌后 15 d，平作补灌 CK 处理 30 ~ 100 cm 土层的平均含水率增加幅度最大，2 年增幅分别为 8.62% 和 8.28%。2012—2013 年 30 ~ 100 cm 土层的平均含水率随时间推移逐渐下降，其变化趋势与 0 ~ 30 cm 土层含水率的变化趋势基本一致。2013—2014 年 30 ~ 100 cm 土层的平均含水率随时间呈上下波动状态，但 CK 处理的变化趋势与 0 ~ 30 cm 土层有所不同。在补灌后 30 ~ 60 d，随降水量的大幅增加，平作补灌 CK 处理 30 ~ 100 cm 土层的平均土壤含水率迅速上升，在补灌后 50 d 左右，CK 处理 30 ~ 100 cm 土层的土壤含水率高于集雨处理。补灌后 75 d，CK 处理 30 ~ 100 cm 土层的平均含水率比集雨处理高 3.98% ~ 6.09%。

综上分析，集雨处理增加了冬油菜 0 ~ 30 cm 土层的含水率，并在灌水和强降水的情况下，防止了大量水分下渗到深层土壤，提高了冬油菜对水分的利用效率。蕾薹期补灌有利于集雨处理表层土壤含水率的增加，而灌水和强降水则主要增加了平作处理深层

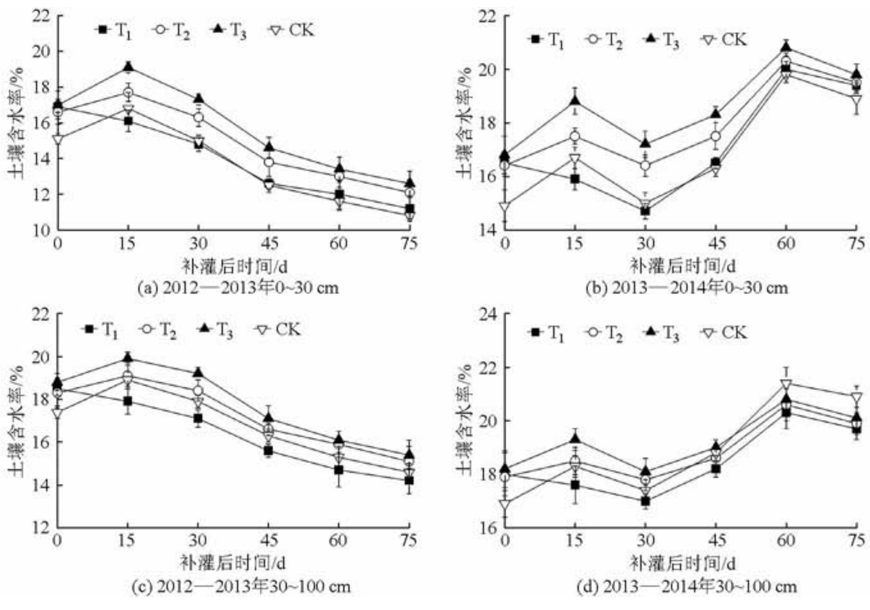

图 3　补灌后冬油菜不同土层土壤含水率的动态变化

Fig. 3　Dynamics of soil moisture content at different soil layers after supplemental irrigation

土壤的含水率,不利于冬油菜对水分的高效利用。

2.3 集雨补灌对冬油菜地上部干物质量的影响

不同处理对冬油菜地上部干物质量有显著影响(表1)。2年蕾薹期(补灌前)集雨种植处理(T_1、T_2和T_3)地上部干物质量比平作种植处理CK分别平均增加22.97%和20.44%,可见集雨种植能明显增加冬油菜地上部干物质量。补灌后,2年初花期、盛花期和角果期冬油菜地上部干物质量均表现为T_2和T_3(二者差异不显著)处理显著大于T_1和CK(二者差异不显著)处理。角果期,T_2和T_3处理的2年平均地上部干物质量比T_1分别增加24.42%和35.45%,比CK分别增加29.78%和41.30%。可见,对集雨种植冬油菜在蕾薹期进行适量补灌,能明显促进地上部干物质的积累,但过量补灌其促进作用不再显著提升。

由于2年降水量的不同,造成2年地上部干物质量的明显差异,2013—2014年初花期到角果期的降水量大,其同一生育期冬油菜的地上部干物质量均明显大于2012—2013年。角果期,2013—2014年各处理的平均地上部干物质量比2012—2013年增加32.20%。

2.4 集雨补灌对冬油菜主根性状和侧根密度分布的影响

2.4.1 集雨补灌对冬油菜主根性状的影响

发达的根系不仅有利于油菜吸收水分和养分,而且能提高油菜的抗倒伏能力,降低油菜因倒伏而减产的可能性。主根下扎深度和根干质量与油菜的抗倒伏系数显著相关[21-22]。2年不同处理对冬油菜主根性状的影响达显著水平($P<0.05$)(表2)。

表1 不同处理冬油菜的地上部干物质量

Tab.1 Aboveground dry matter of winter oilseed rape under different treatments kg/hm²

生长年份	处理	蕾薹期	初花期	盛花期	角果期
2012—2013	T_1	1 284^a	2 215^b	3 533^b	7 072^b
	T_2	1 302^a	2 869^a	4 980^a	9 271^a
	T_3	1 269^a	3 016^a	5 672^a	10 301^a
	CK	1 045^b	2 437^b	3 859^b	7 286^b
2013—2014	T_1	1 568^a	3 040^b	5 104^b	10 216^b
	T_2	1 605^a	3 518^a	6 528^a	12 238^a
	T_3	1 582^a	3 769^a	7 177^a	13 116^a
	CK	1 316^b	3 162^b	4 872^b	9 287^b

注:同一列数据后不同字母表示处理间达到显著性差异($P<0.05$),下同。

表2 不同处理冬油菜的主根生长性状

Tab.2 Taproot growth parameters of winter oilseed rape under different treatments

生长年份	处理	蕾薹期					角果期				
		主根长/cm	主根直径/mm			主根干质量/(g·株$^{-1}$)	主根长/cm	主根直径/mm			主根干质量/(g·株$^{-1}$)
			顶端	5 cm处	10 cm处			顶端	5 cm处	10 cm处	
2012—2013	T_1	12.1^b	13.6^a	7.3^a	3.2^a	4.0^a	20.7^a	14.1^b	9.5^b	4.5^b	5.1^b
	T_2	11.7^b	13.1^a	7.0^a	2.9^a	3.8^a	18.1^b	15.3^a	11.4^a	5.7^a	6.3^a
	T_3	12.3^b	12.9^a	7.7^a	3.0^a	4.1^a	17.9^b	15.9^a	11.8^a	6.1^a	6.7^a
	CK	14.9^a	10.3^b	5.2^b	1.6^b	3.0^b	21.3^a	13.5^b	9.3^b	4.0^b	4.5^b
2013—2014	T_1	12.5^b	12.8^a	6.1^a	3.0^a	3.6^a	20.3^a	14.9^b	10.3^b	5.1^b	5.3^b
	T_2	12.8^b	12.5^a	6.7^a	2.8^a	3.4^a	16.9^b	16.3^a	11.6^a	6.4^a	6.4^a
	T_3	13.0^b	12.9^a	6.5^a	2.7^a	3.9^a	17.6^b	16.5^a	12.9^a	6.7^a	6.9^a
	CK	15.7^a	9.7^b	5.0^b	1.5^b	2.3^b	20.8^a	14.2^b	9.4^b	4.6^b	5.0^b

蕾薹期(补灌前),2年集雨种植T_1、T_2和T_3处理的主根长均显著小于平作种植CK($P<0.05$),但其主根顶端、5 cm处和10 cm处的直径以及主根干质量均显著大于平作种植CK($P<0.05$)。

角果期,2年集雨补灌T_2和T_3处理的主根长均显著小于集雨雨养处理T_1和平作补灌CK($P<0.05$),T_2和T_3处理的主根顶端、5 cm处和10 cm处的直径以及主根干质量均显著大于T_1和CK($P<0.05$)。2年T_2与T_3、T_1与CK处理间的各主根性状均不存在显著差异($P>0.05$)。可见,在蕾薹期对集雨种植冬油菜进行适量补灌,能明显增加主根茎粗和干质量,但主根长度有所降低,过量补灌不能进一步改善冬油菜的主根性状。

2.4.2 集雨补灌对冬油菜侧根密度分布的影响

不同处理对冬油菜0~10 cm、10~20 cm和20~30 cm土层深度处的侧根密度有显著影响($P<0.05$)(图4,不同小写字母表示在$P<0.05$水平差异显著,下同)。2年蕾薹期和角果期不同处理冬油菜0~10 cm土层的侧根密度均为最大,且侧根密度随土层深度加深而大幅度降低,蕾薹期和角果期0~10 cm土层的侧根密度分别占0~30 cm土层的63.75%~71.07%和71.14%~75.90%。

蕾薹期(补灌前),2年集雨种植T_1、T_2和T_3处理0~10 cm、10~20 cm土层的侧根密度均显著大于平作种植CK($P<0.05$),20~30 cm土层的侧根密度均显著小于平作种植CK($P<0.05$)。可见,集

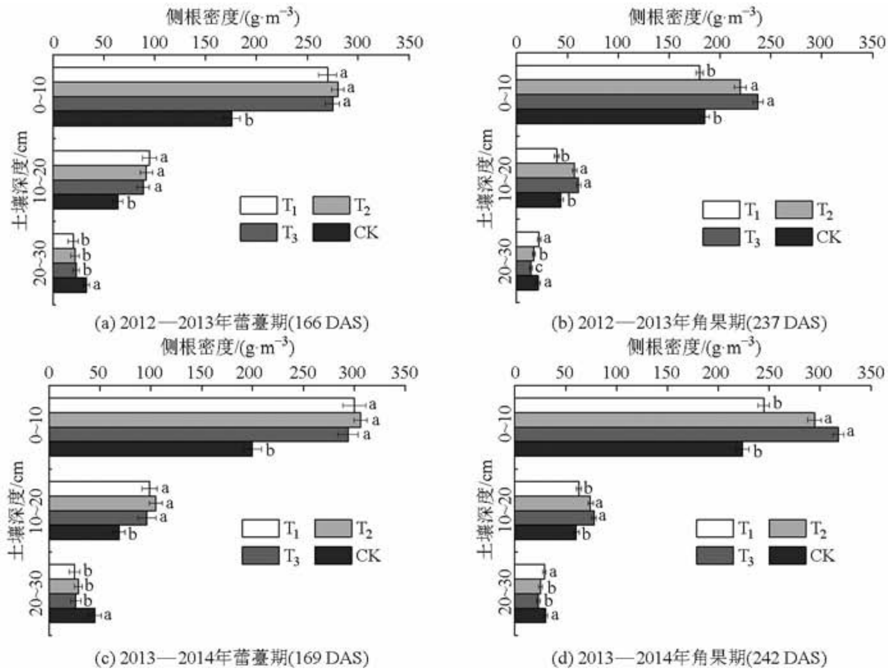

图 4　不同处理冬油菜的侧根密度分布

Fig. 4　Distributions of lateral root density of winter oilseed rape under different treatments

雨种植较高的土壤含水率能促进 0 ~ 10 cm、10 ~ 20 cm 土层的侧根密度显著增加。

角果期，2 年集雨补灌 T_2 和 T_3 处理 0 ~ 10 cm、10 ~ 20 cm 土层的侧根密度均显著大于集雨雨养处理 T_1 和平作补灌 CK（$P < 0.05$），且 T_2 与 T_3、T_1 与 CK 处理间侧根密度的差异不显著。2012—2013 年，T_1 与 CK 处理 20 ~ 30 cm 土层的侧根密度显著大于 T_2（$P < 0.05$），且 T_2 显著大于 T_3（$P < 0.05$）；2013—2014 年 T_1 与 CK 处理 20 ~ 30 cm 土层的侧根密度显著大于 T_2 和 T_3 处理（$P < 0.05$），但 T_2 和 T_3 处理间差异不显著，这可能是由于 2 年降水量的差别造成的。

2.5　集雨补灌对冬油菜产量及水分利用效率的影响

2.5.1　集雨补灌对冬油菜产量及产量构成的影响

不同处理对冬油菜产量及产量构成要素有显著影响（$P < 0.05$）（图 5）。由图 5 分析可知，除 2013—2014 年每角籽粒数和千粒质量外，2 年集雨补灌 T_2 和 T_3 处理的单株分枝数、单株角果数、单位面积籽粒数和籽粒产量均显著大于集雨雨养处理 T_1 和平作补灌 CK（$P < 0.05$），且 T_2 和 T_3、T_1 和 CK 处理间均不存在显著差异。2 年集雨补灌 T_2 和 T_3 处理的平均籽粒产量与 T_1 相比，分别增加 50.99%

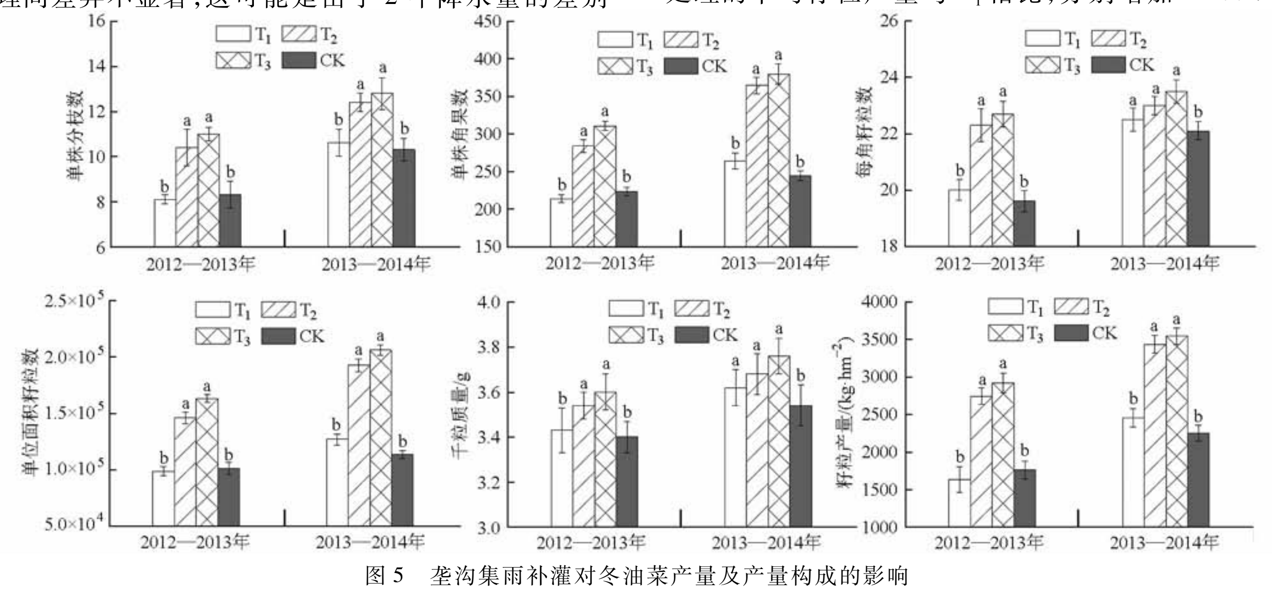

图 5　垄沟集雨补灌对冬油菜产量及产量构成的影响

Fig. 5　Effects of supplemental irrigation under ridge and furrow rain harvesting cultivation on yield and yield components of winter oilseed rape

和 58.15%；与平作补灌 CK 相比，分别增加 53.89% 和 61.19%。可见，对集雨种植冬油菜在蕾薹期进行适量补灌，能增加冬油菜的分枝数、角果数、籽粒数和千粒质量，并显著提高冬油菜产量（$P<0.05$），过量补灌对冬油菜的增产效果不显著。

2013—2014 年冬油菜生育期降水较多，各处理的产量及产量构成要素均明显大于 2012—2013 年，2013—2014 年平均产量比 2012—2013 年增加 28.98%，且 2013—2014 年集雨处理 T_1、T_2、T_3 的每角籽粒数和千粒质量不存在显著差异，但均显著大于 CK（$P<0.05$）。

2.5.2 集雨补灌对冬油菜耗水量及水分利用效率的影响

不同处理冬油菜的耗水量和灌水利用效率、降水利用效率及水分利用效率见表 3。由表 3 可知，2 年集雨种植处理 T_1、T_2 和 T_3 的耗水量均显著小于 CK（$P<0.05$），且 T_3 显著大于 T_1 和 T_2，2 年 T_1、T_2 和 T_3 处理的平均耗水量相比 CK，分别减小 27.72%、20.17% 和 8.91%。

2 年集雨补灌处理 T_2 和 T_3 的灌水利用效率均显著大于 CK（$P<0.05$），且 T_2 显著大于 T_3（$P<0.05$），2 年 T_2 和 T_3 的平均灌水利用效率与 CK 相比，分别提高 182.40% 和 61.65%。2 年 T_2 和 T_3 的降水利用效率均显著大于 T_1 和 CK（$P<0.05$），且 T_2 与 T_3、T_1 与 CK 处理间的差异不显著，2 年 T_2 和 T_3 的平均降水利用效率比 T_1 分别提高 58.04% 和 66.87%，比 CK 分别提高 54.61% 和 63.25%。

表 3 不同处理冬油菜的耗水量、灌水利用效率、降水利用效率和水分利用效率

Tab. 3 Crop evapotranspiration (ET), irrigation water use efficiency (IUE), precipitation utilization efficiency (PUE) and water use efficiency (WUE) of winter oilseed rape under different treatments

生长年份	处理	耗水量/mm	灌水利用效率/(kg·m^{-3})	降水利用效率/(kg·m^{-3})	水分利用效率/(kg·m^{-3})
2012—2013	T_1	232^d		1.37^b	0.71^b
	T_2	274^c	4.57^a	2.29^a	1.00^a
	T_3	319^b	2.44^b	2.44^a	0.92^a
	CK	341^a	1.47^c	1.47^b	0.52^c
2013—2014	T_1	352^c		0.73^b	0.70^b
	T_2	371^c	3.82^a	1.02^a	0.93^a
	T_3	417^b	2.36^b	1.06^a	0.85^a
	CK	467^a	1.50^c	0.67^b	0.48^c

2 年 T_2 和 T_3 处理的水分利用效率均显著大于 T_1 和 CK（$P<0.05$），且 T_1 显著大于 CK（$P<0.05$），2 年 T_2 和 T_3 处理的平均水分利用效率与 T_1 相比，分别提高 37.28% 和 25.98%，与 CK 相比，分别提高 92.77% 和 76.90%；T_1 的平均水分利用效率比 CK 提高 40.42%。

2 年 T_2 的平均耗水量比 T_3 减少 45.5 mm，灌水及水分利用效率比 T_3 分别提高 74.70% 和 8.97%。可见，集雨种植能降低冬油菜的耗水量，提高降水及水分的利用效率，在冬油菜蕾薹期补灌，T_2 和 T_3 处理的产量显著增加，虽然其耗水量有所增加，但水分利用效率却显著提高。

3 讨论

3.1 集雨补灌对冬油菜根系的影响

根系是作物吸收水分、养分及合成多种生理活性物质的重要器官，其功能的发挥与根系形态和生理特性密切相关，常通过根系构型改变和时空分布来适应生境的变化[23]。植物对养分的吸收以及最终产量的形成是根系形态特征和生理特性共同影响的结果[24]。垄沟集雨种植技术改变了农田作物生长微地形，从而使植株根系在土壤空间格局发生变化[25]。何峰等[11]研究发现，集雨种植沟内土壤水分状况明显改善，使土壤表层 0~10 cm 土层的地下生物量显著大于平作种植，而 10~20 cm 和 20~30 cm 土层的地下生物量显著小于平作种植，且随着深度的增加含水率的差异变小，根系生物量差异也减小。李富春等[26]发现燕麦根干质量、根长、根表面积和根体积随土壤深度增加而减少，膜垄种植中，0~10 cm、10~20 cm 和 20~30 cm 的燕麦根干质量占 0~30 cm 燕麦总根干质量的比例分别为 61%、25% 和 14%。本研究中，2 年蕾薹期补灌后，冬油菜角果期侧根密度随土壤深度增加而减少，0~10 cm、10~20 cm 和 20~30 cm 土层的侧根密度占 0~30 cm 冬油菜总侧根密度的比例分别为 71.14%~75.90%、16.34%~19.49% 和 4.63%~9.65%。2 年集雨补灌 T_2 和 T_3 处理角果期 0~10 cm、10~20 cm 土层的侧根密度和主根干质量、主根直径均显著大于集雨雨养 T_1、平作补灌 CK 处理，且 T_2、T_3 处理各指标间的差异不显著。2 年集雨补灌 T_2、T_3 处理角果期 20~30 cm 土层的侧根密度均表现为 $T_2>T_3$，但 2012—2013 年（干旱年）T_2 显著大于 T_3，2013—2014 年（降水较多）T_2、T_3 处理间的差异不显著，这可能是由于在补灌后到角果期 2 年降水量的差别造成的。

3.2 集雨补灌对土壤含水率的影响

垄覆膜集雨种植能使垄上降水流入沟中，产生水分叠加，同时田间垄沟能降低风速，抑制蒸发，提高入渗深度，起到蓄积雨水、增加土壤含水率的作用[27]。任小龙等[14]通过模拟降水研究发现，垄沟

集雨种植夏玉米沟中 0 ~ 120 cm 土层平均含水率均显著高于对照平作区，表层土壤含水率变化较大，100 cm 土层以下土壤含水率变化不明显。韩娟等[28]研究发现垄覆膜集雨种植能显著增加冬小麦播种至拔节期、抽穗期至灌浆期 0 ~ 20 cm 和 20 ~ 100 cm 土壤贮水量。寇江涛等[20]研究发现垄覆膜集雨处理在集雨前期(4 月中旬至 6 月上旬)显著提高苜蓿 0 ~ 20 cm 土层土壤含水率，在集雨中后期(6 月中旬至 9 月下旬)显著提高 0 ~ 120 cm 土层平均含水率。本研究中，在补灌前，2 年垄覆膜集雨种植沟中 0 ~ 30 cm 土层的平均含水率显著大于平作 CK 处理，平均增幅为 11.33%；30 ~ 100 cm 土层的平均含水率略大于平作 CK 处理，平均增幅为 6.61%。补灌后，2 年不同处理 0 ~ 30 cm 土层的平均含水率发生显著变化，不同时期集雨补灌 120 mm (T_3)处理 0 ~ 30 cm 土层的平均含水率均显著大于其它处理，除 2013—2014 年补灌后 75 d 外，集雨补灌 60 mm(T_2)处理 0 ~ 30 cm 土层的平均含水率均明显大于集雨雨养(T_1)和平作补灌 120 mm(CK)处理；2 年集雨补灌(T_1、T_2 和 T_3)处理 30 ~ 100 cm 土层的平均含水率变化幅度不大，而平作补灌 CK 处理变化幅度较大。

张玉等[2]研究发现集雨处理主要增加了小麦 0 ~ 40 cm 的土壤含水率，返青期补灌有利于集雨处理表层土壤含水率的增加；灌水和强降水主要增加了平作处理深层土壤含水率，并不利于冬小麦利用土壤水分。这与本研究结果基本一致，本研究中，补灌后或强降水后，集雨处理 0 ~ 30 cm 表层土壤的含水率显著提高，而平作补灌 CK 处理显著增加了 30 ~ 100 cm 土层的平均含水率，说明集雨处理能有效促进冬油菜对灌溉水或降水的利用。

3.3 集雨补灌对冬油菜产量及水分利用效率的影响

垄沟集雨栽培技术能有效调控土壤水分亏缺，提高水分利用效率，增加农作物产量。韩娟等[29]通过研究发现，垄沟集雨种植能显著提高冬小麦的土壤贮水量、产量和水分利用效率；寇江涛等[20]研究发现垄覆膜集雨处理苜蓿的平均水分利用效率为 34.91 kg/(hm^2·mm)，为平作处理的 2.25 倍。张玉等[2]研究发现集雨不补灌、集雨补灌 375 m^3/hm^2 和 750 m^3/hm^2 冬小麦籽粒产量分别比平作补灌 750 m^3/hm^2 增加 2.8%、9.6% 和 18.9%，水分利用效率分别提高 17.9%、10.4% 和 15.4%。本研究中，2 年中 T_1、T_2 和 T_3 处理冬油菜籽粒产量分别比 CK 增加 1.92%、53.89% 和 61.19%，水分利用效率分别提高 40.42%、92.77% 和 76.90%。2013—2014 年在冬油菜关键生育期(3—4 月份)的降水量比 2012—2013 年多 156.4 mm，充足的降水使 2013—2014 年平均产量比 2012—2013 年增加 28.98%。

4 结论

(1)垄沟集雨种植冬油菜在蕾薹期补灌 60 mm (T_2)和 120 mm(T_3)处理不同时期 0 ~ 30 cm 土层的平均含水率均明显大于集雨雨养(T_1)和平作补灌 120 mm(CK)处理；补灌后，T_2 和 T_3 处理初花期、盛花期和角果期地上部干物质量显著大于 T_1 和 CK；角果期 T_2 和 T_3 处理主根直径和干质量、0 ~ 10 cm 和 10 ~ 20 cm 侧根密度显著增加。

(2)垄沟集雨种植能显著提高冬油菜产量和水分利用效率。T_2 和 T_3 处理 2 年平均籽粒产量与 T_1 相比，分别增加 50.99% 和 58.15%，与 CK 相比，分别增加 53.89% 和 61.19%；T_2 和 T_3 的平均水分利用效率与 T_1 相比，分别提高 37.28% 和 25.98%，与 CK 相比，分别提高 92.77% 和 76.90%。

(3)2 年中 T_3 处理均能获得最高的籽粒产量，但 T_3 与 T_2 处理间产量的差异不显著，2 年中 T_3 平均产量较 T_2 增加 4.74%，但 T_2 比 T_3 减少灌水量 60 mm，减少耗水量 45.5 mm，2 年平均水分利用效率比 T_3 提高 8.97%。

(4)全面考虑节水、增产的目的，采用垄沟集雨种植并在蕾薹期补灌 60 mm 为较优的冬油菜栽培灌溉措施。

参 考 文 献

1 魏晓妹，把多铎. 我国北方灌区地下水资源演变与农田生态环境问题[J]. 灌溉排水学报，2003，22(5)：25 - 28.
WEI Xiaomei, BA Duoduo. Groundwater resource evolution and agricultural eco-environmental issues in the irrigation areas in North China[J]. Journal of Irrigation and Drainage, 2003, 22(5): 25 - 28. (in Chinese)

2 张玉，韩清芳，成雪峰，等. 关中灌区垄沟集雨种植补灌对冬小麦光合特征、产量及水分利用效率的影响[J]. 应用生态学报，2015，26(5)：1382 - 1390.
ZHANG Yu, HAN Qingfang, CHENG Xuefeng, et al. Effects of ridge and furrow rain harvesting with supplemental irrigation on winter wheat photosynthetic characteristics, yield and water use efficiency in Guanzhong irrigation district[J]. Chinese Journal of Applied Ecology, 2015, 26(5): 1382 - 1390. (in Chinese)

3 韩清芳，李向拓，王俊鹏，等. 微集水种植技术的农田水分调控效果模拟研究[J]. 农业工程学报，2004，20(2)：78 - 82.
HAN Qingfang, LI Xiangtuo, WANG Junpeng, et al. Simulated study on soil moisture of field under water micro-collecting farming

conditions[J]. Transactions of the CSAE, 2004, 20(2): 78 - 82. (in Chinese)
4 LI X Y, GONG J D. Effects of different ridge, furrow ratios and supplemental irrigation on crop production in ridge and furrow rainfall harvesting system with mulches[J]. Agricultural Water Management, 2002, 54(12): 243 - 254.
5 王晓凌，陈明灿，易现峰，等. 垄沟覆膜集雨系统垄宽和密度效应对玉米产量的影响[J]. 农业工程学报，2009，25(8)：40 - 47.
WANG Xiaoling, CHEN Mingcan, YI Xianfeng, et al. Effects of ridge width and planting density on corn yields in rainwater-harvesting system with plastic film mulching on ridge[J]. Transactions of the CSAE, 2009, 25(8): 40 - 47. (in Chinese)
6 KEMPER W D, NOONAN L. Runoff as affected by salt treatments and soil texture[J]. Soil Science Society of America Journal, 1970, 34(1): 126 - 130.
7 WIYO K A, KASOMEKERA Z M, FEYEN J. Variability in ridge and furrow size and shape and maize population on density on small sunsistence farms in Malawi[J]. Soil and Tillage Research, 1999, 51(1 - 2): 113 - 119.
8 MYERS L E. Sprayed asphalt pavements for water harvesting[J]. Journal of the Irrigation and Drainage Division, 1967, 93: 79 - 97.
9 LI F M, GUO A H, WEI H. Effects of clear plastic film mulch on yield of spring wheat[J]. Field Crops Research, 1999, 63(1): 79 - 86.
10 FISHER P D. An alternative plastic mulching system for improved water management in dryland maize production[J]. Agricultural Water Management, 1995, 27(2): 155 - 166.
11 何峰，王堃，李向林，等. 垄沟集雨对干旱半干旱区土壤水热条件及老芒麦产草量的影响[J]. 农业工程学报，2012，28(12)：122 - 126.
HE Feng, WANG Kun, LI Xianglin, et al. Effects of ridge and furrow rainfall harvesting system on soil hydrothermal condition and yields of *Elymus sibiricus* L. in arid and semiarid regions[J]. Transactions of the CSAE, 2012, 28(12): 122 - 126. (in Chinese)
12 NIU J, GAN Y T, ZHANG J W, et al. Postanthesis dry matter accumulation and redistribution in spring wheat mulched with plastic film[J]. Crops Science, 1998, 38(6): 1562 - 1568.
13 DONG H Z, LI W J, TANG W, et al. Early plastic mulching increases stand establishment and lint yield of cotton in saline fields [J]. Field Crops Research, 2009, 111(3): 269 - 275.
14 任小龙，贾志宽，陈小莉，等. 半干旱区垄沟集雨对玉米光合特性及产量的影响[J]. 作物学报，2008，34(5)：838 - 845.
REN Xiaolong, JIA Zhikuan, CHEN Xiaoli, et al. Effects of ridge and furrow planting for rainfall harvesting on photosynthetic characteristics and yield in corn in semi-arid regions[J]. Acta Agronomica Sinica, 2008, 34(5): 838 - 845. (in Chinese)
15 王彩绒，田霄鸿，李生秀. 垄沟覆膜集雨栽培对冬小麦水分利用效率及产量的影响[J]. 中国农业科学，2004，37(2)：208 - 214.
WANG Cairong, TIAN Xiaohong, LI Shengxiu. Effects of plastic sheet-mulching on ridge for rainwater-harvesting cultivation on WUE and yield of winter wheat[J]. Scientia Agricultura Sinica, 2004, 37(2): 208 - 214. (in Chinese)
16 ZHANG S L, LI P R, YANG X Y, et al. Effects of tillage and plastic mulch on soil water, growth and yield of spring-sown maize [J]. Soil Tillage Research, 2011, 112(1): 92 - 97.
17 WANG X L, LI F M, JIA Y, et al. Increasing potato yields with additional water and increased soil temperature[J]. Agricultural Water Management, 2005, 78(3): 181 - 194.
18 苏旺，屈洋，冯佰利，等. 垄沟覆膜集水模式提高糜子光合作用和产量[J]. 农业工程学报，2014，30(13)：137 - 145.
SU Wang, QU Yang, FENG Baili, et al. Photosynthesis characteristics and yield of broomcorn millet under film mulching on ridge-furrow for harvesting rainwater model in semi-arid region of Northern Shaanxi[J]. Transactions of the CSAE, 2014, 30(13): 137 - 145. (in Chinese)
19 强生才，张恒嘉，莫非，等. 微集雨模式与降水变律对燕麦大田水生态过程的影响[J]. 生态学报，2011，37(9)：2365 - 2373.
QIANG Shengcai, ZHANG Hengjia, MO Fei, et al. The effects of micro-rain water harvesting pattern and rain fall variability on water ecological stoichiometry in oat (*Avenasativa* L.) field[J]. Acta Ecologica Sinica, 2011, 37(9): 2365 - 2373. (in Chinese)
20 寇江涛，师尚礼. 垄覆膜集雨对苜蓿草地土壤水分动态及利用效率的影响[J]. 中国生态农业学报，2011，19(1)：47 - 53.
KOU Jiangtao, SHI Shangli. Effect of rainwater harvesting via plastic film-covered ridge on soil moisture in *Medicago sativa* grassland and water use efficiency[J]. Chinese Journal of Eco-Agriculture, 2011, 19(1): 47 - 53. (in Chinese)
21 马霓，李玲，徐军，等. 甘蓝型油菜抗倒伏性及农艺性状研究[J]. 作物杂志，2010(6)：36 - 41.
MA Ni, LI Ling, XU Jun, et al. Researches on the lodging resistance and agronomic traits of winter rape (*Brassica napus* L.) [J]. Crops, 2010(6): 36 - 41. (in Chinese)
22 陈新军，戚存扣，浦惠明，等. 甘蓝型油菜抗倒性评价及抗倒性与株型结构的关系[J]. 中国油料作物学报，2007，29(1)：54 - 57.
23 王法宏，王旭清，刘素英，等. 根系分布与作物产量的关系研究进展[J]. 山东农业科学，1997(4)：48 - 51.

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8 吴军虎,费良军,王文焰. 膜孔灌溉单孔入渗特性研究[J]. 水科学进展,2001,12(3):307－311.
WU Junhu,FEI Liangjun,WANG Wenyan. Study on the infiltration characteristics of single filmed hole and its mathematical model under filmed hole irrigation[J]. Advances in Water Science, 2001,12(3):307－311. (in Chinese)

9 费良军,程东娟,朱兴华. 单膜孔点源肥液入渗水氮分布特性试验研究[J]. 农业工程学报,2006,22(10):12－15.
FEI Liangjun, CHENG Dongjuan, ZHU Xinghua. Water and NO_3^--N distribution characteristics in single film hole point source fertile solution infiltration[J]. Transactions of the CSAE,2006,22(10):12－15. (in Chinese)

10 费良军,程东娟,雷雁斌,等. 膜孔灌单点源入渗特性与数学模型研究[J]. 西北农林科技大学学报:自然科学版,2007,35(5):212－216.
FEI Liangjun, CHENG Dongjuan,LEI Yanbin,et al. Study on the infiltration characteristic and the mathematical model of the point source free infiltration under film hole irrigation[J]. Journal of Northwest A&F University:Nature Science Edition,2007,35(5):212－216. (in Chinese)

11 穆红文. 膜孔灌自由入渗氮素运移转化特性试验及数值模拟研究[D]. 西安:西安理工大学,2007.
MU Hongwen. Water and nitrogen transport and translation characteristics research and numerical simulation under film hole free infiltration[D]. Xi'an:Xi'an University of Technology,2007. (in Chinese)

12 吴军虎. 膜孔灌溉入渗特性与技术要素试验研究[D]. 西安:西安理工大学,2000.
WU Junhu. The study on infiltration characteristics and technical parameters of film hole irrigation[D]. Xi'an:Xi'an University of Technology,2000. (in Chinese)

13 费良军,王文焰. 泥沙粒度组成对浑水间歇入渗特性的影响研究[J]. 农业工程学报,1999,15(1):139－143.
FEI Liangjun, WANG Wenyan. Effect of clay and sand grade of muddy water onits characteristics of intermittent infiltration [J]. Transactions of the CSAE,1999,15(1):139－143. (in Chinese)

14 费良军. 浑水波涌灌理论与技术要素试验研究[D]. 西安:西安理工大学,1997.
FEI Liangjun. The study on theory and technical parameters of surge flow irrigation with muddy water[D]. Xi'an:Xi'an University of Technology,1997. (in Chinese)

15 缴锡云,王文焰,张建丰. 单点膜孔入渗特性的试验研究[J]. 水利学报,1999,30(7): 33－39.
JIAO Xiyun, WANG Wenyan, ZHANG Jianfeng. Experimental research on infiltration from single hole of membrane[J]. Journal of Hydraulic Engineering,1999,30(7): 33－39. (in Chinese)

16 王文焰,张建丰,王全九,等. 黄土浑水入渗能力的试验研究[J]. 水土保持学报,1994,8(1):59－62.
WANG Wenyan, ZHANG Jianfeng,WANG Quanjiu,et al. Experimental studies on infiltration capability of silt-1aden water into the loess[J]. Journal of Soil and Water Conservation, 1994,8(1):59－62. (in Chinese)

17 孙存喜,吴发启,王健,等. 不同浓度浑水入渗试验研究[J]. 水土保持通报,2009,29(4):57－60.
SUN Cunxi,WU Faqi,WANG Jian,et al. Experimental studies on muddy water infiltration with different concentrations[J]. Bulletin of Soil and Water Conservation,2009,29(4):57－60. (in Chinese)

(上接第 98 页)

24 LYNCH J. Root architecture and plant productivity [J]. Plant Physiology, 1995, 109(1): 7－13.

25 任小龙, 贾志宽, 陈小莉, 等. 模拟降水量条件下垄沟集雨种植对土壤养分分布及夏玉米根系生长的影响[J]. 农业工程学报, 2007, 23(12): 94－99.
REN Xiaolong, JIA Zhikuan, CHEN Xiaoli, et al. Effect of ridge and furrow planting of rainfall harvesting on soil available nutrient distribution and root growth of summer corn under simulated rainfall conditions[J]. Transactions of the CSAE, 2007, 23(12): 94－99. (in Chinese)

26 李富春, 任祥, 王琦, 等. 垄沟集雨种植对燕麦根系分布特征的影响[J]. 生态学杂志, 2013, 32(11): 2966－2972.
LI Fuchun, REN Xiang, WANG Qi, et al. Effects of rainfall harvesting in ridges and furrows on root distribution patterns of oat in semi-arid area of Gansu, Northwest China[J]. Chinese Journal of Ecology, 2013, 32(11): 2966－2972. (in Chinese)

27 李凤民, 王静, 赵松岭. 半干旱黄土高原给水高效农业的发展[J]. 生态学报, 1999, 19(2): 259－264.
LI Fengmin, WANG Jing, ZHAO Songling. The rainwater harvesting technology approach for dryland agriculture in semi-arid Loess Plateau of China[J]. Acta Ecologica Sincia, 1999, 19(2): 259－264. (in Chinese)

28 韩娟, 廖允成, 贾志宽, 等. 半湿润偏旱区垄沟覆盖种植对冬小麦产量及水分利用效率的影响[J]. 作物学报, 2014, 40(1): 101－109.
HAN Juan, LIAO Yuncheng, JIA Zhikuan, et al. Effects of ridging with mulching on yield and water use efficiency in winter wheat in semi-humid drought-prone region in China[J]. Acta Agronomica Sinica, 2014, 40(1): 101－109. (in Chinese)