Proper Border Length Can Improve Soil Water Distribution, Promote Grain Yield of Winter Wheat, and Potentially Save Water Resources

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Research Article

Keywords: water resources, irrigation systems, control treatment without irrigation, winter wheat

Posted Date: February 15th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-225157/v1

Proper border length can improve soil water distribution, promote grain yield of winter wheat, and potentially save water resources

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Abstract

With water resources becoming scarcer and a growing demand for increased food supplies, there is an urgent need to maximize the efficiency of irrigation systems. We aimed to find a suitable border length to reduce the quantity of irrigation water through a traditional border irrigation system and, thus, alleviate groundwater depletion in Huang-Huai-Hai Plain (3HP). A 2-year experiment (2017–2019) was conducted in 3HP, which three border lengths were tested: 15 m (L15), 25 m (L25), and 35 m (L35); supplementary irrigation was implemented during jointing and anthesis, inflow cutoff was set at 90%, and set a control treatment without irrigation (CK). The results showed that L25 significantly improved soil water distribution after irrigation, and increased soil water consumption compared with L15 and L35. The the dry matter accumulation post-anthesis was also higher in L25 than in the other treatments, as well as the WUE. The correlation analysis of soil water content after irrigation with yield confirmed that L25 was more conducive to high grain yield. Hence, under these test conditions, the irrigation field treatments with a border length

of 25 m were considered the most efficient, given that these allow the reduction of the amount of water necessary for irrigation without compromising grain yield of winter wheat.

Introduction

The production of China's wheat in 2016 was approximately 129 million tons, of which more than 60% originated from Huang-Huai-Hai Plain (3HP); however, water resources in this area accounted for only 7% of China's total[1,2]. Because of the monsoon climate affecting this region, the precipitation is mainly concentrated in summer, which is insufficient to meet the water requirements for this region (400–500 mm)[3,4]. Since this has become an important limiting factor for the yield of wheat production[5], groundwater irrigation has been the main strategy employed to solve this problem[6]. However, inefficient irrigation techniques lead to the waste of water resources and the consequent depletion of groundwater levels, which prevents the development of sustainable wheat production systems[7]. Therefore, there is an urgent need to optimize irrigation techniques to improve water efficiency[8].

Because of its low cost and unchallenging implementation, traditional border irrigation is still the principal irrigation method used in the 3HP[9]. Studies show that the border length of irrigation fields can significantly affect soil water distribution and water use efficiency (WUE)[10,11]. For instance, with a border width of 2–3 m, fields with a border length of 50 m had the highest irrigation efficiency, while an increase in border length from 50 m to 115 m decreased irrigation efficiency and uniformity by

17.15% and 6.09%, respectively[12]. Other studies have shown that when the border length was between 80 m and 100 m, the single irrigation amount was generally approximately 100–150 mm. Thus, excessive border length leads to excessive irrigation and consequently a significant reduction in WUE[13]. In fact, the extensive research conducted by Wang et al. at 3HP showed that during the wheat growing season, the average irrigation amount is 101.8 mm, ranging between 51 mm and 172 mm, which is sufficient to ensure wheat yield[14]. However, a survey of approximately 300 plots in Huimin, Shandong Province, revealed that the border lengths of 87% of the irrigation fields were longer than 100 m, illustrating that excessive border length was a common problem in this area [15]. Therefore, it is necessary to shorten the fields' border length to reduce the amount of irrigation and improve its uniformity. Nevertheless, a field experiment is needed to determine the appropriate border length of irrigation fields.

More than 70% of the grain yield of wheat is owing to the accumulation of photosynthetic products after anthesis, and the soil water condition can significantly affect the accumulation of dry matter[16,17]. Drought after anthesis will have a negative effect on photosynthesis by shortening its duration and reducing the accumulation of photosynthetic product[18]. Indeed, a treatment of 70%–75% soil water content showed a significantly higher net photosynthetic rate of flag leaves after anthesis, as well as an increase in dry matter accumulation, than with a treatment of 50%–55% soil water content[19]. Underwater stress conditions can promote wheat grain filling and increase dry matter accumulation during maturity, while excessive irrigation can reduce the distribution of dry matter in the grains after anthesis, thereby reducing grain yield[20,21]. For example, Ren et al. found that a field treatment with a 65% water holding capacity had significantly higher levels of dry matter accumulation and grain yield than those of a field treatment with a water holding capacity of 80%[22]. Moreover, the effect of soil water stress on dry matter accumulation and distribution is relatively clear, and few have studied the effect of different border lengths of irrigation fields on soil water content and dry matter accumulation.

The objectives of the this experiment are to (1) compare the distribution of soil moisture in the 0-40 cm soil layer after irrigation with different side lengths, (2) investigate the differences in soil water consumption (ΔW), dry matter accumulation and grain yield with different border lengths, (3) clarify the relationship between soil water content in the 0–40 cm soil layer and grain yield after irrigation at jointing and anthesis stages.

Results

Irrigation amount

The irrigation amount increased significantly with the increase of border length. In the two growing seasons, the irrigation amount of L25 was lower than that of L35 by 27.66 mm on average, which in turn was superior to that of L15 by 18.36 mm on average (Fig. 1).

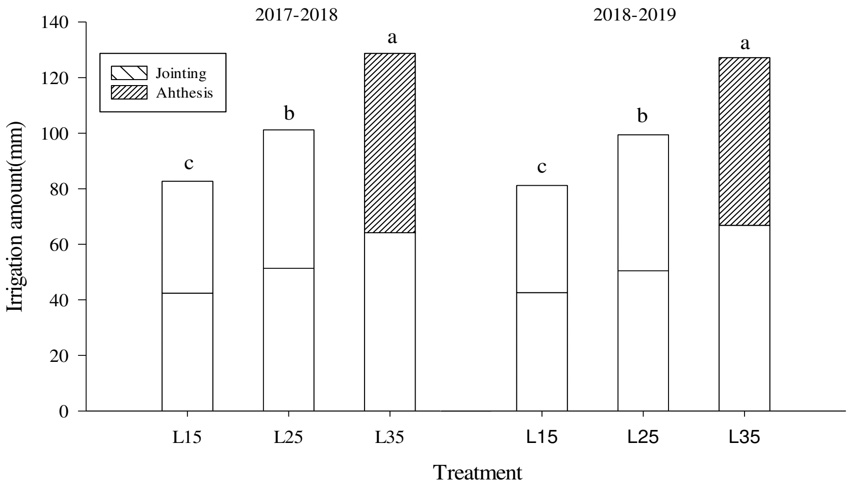

Fig. 1 The irrigation amount at jointing and anthesis stages in 2017-2018 and 2018-2019. Bars with different letters significantly different at 0.05. L15, L25, L35: irrigation with border length of 15, 25, 35 m.

Soil water content and distribution after irrigation

The results obtained for the two growing seasons were consistent. Compared with CK, soil water content increased significantly after irrigation. Soil water content was the highest in L35, followed by L25 and L15 (Fig. 2). Within each treatment, the soil water content gradually decreased from sections A to G. Still, there was no significant difference in the distribution of soil water in L25 and L15, apart from L35 where the soil water content of the latter section was significantly lower than that of the front section. After irrigation, the coefficient of variation of soil water content in L25 and L15 was significantly lower than that of L35 (Table 3).

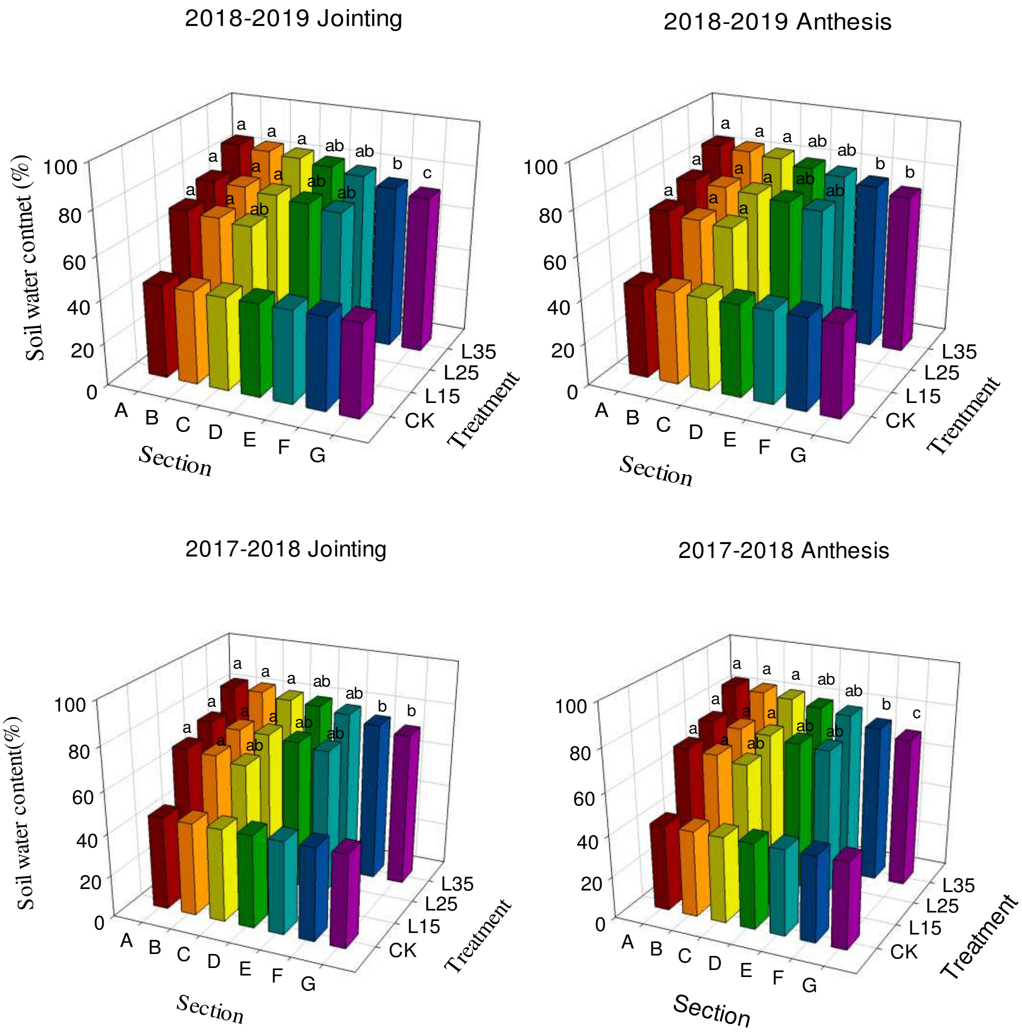

Fig. 2 The soil water content of 0-40 cm soil layer after irrigation at jointing stage and anthesis stage in 2017-2018 and 2018-2019. Different letters on the same row of columns indicate significantly different at 0.05. CK: no irrigation. L15, L25, L35: irrigation with border length of 15, 25, 35 m. A, B, C, D, E, F, G: section with 0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-35 m.

Table 3 Coefficient of variation of soil water content under different treatments.

Treatment	2017-2018		2017-2018	
	Jointing	Anthesis	Jointing	Anthesis
L15	2.48b	2.42c	1.98c	2.12c
L25	2.71b	2.87b	3.29b	2.85b
L35	5.12a	6.28a	5.93a	5.51a

Different letters indicate significant statistical differences between treatments ($p < 0.05$). L15, L25, L35: irrigation with border length of 15, 25, 35 m.

Soil water consumption

In 2017–2018, there were no significant differences in the ΔW between the treatments in the 0–20 cm and 120–200 cm, and in the 20–40 cm, the ΔW values of CK were significantly higher. In the 60–120 cm, the ΔW value was higher in L25 than in L35 and L15. In 2018–2019, the ΔW in the 0–40 cm and 100–180 cm was significantly lower in L35, whereas in the 40–100 cm, it was highest in CK, followed by L25. There was no significant difference in ΔW in the 180–200 cm (Fig. 3).

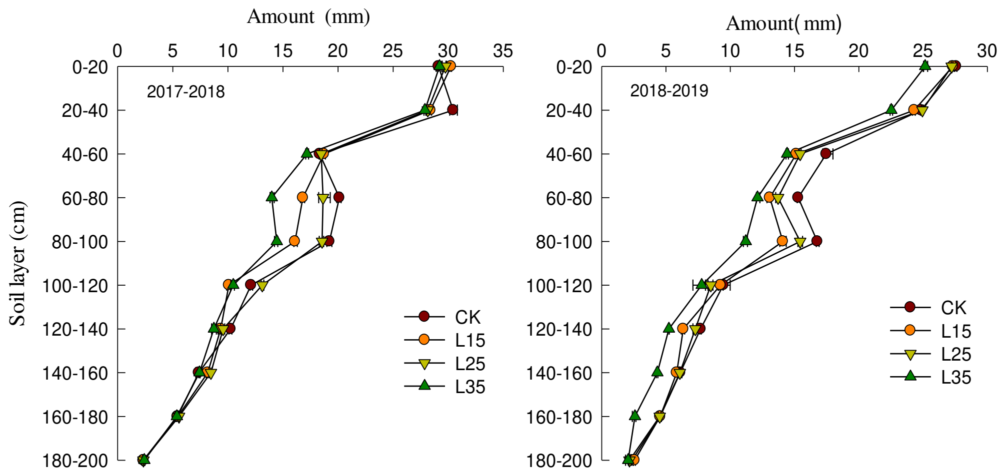

Fig. 3 Soil water consumption (ΔW) in the 0-200 cm soil layers in 2017-2018 and 2018-2019. CK: no irrigation. L15, L25, L35: irrigation with border length of 15, 25, 35 m.

Contributions of different water sources for ET

The highest ET value was observed in L35, followed by L25, L15, with CK presenting the lowest value. The ratio of irrigation water amount to ET under L25 and L15 was significantly lower than that under L35. The ratio of precipitation amount to ET decreased in the order L35 < L25 < L15 < CK. There was no significant difference between L25 and L15 in the ratio of ΔW to ET, which were both significantly higher than that of L35 (Table 4).

Table 4 The contributions of different water sources for ET under different treatments.

Growing season	Treatment	ET (mm)	Irrigation		Precipitation		Soil water consumption	
			Amount (mm)	Percentage (%)	Amount (mm)	Percentage (%)	Amount (mm)	Percentage (%)
2017-2018	CK	306.74d	—	—	151.9	49.52a	154.84a	50.48a
	L15	380.08c	82.68c	21.75c	151.9	39.97b	145.50b	38.28b
	L25	405.51b	101.18b	24.95b	151.9	37.46c	152.43a	37.59b
	L35	417.76a	128.7a	30.81a	151.9	36.36c	137.16c	32.83c
2018-2019	CK	422.27d	—	—	289.9	68.65a	132.37a	31.35a
	L15	493.47c	81.18c	16.45c	289.9	58.75b	122.39b	24.80b
	L25	514.52b	99.39b	19.24b	289.9	56.13bc	127.23ab	24.63b
	L35	525.58a	127.19a	24.20a	289.9	55.16c	108.49c	20.64c

Different letters indicate significant statistical differences between treatments ($p < 0.05$). CK: no irrigation. L15, L25, L35: irrigation with border length of 15, 25, 35 m.

Dry matter accumulation post-anthesis (DMPA) and its contribution to grain (CR)

The DMPA and CR were the lowest in CK in the two growing seasons. DMPA of L25 was significantly higher than that of L35 and L15, and CR of L15 was significantly lower than that of the other treatments. In 2018–2019, DMPA and CR values were the highest in L25 (Fig. 4).

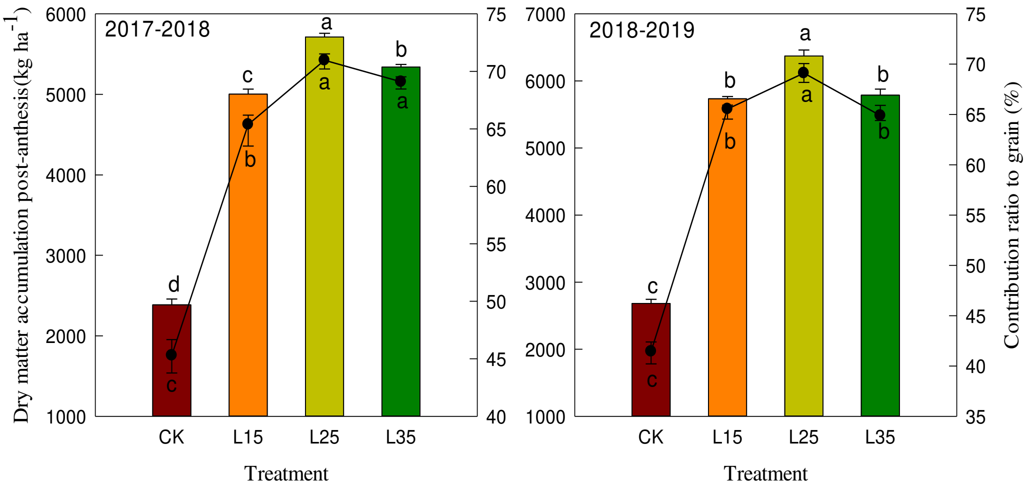

Fig. 4 Dry matter accumulation post-anthesis and their contribution ratio to grain in 2017-2018 and 2018-2019. The different letters above the bar and below the scattered points represent significant differences between the treatments at the P<0.05 level. CK: no irrigation. L15, L25, L35: irrigation with border length of 15, 25, 35 m.

Dry matter accumulation at maturity

During the two growing seasons, the dry matter accumulation of CK was significantly lower than that of other treatments (Fig. 5). Along the irrigation direction, the dry matter of each section of L25 increased first and then decreased, that of L15 gradually decreased, and that of L35 gradually increased. In section A, dry matter accumulation was the highest in L15, followed by L25 and L35. The dry matter accumulation in B, C, D, and E sections of L25 was significantly higher than L35 and L15.

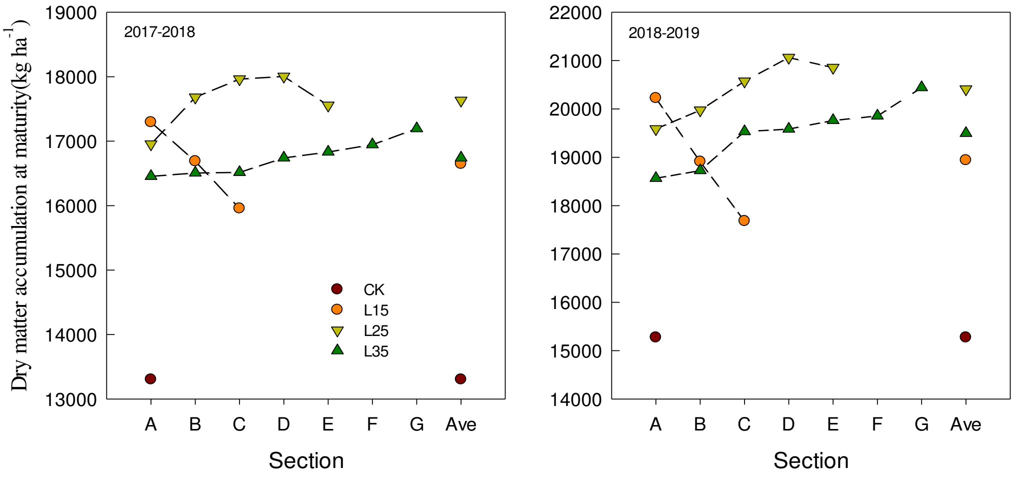

Fig. 5 Different sections and average dry matter accumulation at maturity in 2017-2018 and 2018-2019. CK: no irrigation. L15, L25, L35: irrigation with border length of 15, 25, 35 m. A, B, C, D, E, F, G: section with 0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-35 m. Ave: average value of each sections.

Grain yield and WUE

Compared with CK, the irrigation treatments significantly improved grain yield and WUE (Fig. 6). In 2017–2018, CR of L25 was 5.90% higher than L15 and 4.36% higher than L35. In 2018–2019, this value in L25 was 5.92% higher than L15 and 3.18% higher than L35. There was no significant difference in WUE between L25 and L15, although it was higher than that of L35.

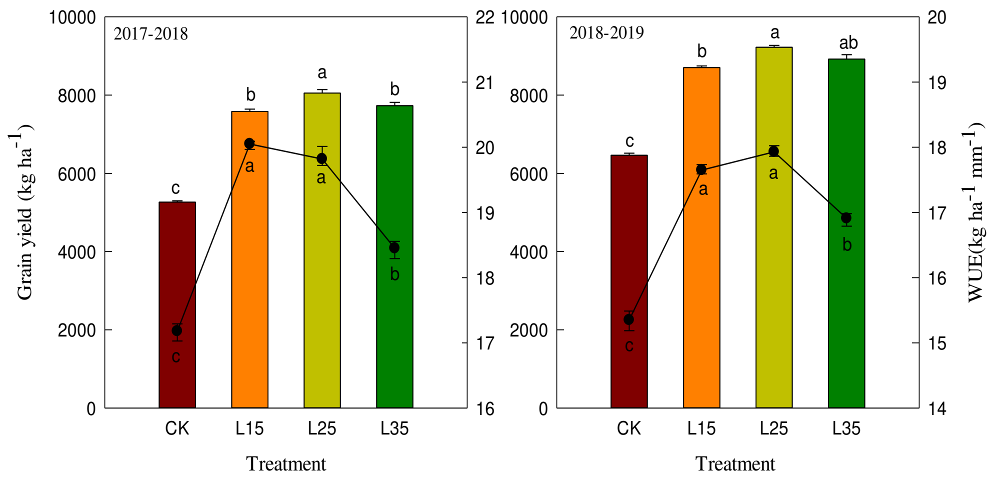

Fig. 6 Grain yield and water use efficiency of different treatments in2017-2018 and 2018-2019. The different letters above the bar and below the scattered points represent significant differences between the treatments at the P<0.05 level. CK: no irrigation. L15, L25, L35: irrigation with border length of 15, 25, 35 m. WUE: water use efficiency.

Correlation analysis of soil water content after irrigation with grain yield and dry matter accumulation

The dry matter accumulation at maturity and grain yield have a quadratic relationship with the water content of the 0–40 cm soil layer after irrigation (Fig. 7). Within a certain range, dry matter accumulation during maturity and grain yield increased with the increase of soil water content. According to the functional relationship between the two wheat growing seasons, when the soil water content was 70.83% and 72.22%, respectively, the dry matter accumulation during maturity reached its maximum, and when the soil water content was 73.99% and 73.18%, respectively, the grain yield reached its maximum.

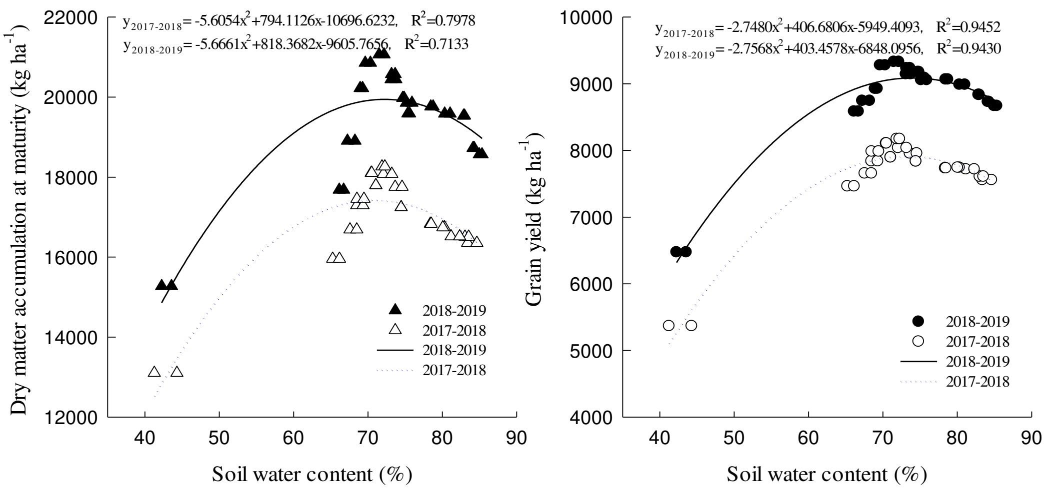

Fig. 7 Correlation analysis of soil water content after irrigation of 0-40 cm soil layer with grain yield and dry matter accumulation in 2017-2018 and 2018-2019.

Discussion

Although in traditional border irrigation, the irrigation is generally stopped after the water front reaches the end of the border, this water continues to flow toward the end of the field. Therefore, an increase in border length will not only lead to excessive irrigation but also an uneven distribution of irrigation water[10]. The results obtained in the present study corroborate these findings; the amount of irrigation water increased with border length and the uniformity of soil water distribution decreased with border length. In fact, some studies seem to confirm the inefficiency of longer border lengths. For instance, the irrigation amount of a treatment with a 180 m border length was 30 mm higher than that of a treatment with a border length of 90 m, yet the grain yield was not significantly increased, and the soil water content varied throughout the irrigation field[15]. In an attempt to solve this, studies have shown that an inflow cutoff of 90% (that is, when irrigation is stopped when the water front reaches 90% of the border length) can efficiently reduce the amount of irrigation water and improve WUE of crops[23]. However, even with the implementation of this method, uneven distribution of irrigation water and decreased WUE were still found in treatments with longer border lengths[24]. This was evident even in the results of our study, which implemented this method with significantly shorter border lengths (15–35 m). The coefficients of variation of soil water content obtained for L35 were higher than those for L25 and L15 (Table 3), indicating that water distribution was more uniform in the last two treatments, as shown in Fig. 2. Similarly, WUE values were consistently the lowest in L35.

We found a gradual increase of wheat ET associated with the increase of irrigation water amount, and consequently, with the increase of border length, which is consistent with the findings of other studies[25]. The ET of 75 mm irrigation was higher by 21 mm at both jointing and filling stages than that at jointing stage[26]. Because the ET values of L15 were lower, its WUE was not significantly different from that of L25, despite the difference irrigation water amount. This contrasts with the results obtained for L35, in which owing to a higher amount of irrigation water and higher ET values, the WUE was significantly lower than that of L25. Soil water consumption has a quadratic relationship with irrigation amount, such that in a range of 0–150 mm, soil water consumption increases with the increase of irrigation water amount[27]. However, in this experiment soil water consumption increased from L15 to L25 then decreased from L25 to L35. As soil water consumption was the highest in L25, it could be stated that increasing the contribution of rainwater to supplement soil moisture could be beneficial, since it improves WUE while removing the need for additional irrigation water amount. Additionally, Mo F's showed that increasing wheat consumption of soil water in the 20–100 cm soil layers can promote the increase of crop biomass[28]. Hence, the increased consumption of soil water of L25 in the 60–120 cm soil layers may explain why DMPA was significantly higher than L15 and L35.

Increasing DMPA or increasing the distribution of dry matter in the grain during maturity is an effective way to increase grain yield[29,30]. Research indicates that soil water content in the 0–50 cm soil layers is significantly affected by irrigation water amount during jointing and anthesis stages[31], which in turn can have a considerable effect on dry matter accumulation of wheat. Zhang et al. found that when soil water content is 70%–80%, the photosynthetic rate at grain filling stage and dry matter accumulation at maturity were 35.5% and 197.7% higher than those when the soil water content is 40%–50%[32]. In this study, when the irrigation water of L25 and L15 was evenly distributed, soil water content of the 0–40 cm soil layer after irrigation in L25 was 69%–75%, whereas in L15, this value was 65%–69%. Since DMPA and CR reached their highest values in L25, the results obtained in this study are in accordance with those presented by Zhang et al. Moreover, the correlation analysis of soil water content in the 0–40 cm soil layer with dry matter accumulation at maturity shows that when the soil water content was 70.83% for 2017-2018 and 72.22% for 2018-2019, respectively, the dry matter accumulation at maturity reached the highest point.

Additionally, the correlation analysis between grain yield and soil water content in the 0–40 cm soil layers confirmed that L25 was more conducive to a higher yield. Because the water stress of L15 can improve the translocation of dry matter, and thus, decrease dry matter accumulation after anthesis, its grain yield was significantly lower than that of L25. The grain yield of L35 was lower than that of L25. Therefore, L25 was considered the best irrigation border length for both high yield and water saving in this experiment.

With the increase of soil water content, dry matter accumulation and grain yield increased from L15 to L25, then decreased from L25 to L35. In both growing seasons, when the soil water content was 70.83%–73.99% the values of dry matter accumulation and grain yield were the highest in the maturity stage. This result is consistent with the previous research conclusions of our group, that is, supplemental irrigation of the 0–40 cm soil layer to reach a target soil water content of 70% at jointing and anthesis can effectively increase the grain yield of wheat[33].

Although many new irrigation methods have been developed, the high cost and complexity of operation have resulted in low usage by farmers. Changing border length and adjusting border field layout is a straightforward and low-cost method, which can significantly reduce irrigation water and realize uniform irrigation. Therefore, this experiment is of great significance for reducing agricultural irrigation water and maintaining sustainable agricultural development in the 3HP. In this study, we only study the influence of border length on irrigation, so the influence of border width on irrigation water is worthy of further study in the future.

Conclusion

Overall, our results show that, under supplemental irrigation at jointing and anthesis with an inflow cutoff of 90%, the most efficient border irrigation treatment was the one with a border length of 25 m. This treatment had a higher water use efficiency, and the soil water content of its 0–40 cm soil layer after irrigation was more conducive to the growth and development of wheat. Compared with the treatments with border lengths of 15 m and 35 m, this treatment significantly increased the consumption of soil water in the 60–120 cm soil layers, which was beneficial to the accumulation of dry matter after anthesis and increased grain yield. Therefore, these results demonstrate that proper border irrigation can effectively save water resources by improving soil water distribution and increasing dry matter accumulation, without sacrificing grain yield of wheat.

Materials and methods

Experimental site. In the 2017 and 2018 winter wheat growing seasons, field experiment was carried out at the Experimental station of Shijiawangzi Village, Shandong Province, China (35°42′N, 116°41′N), which experiences a warm temperature continental climate. This area has a light foam soil type. And Table 1 shows nutrient content in 0-20 cm soil layer, and Table 2 shows precipitation at different stages of wheat growth in this experiment.

Table 1 The nutrient content in the 0-20 cm soil layer before sowing

Items	Growing season	
	2017-2018	2018-2019
Soil organic matter（$mg \cdot kg^{-1}$）	14.31	14.24

Total nitrogen （g·kg^{-1}）	1.17	1.09
Available nitrogen （mg·kg^{-1}）	118.82	117.32
Available phosphorus （mg·kg^{-1}）	39.29	36.71
Available potassium （mg·kg^{-1}）	116.37	122.18

Table 2 Precipitation at different wheat growth stages (mm)

Growing season	Sowing-jointing	Jointing- anthesis	Anthesis - maturity	Total
2017-2018	37.6	40.5	73.8	151.9
2018-2019	7.7	85.7	196.5	289.9

Experimental design and crop management. During the wheat growing seasons from 2017 to 2019, irrigation fields with three different border lengths were set up (border width, 2 m): 15 m (L15), 25 m (L25), and 35 m (L35), and a control treatment without irrigation (CK). The treatments were randomly grouped, and each treatment had three replicates. All treatments were irrigated from the same side of the field during the jointing and anthesis stages. Inflow cutoff was designed at 90%[23], and measure irrigation by flow meter.

The high-yielding wheat variety ‘Jimai 22’, the most widely cultivated commercial variety in the 3HP, was used for this experiment. N 105 kg ha^{-1}, P_2O_5 150 kg ha^{-1}, and K_2SO_4 150 kg ha^{-1} were applied as basal fertilizers on all fields before sowing, and topdressing N 135 kg ha^{-1} at jointing stage. Wheat was sown in October 2017 and October 2018, the seeding density was 1.8 million ha^{-1} and harvested in June 2018 and June 2019. Other management practices were equivalent to the traditional practice of growing wheat in this environment.

Sectioning of the sampling region. For each field, sections were created and labeled from A to G. Each section was defined every 5 m along the direction of irrigation.

Random sampling was performed at each section, and test results represent the average of point measurements for each section.

Soil water content. Soil samples were collected using a soil auger with 20 cm increments up to a depth of 200 cm before sowing and at maturity stage in all fields. Additional samples were collected using the same method up to a depth of 40 cm, 3 days after irrigation in all fields. The soil water content was measured by the oven-drying method[34].

Dry matter accumulation. At anthesis and maturity stages, 20 plants of wheat accumulated on the ground were collected from each field. All plant samples were dried at 75°C to a constant weight for determination of their biomass. The dry matter accumulation after anthesis (DMPA) was measured as the biomass difference between the plants collected at maturity and anthesis stages[35]. The contribution of DMPA to grain yield was calculated using the ratio between the two.

Grain yield (GY), ET and WUE. Grain yield was determined from a 2 m^2 area from each field at the maturity stage. The soil water consumption (ΔW) was calculated by the soil water content during the sowing and maturation period. In this experiment station, groundwater recharge and runoff can be ignored[36]. Crop ET was calculated using the following soil water balance equation[37]:

$$ET = irrigation + precipitation + \Delta W,$$

WUE was defined as follows[5]:

$$WUE = GY/ET$$

Statistical analysis

SPSS Statistics 22.0 was used to analyze the data and LSD method was used to compare the differences between different treatments. All charts were made using Excel and Sigmaplot.

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Acknowledgement

This study was supported by the National Natural Science Foundation of China (No. 31771715); Project of Technology System in Modern Wheat Industry, Ministry of Agriculture, China (No. CARS-3-1-19); Field Station Union Project of Chinese Academy of Sciences (No. KFJ-SW-YW035).

Author Contributions

YZ and YF initiated and designed the research. YF analyzed the data and wrote the manuscript. YS revised and edited the manuscript and provided advice on the experiments.

Competing interests

The authors declare no competing interests.

Additional information

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Figures

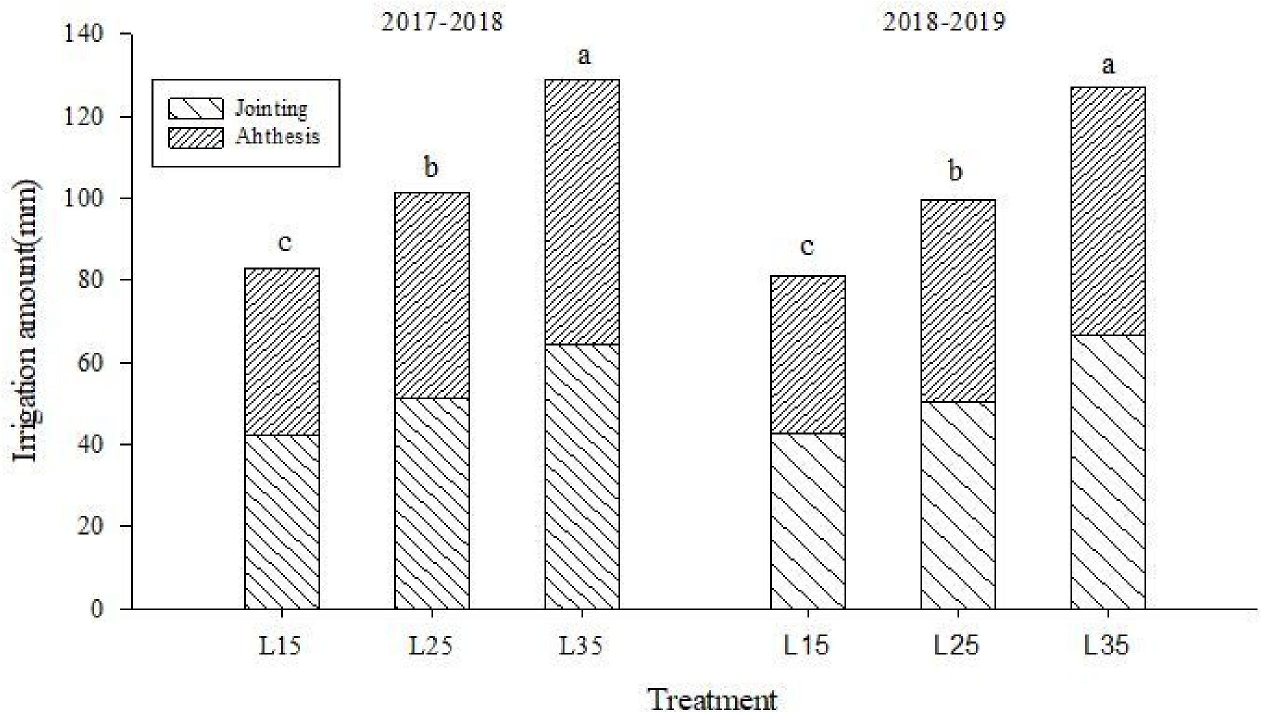

Figure 1

The irrigation amount at jointing and anthesis stages in 2017-2018 and 2018-2019. Bars with different letters significantly different at 0.05. L15, L25, L35: irrigation with border length of 15, 25, 35 m.

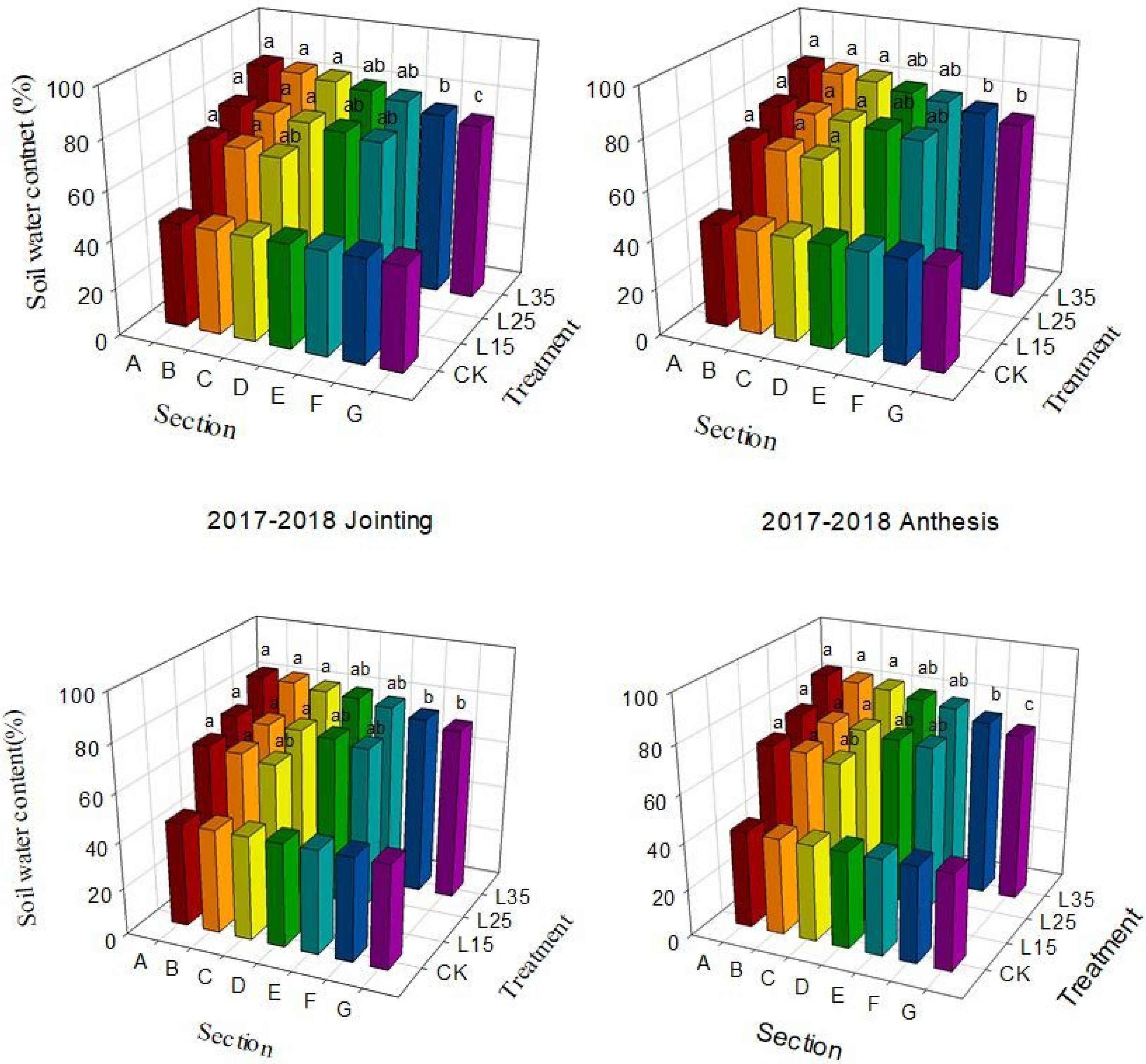

Figure 2

The soil water content of 0-40 cm soil layer after irrigation at jointing stage and anthesis stage in 2017-2018 and 2018-2019. Different letters on the same row of columns indicate significantly different at 0.05. CK: no irrigation. L15, L25, L35: irrigation with border length of 15, 25, 35 m. A, B, C, D, E, F, G: section with 0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-35 m.

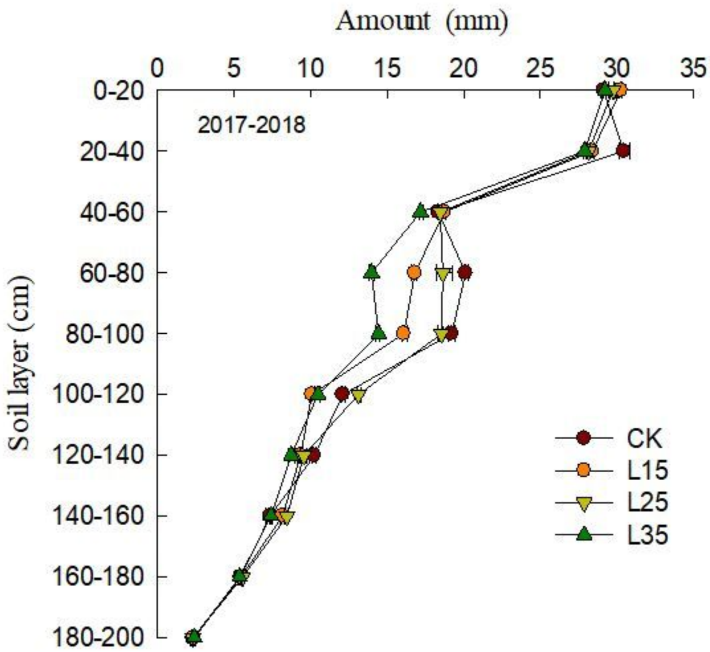

Figure 3

Soil water consumption (W) in the 0-200 cm soil layers in 2017-2018 and 2018-2019. CK: no irrigation. L15, L25, L35: irrigation with border length of 15, 25, 35 m.

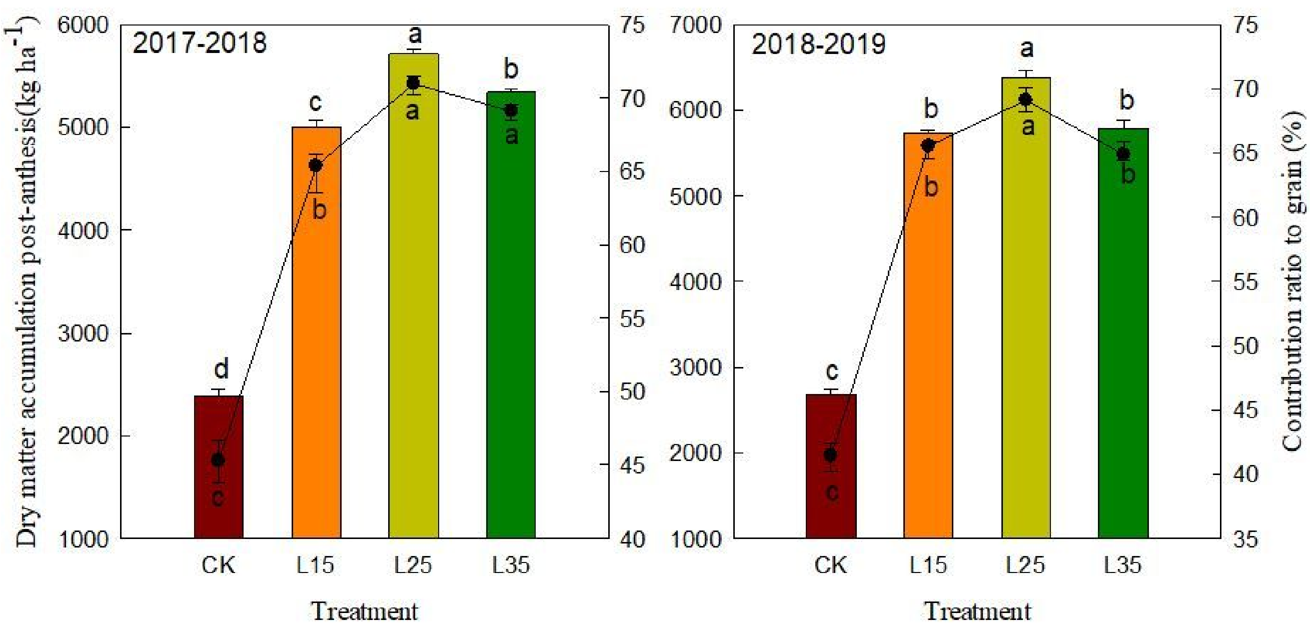

Figure 4

Dry matter accumulation post-anthesis and their contribution ratio to grain in 2017- 2018 and 2018-2019. The different letters above the bar and below the scattered points represent significant differences between the treatments at the P<0.05 level. CK: no irrigation. L15, L25, L35: irrigation with border length of 15, 25, 35 m.

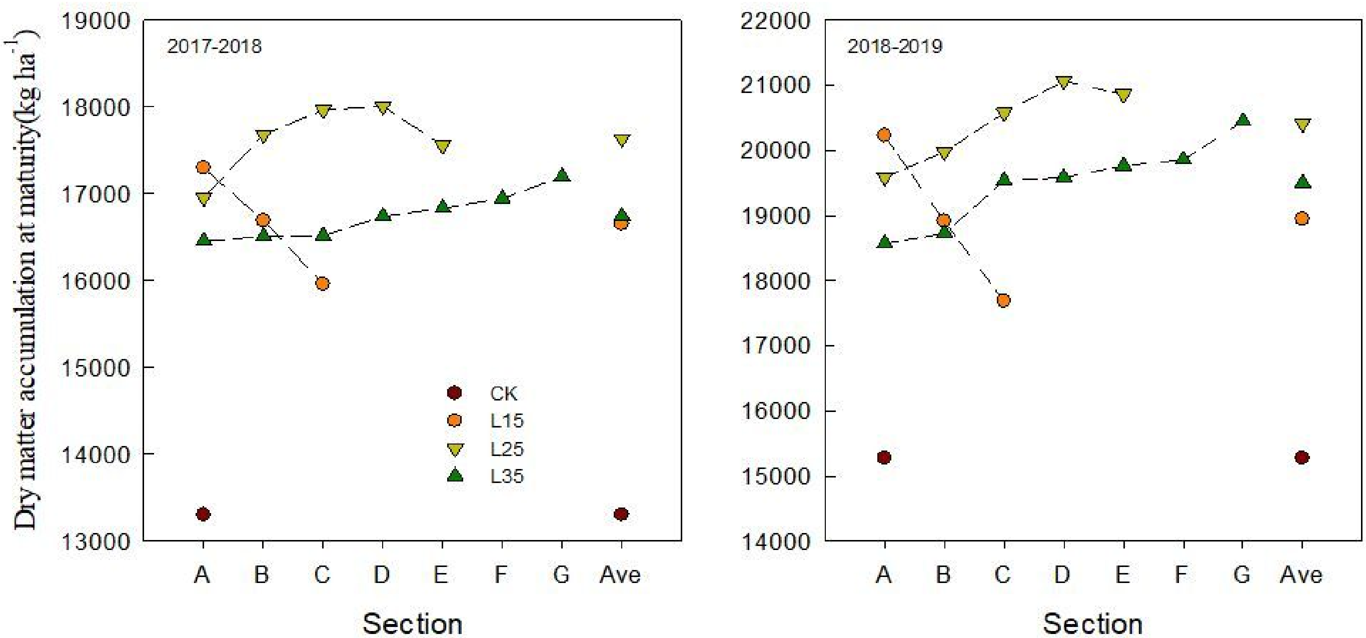

Figure 5

Different sections and average dry matter accumulation at maturity in 2017-2018 and 2018-2019. CK: no irrigation. L15, L25, L35: irrigation with border length of 15, 25, 35 m. A, B, C, D, E, F, G: section with 0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-35 m. Ave: average value of each sections.

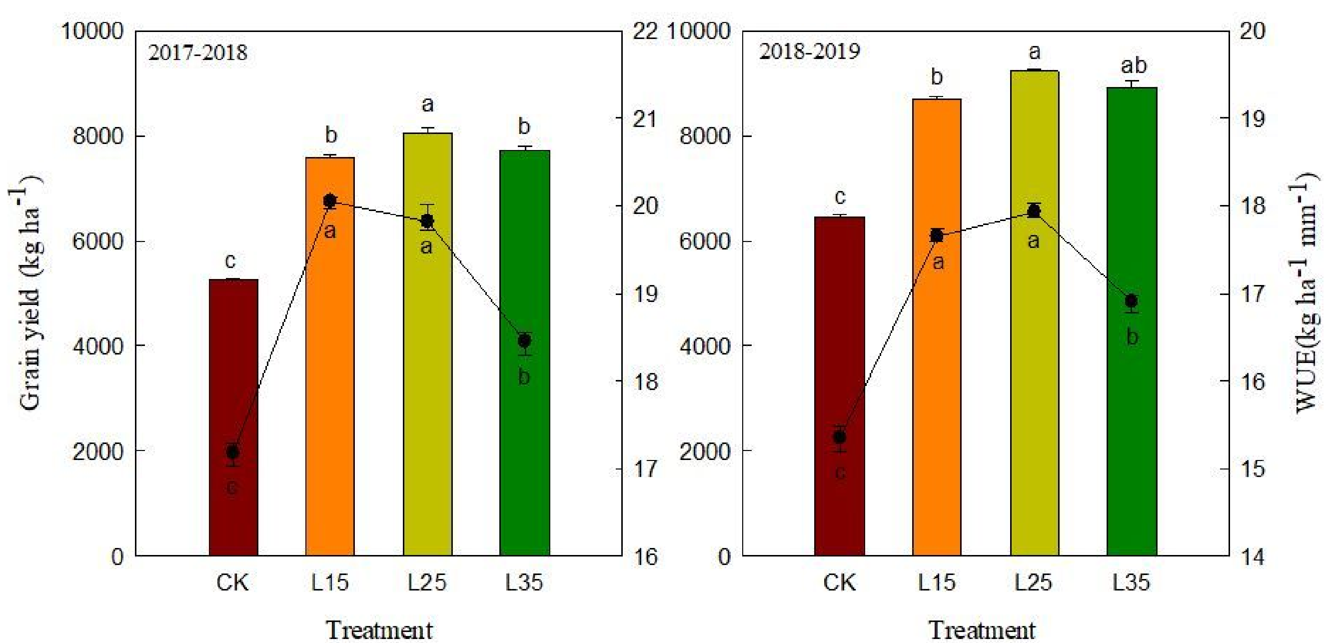

Figure 6

Grain yield and water use efficiency of different treatments in2017-2018 and 2018-2019. The different letters above the bar and below the scattered points represent significant differences between the treatments at the P<0.05 level. CK: no irrigation. L15, L25, L35: irrigation with border length of 15, 25, 35 m. WUE: water use efficiency.

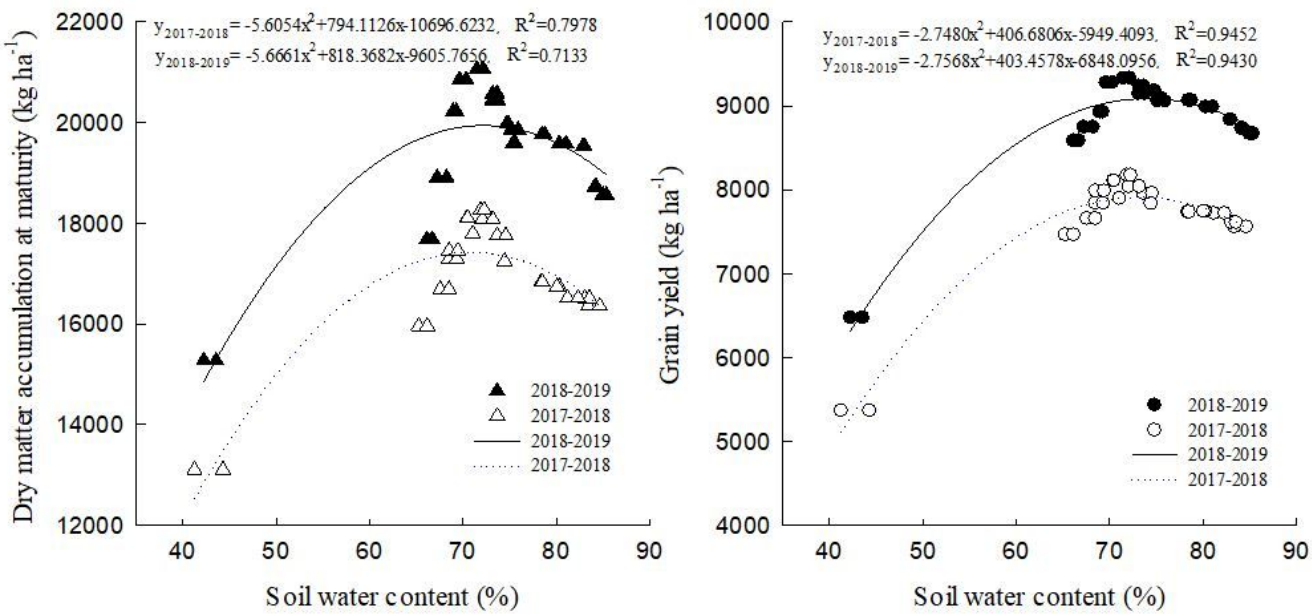

Figure 7

Correlation analysis of soil water content after irrigation of 0-40 cm soil layer with grain yield and dry matter accumulation in 2017-2018 and 2018-2019.