

Effects of Different Border Lengths on Winter Wheat Yield and Water Use Characteristics Under Irrigation: Postprint

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Abstract

To investigate the effects of border length on water consumption, yield, and water use characteristics of winter wheat, this experiment was conducted using the winter wheat variety ‘Kenong 2011’ as test material during the 2014-2015 wheat growing season at the Luancheng Agro-ecosystem Experimental Station of the Chinese Academy of Sciences. Under a border width of 5 m, five border lengths of 4 m, 5 m, 10 m (farmer’s conventional border length), 50 m, and 100 m were established. All treatments were irrigated at the jointing and grain-filling stages by delivering water from the wellhead to the border head using plastic hoses, with a water meter installed at the hose outlet to measure irrigation amount and a stopwatch used to record irrigation time. The study investigated the effects of different border length treatments on winter wheat water characteristics, irrigation quota and irrigation time, soil water content differences at various positions within the border, grain yield, and yield and irrigation water use efficiency. The results showed that with increasing border length, irrigation amount and total water consumption gradually increased, as did the proportion of irrigation amount to total water consumption. Grain yield also increased gradually, but not significantly. Soil water storage consumption, yield water use efficiency, and irrigation water use efficiency decreased with increasing border length. Compared with the farmer’s conventional border length of 10 m, the 4 m border length treatment reduced irrigation amount by 34.50%, consumed 58.92 mm more deep soil water storage, decreased total water consumption by 1.61%, increased yield water use efficiency by 1.15%, increased irrigation water use efficiency by 51.96%, and reduced irrigation time per event by 42.75%. The 100 m border length treatment, without significant yield improvement, increased total water consumption by 9.58%, increased irrigation water by 38.08%, decreased yield water use efficiency by 9.88%, decreased irrigation water use efficiency by 26.20%, and increased irrigation time per event

by 65.61%. Considering grain yield, irrigation amount, and water use efficiency comprehensively, the 4 m border length is the optimal treatment that balances high yield and water saving under the conditions of this experiment.

Full Text

Effects of Irrigated Field Border Length on Grain Yield and Water Use Characteristics of Winter Wheat

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Abstract

Winter wheat is a high water consumption crop, and Hebei Province, as a major production area, faces severe water scarcity. With increasing restrictions on groundwater exploitation, developing efficient water use technologies for agricultural production has become critical. Surface irrigation, an ancient yet widely adopted method in China, is predominant in the Hebei Plain where most fields employ ground furrow irrigation. Under this system, border length is approximately 10 m with a width of 5–6 m, and water furrows occupy 5%–10% of the total field area. Surface irrigation creates significant spatial heterogeneity in soil water content within a border, with water and nutrient leakage at the head and deficiency at the tail. Determining optimal border length is essential for water-saving agriculture under restricted groundwater exploitation, yet few studies have examined its effects on winter wheat yield and water use characteristics.

This study investigated the winter wheat cultivar ‘Kenong 2011’ under five border lengths (4 m, 5 m, 10 m [conventional length], 50 m, and 100 m) during the 2014–2015 growing season at the Luancheng Agro-Ecosystem Experimental Station of the Chinese Academy of Sciences. All treatments maintained a 5 m border width and received irrigation at the jointing and grain-filling stages. Water was delivered through plastic pipes from a well pump to the head of each border, with water meters measuring application volumes and stopwatches recording irrigation duration. We analyzed water consumption patterns, irrigation requirements and timing, spatial variation in soil water content within borders, grain yield, and both yield-level and irrigation water use efficiencies across different border lengths.

Results showed that irrigation amount, total water consumption, and the proportion of irrigation to total consumption all increased with border length. Grain yield also increased but not significantly. Soil water storage consumption, water use efficiency at the yield level (WUE_y), and irrigation water use efficiency

(WUEi) all decreased with increasing border length. Compared with the conventional 10 m border length, the 4 m treatment reduced irrigation amount by 34.50% and total water consumption by 1.61%, while increasing deep soil water consumption by 58.92 mm, WUEy by 1.15%, and WUEi by 51.96%, with a 42.75% reduction in irrigation time per application. The 100 m treatment increased total water consumption by 9.58% and irrigation amount by 38.08% without significant yield improvement, while decreasing WUEy by 9.88% and WUEi by 26.20%, and increasing irrigation time by 65.61%. Based on comprehensive consideration of grain yield, irrigation amount, and water use efficiency, the 4 m border length represents the optimal treatment for achieving both high yield and water savings under our experimental conditions.

Keywords: Winter wheat; Border length; Grain yield; Irrigation water use; Required irrigation time; Water use efficiency

Introduction

Surface irrigation technology represents the world's oldest and most common irrigation method, still employed globally including in the United States. Currently, surface irrigation accounts for over 95% of China's total irrigated area and will remain dominant for the foreseeable future. The North China Plain predominantly uses traditional furrow-border irrigation. Previous research has focused largely on field geometric parameters, optimized irrigation management, and irrigation process control, with less attention to how border specifications affect yield and water use efficiency. As water resources become increasingly scarce, some scholars have begun investigating border specifications, though most studies have concentrated in the Yellow River irrigation districts with border lengths averaging several hundred meters.

Research in Yanjiahe Village, Zijiao Town, Huimin County, Shandong Province, demonstrated that an 80 m border length was optimal, significantly reducing total water consumption during the wheat growing period while improving both grain yield and water use efficiency, attributed to more uniform soil water distribution within the border. However, in water-deficient high-yield regions of Hebei, current farmer practices employ borders of approximately 50 m² (about 10 m length × 5-6 m width). Despite substantially reduced area compared to Yellow River districts, these systems face several problems: (1) excessive irrigation volumes that saturate entire small borders, effectively creating "small-border flood irrigation" and wasting water; (2) poor irrigation uniformity with leakage at border heads and water/nutrient deficiency at tails; (3) traditional layouts with water conveyance ditches every 5-6 m occupying 5-10% of field area, with unlined channels in 100 m-long cultivation blocks increasing deep percolation and reducing land use efficiency; and (4) increased per-irrigation volumes, time, costs, and labor requirements.

The North China Plain constitutes a major grain production region with severe

water shortages. As Hebei Province implements stricter groundwater exploitation controls, eliminating wasteful water use and developing efficient agricultural water technologies have become priorities. Research on new border specifications and precise water control systems under groundwater exploitation restrictions is therefore critically important. This study examines how different border lengths affect water consumption characteristics, irrigation time and costs, yield, and multi-level water use efficiency in Shijiazhuang' s high-yield wheat region, providing theoretical support and technical guidance for water-saving irrigation under exploitation control policies.

1.1 Experimental Site Description

The experiment was conducted during the 2014–2015 winter wheat season at the Luancheng Agro-Ecosystem Experimental Station of the Chinese Academy of Sciences (114°11 E, 37°53 N, elevation 50.1 m). The station experiences a semi-humid, semi-arid monsoon climate with a typical winter wheat-summer maize double-cropping system representative of the entire piedmont plain region. Multi-year average precipitation is 450–600 mm, concentrated in July–September. During our study period, the wheat growing season received only 77.1 mm of rainfall compared to the long-term average of 115.3 mm, characterizing it as a dry year [Figure 1: see original paper].

The site features flat terrain with deep soil profiles classified as cinnamon loess, with texture varying from sandy loam to loam to clay loam with depth. The soil is relatively fertile with strong water and nutrient retention capacity. Pre-sowing topsoil (0–20 cm) contained 18.7 g · kg⁻¹ organic matter, 1.884 g · kg⁻¹ total nitrogen, 76 mg · kg⁻¹ alkali-hydrolyzable nitrogen, 23 mg · kg⁻¹ available phosphorus, and 162 mg · kg⁻¹ available potassium. Soil bulk density averaged 1.53 g · cm⁻³, with saturated volumetric water content of 44.1%, field capacity of 35.4%, and wilting point of 13.2%. The border slope was less than 1‰.

1.2 Experimental Design

The winter wheat cultivar ‘Kenong 2011’ was used. Experimental plots maintained a 5 m border width with five border length treatments: 4 m (L4), 5 m (L5), 10 m (L10, conventional farmer practice), 50 m (L50), and 100 m (L100). A randomized complete block design with four replications was employed, with 1.5 m isolation zones between plots to prevent cross-boundary water movement. All treatments received one freezing irrigation of 75 mm. Post-green-up, irrigation was applied at the jointing and grain-filling stages using plastic pipes delivering water directly to the border head, with water meters measuring application volumes for each border. We modified farmer irrigation practices by implementing a 90% cutoff ratio—stopping irrigation when the water front reached 90% of the border length rather than waiting for the tail water surface to reach border ridge height, immediately moving to the next border.

Base fertilizer application included compound fertilizer (N 46%) at 140 kg · hm⁻²,

diammonium phosphate (P_2O_5 46%, N 18%) at $230 \text{ kg} \cdot \text{hm}^{-2}$, and potassium chloride (K_2O 60%) at $250 \text{ kg} \cdot \text{hm}^{-2}$. Sowing occurred on October 13, 2014, with a seeding rate of $202.5 \text{ kg} \cdot \text{hm}^{-2}$, and mechanical harvest on June 15, 2015. Pre-sowing soil moisture content in 10 cm increments from 0–150 cm ranged from 14.15% to 16.16% (mass water content). Other management practices followed standard high-yield protocols.

1.3 Measurement Methods

Irrigation Time Measurement: Irrigation duration was measured with a stopwatch, starting when the water front reached and entered the border head and ending when irrigation stopped for that border.

Soil Water Content Determination: Soil water content was measured using the oven-drying method. Soil samples were collected with an auger before sowing, after jointing irrigation, after grain-filling irrigation (generally 3–5 days post-irrigation when field accessible), and at maturity. Samples were taken in 20 cm increments to 150 cm depth at three positions within each border (head, middle, and tail) to assess spatial variability.

Field Water Consumption Calculation: Water consumption was calculated using the soil water balance equation: $ET = P + I - R - D - \Delta W$, where ET is evapotranspiration, P is precipitation (from meteorological station), I is irrigation amount (from water meters), R is surface runoff, D is deep percolation, and ΔW is the change in soil water storage. Given the fertile soil with strong water retention, deep groundwater table (approximately 47 m), and minimal surface runoff and deep percolation, the equation was simplified to $ET = P + I - \Delta W$ [14].

Water Use Efficiency Calculations: Yield-level water use efficiency (WUE_y) was calculated as $WUE_y = Y/ET$, where Y is grain yield and ET is total seasonal water consumption. Irrigation water use efficiency (WUE_i) was calculated as $WUE_i = Y/IWU$, where IWU is total seasonal irrigation amount.

Yield Measurement: At maturity, random area samples were harvested from border head, middle, and tail positions in each plot, dried, threshed, and weighed. Treatment yields were represented as the average of replicate samples across all positions.

1.4 Data Analysis

All data were analyzed using SPSS 13.0 and Microsoft Excel software.

2.1 Effects of Border Length on Spatial Distribution of Soil Water Content

Under identical well pump discharge, 5 m border width, and similar pre-irrigation soil moisture, increasing border length created substantial differences

in soil water content. As shown in [Figure 2: see original paper], L4 and L5 treatments exhibited uniform soil water storage of 258.64–263.77 mm across 0–150 cm depth at border head, middle, and tail positions, with no significant differences among positions. With increasing border length, significant differences emerged among positions. For L10, soil water content at head and middle positions showed no significant difference, but the tail was significantly lower by 25.64 mm, while average storage was significantly greater than L4 and L5. For L50 and L100, all three positions differed significantly, with head-to-tail differences reaching 91.99 mm and 111.84 mm, respectively. These results demonstrate that longer borders increased overall 0–150 cm soil water content while exacerbating spatial heterogeneity. The 4 m and 5 m borders provided the most uniform irrigation distribution, with optimal uniformity achieved in borders of 20–25 m² area.

2.2 Effects of Border Length on Total Water Consumption and Water Sources

[Table 1] shows that total water consumption for L4, L5, and L10 was significantly lower than L50 and L100. Irrigation amount followed a similar trend, with L10 significantly greater than L4 and L5 but significantly less than L50 and L100. Soil water consumption ranked as L4 > L5 > L10 > L50 > L100. L50 and L100 exhibited negative soil water consumption (14–17 mm water storage increase), likely due to the 39.4 mm rainfall event on May 15. Analysis of total consumption, water sources, and their proportions revealed that L4 and L5 had the lowest irrigation amounts and total consumption, with the highest proportions of soil water consumption and rainfall utilization. Rainfall accounted for a higher proportion of total consumption in L4 and L5, with L4 showing 11.36% higher rainfall utilization than L100. These results indicate that border length affects both total water consumption and the proportional contributions from different sources. Borders \leq 5 m minimized irrigation and total consumption while maximizing soil water and rainfall utilization. Borders > 5 m increased both irrigation amount and total consumption.

2.3 Effects of Border Length on Irrigation Time and Amount

[Figure 3: see original paper]A shows irrigation requirement (water amount per application) and [Figure 3: see original paper]B shows average time per irrigation for different border lengths. Irrigation requirement increased significantly with border length in the order L4 < L5 < L10 < L50 < L100. L4 had the smallest requirement at 341.8 m³ · hm⁻², while L100 was largest at 1,344.0 m³ · hm⁻² (3.9 times greater). Compared with conventional L10, L4 and L5 reduced irrigation requirement by 46.96% and 58.23%, respectively, while L50 and L100 increased it by 52.46% and 64.27%. Correspondingly, irrigation time per application followed the same trend, increasing with border length. L4 and L5 reduced irrigation time by 42.75% and 26.57% compared with L10, while L50 and L100 increased it by 58.73% and 65.61%. These results demonstrate that

border length significantly affects both irrigation requirement and duration. The 4–5 m borders required less water and time, while borders >4 m substantially increased both parameters.

2.4 Effects of Border Length on Yield and Water Use Efficiency

[Figure 4: see original paper]A shows that grain yield tended to increase with border length and irrigation amount, with L50 and L100 producing higher yields (maximum $8,094.89 \text{ kg} \cdot \text{hm}^{-2}$) than L4, L5, and L10, though differences were not significant. However, WUE_y showed the opposite trend, decreasing with border length in the order $L4 > L5 > L10 > L50 > L100$. L4 and L5 WUE_y were significantly higher than L50 and L100, with L4 improving WUE_y by 8.77% compared with L100. Comprehensive analysis indicates that L4 and L5 maintained yield without significant reduction while substantially improving WUE_y. Irrigation water use efficiency decreased dramatically with border length ([Figure 4: see original paper]C), ranking as $L4 > L5 > L10 > L50 > L100$, with significant differences among all treatments. L4 WUE_i was 11.17% and 51.96% higher than L5 and L10, respectively, while L50 and L100 were 22.07% and 26.20% lower than L10. These results demonstrate that border length affects both yield and water use efficiency, with the 4 m border providing superior performance in yield, WUE_y, and WUE_i, making it the optimal treatment for high yield and high efficiency.

4 Discussion and Analysis

Increasing border length increased irrigation amount while decreasing uniformity. Simulation studies by Liu et al. [15] found optimal border lengths of 120–150 m for clay loam and 60–80 m for sandy loam, where irrigation precisely met crop needs with good uniformity. However, considering actual field conditions, optimal lengths should be shorter. Ma et al. [8] found that in the Huang-Huai-Hai wheat region with 2.09‰ slope and 2 m border width, irrigation amount increased with border length from 10–100 m, ranging from 37.34–91.28 mm under 163.2–146.6 mm rainfall conditions. Cui et al. [10] reported that 180 m borders increased irrigation by 30 mm compared with 90 m borders, with reduced uniformity and significantly higher tail water content, though yields did not differ significantly [4].

Our study, using 5 m border width and 90% cutoff ratio, also found irrigation amount increased with border length, with a 133.6 mm difference between 4 m and 100 m borders. The 100 m border required approximately double the irrigation water of the 4 m border, demonstrating substantial water savings with short borders. Consistent with previous research, we found uniform soil water distribution in 4 m and 5 m borders, with uniformity decreasing in borders >5 m, though unlike some studies, our tail water content was lower than head content. Differences in optimal border length among studies likely relate to site-specific soil properties, groundwater depth, discharge rates, and flow velocities. Additionally, conveyance methods differ—our study used small-diameter (6–8 cm)

flexible pipes versus farmers' open channels, which may affect optimal length determination. Border width also influences optimal length [8]; with our 5 m width versus other studies' 2 m width, flow advance velocity decreases with increasing width, significantly affecting water amount and irrigation time.

In Hebei' s well-irrigation areas, farmers typically use ~5 m wide \times ~10 m long borders (~50 m² area), irrigating until tail water surfaces nearly reach border ridge height. This practice results in higher tail water content, ~750 m³ · hm⁻² irrigation amounts, and essentially creates small-border flood irrigation with water waste. Reducing border length to 4-5 m with pipe conveyance decreased irrigation amount by 34.50% and 27.83% compared with 10 m borders, with per-application volumes of 341.8-434 m³ · hm⁻² and time savings of 42.75% and 26.57%. The 4-5 m borders improved uniformity while reducing water amount and time, with the 4 m border being particularly water- and energy-efficient.

Border length affects yield, soil water consumption, and water use efficiency. Research shows that water deficit during specific growth stages can have compensatory effects rather than purely negative impacts [16], with moderate water stress potentially promoting yield [17-18]. Jiang et al. [19] found that under 150 mm rainfall, 60 mm total irrigation increased yield by 6.97% compared with 180 mm. Pei et al. [20] demonstrated that moderate drought stress can reduce water consumption without significantly decreasing yield. Our study found that while yield tended to increase with irrigation amount, differences were not significant, indicating that moderate irrigation reduction may not substantially decrease yield. Border length also affected total consumption and soil water utilization. Huang et al. [21] found that 45 mm irrigation increased total consumption by 8.18% but reduced soil water consumption by 17.43% compared with 15 mm. Dong [22] showed that increased irrigation frequency and amount significantly reduced soil water consumption across wheat cultivars. Our results similarly demonstrated that longer borders increased total consumption while decreasing the soil water consumption proportion, with L50 and L100 showing negative consumption (soil water increase). The L4 treatment had significantly higher soil water consumption proportion and WUE_i, indicating that optimal border length can effectively utilize soil water storage, reduce irrigation amount, decrease total consumption, and improve water use efficiency.

Irrigation amount and time requirements relate to rainfall patterns and soil properties. Our study year' s 77.1 mm rainfall was below Luancheng' s 1990-2015 average of 115.3 mm, constituting a dry year [23]. Whether these results hold for normal or wet years requires further investigation.

With increasing water scarcity in the North China Plain, Hebei Province has implemented various groundwater control measures to achieve efficient agricultural water use while maintaining food security [24-25]. Practical applications of water-saving measures across crops demonstrate that reducing border size substantially decreases irrigation water and improves WUE_i. Feng et al. [26] found that reducing border area from 0.17 to 0.10 ha decreased maize irrigation requirement by 90 m³ · hm⁻² (9.7%). Our applications at the Nanpi Eco-

Agriculture Experimental Station showed that using small borders (4 m length \times 5 m width) with pipe conveyance and precise irrigation reduced irrigation water by 35% and increased WUEy by 15.67% while maintaining wheat yield.

Our study demonstrates that under 5 m border width, the 4 m border (20 m² plot area) minimized irrigation and total water consumption while maximizing the proportion of soil water and rainfall utilization, without significantly reducing yield. The WUEi was 51.96% higher than conventional 10 m borders, with modest WUEy improvement. The 4 m border represents the optimal treatment for achieving both high yield and water savings under our experimental conditions.

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