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Plot Layout Method of Field Experiment for Wheat with Border Irrigation Based on Soil Water Content Heterogeneity

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Abstract: The objective of this research was to improve the accuracy and representativeness of experimental plot studies by determining the optimum plot area and replication number for winter wheat with border irrigation. Considering the spatial distribution of soil water content, the border effect in relation to crop growth, and the lateral seepage of soil water, we sought to study and optimize the area and specifications of irrigation experiment plots with different levels and replicates. The results show that the experimental irrigation plot consisted of two parts—the core area and the guard area. The most suitable area for the experiment plot core area, with a single level and without replicates, was 60–80 m^2. The core experimental area can be arranged with two replicates per 40 m^2, with differences in soil moisture content between the treatments reaching more than 15% at the two experiment levels. Each plot comprised two replicates, or if they were 20 m^2, then they contained three replicates; when the soil moisture contents differed between 10% and 15%, the area of each replicate plot was 80 m^2, comprising two replicates, or 30 m^2 with three replicates. When the difference in soil moisture content between the treatments exceeded 15% with the three experimental levels, the area of each plot was 30 m^2 and they contained two replicates, or 20 m^2 containing three replicates; at differences of 10% to 15%, each replicate plot was 50 m^2 containing two replicates, or 30 m^2 with three replicates. The experimental plots were rectangular, with irrigation furrows dug lengthwise; therefore, the plots had aspect ratios between 7:1 and 5:1. The width of the buffer area was over 60 cm. The effect of the border on plant height and LAI for winter wheat primarily emerged with one to three rows (20–60 cm) at the jointing stage, while the effect on grain yield and biomass in winter wheat mainly emerged with one to two rows (20–40 cm). The conclusions of this research will inform the development of surface irrigation methods for silt loam in northern Henan, as a reference for optimizing experiment plots employing border irrigation with different soil textures.

Keywords: soil moisture; heterogeneity; optimum plot area and shapes; buffer area; guard row; winter wheat

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1. Introduction

Experimenting with water-saving in agriculture is the best way to formulate irrigation systems, technical systems, and application modes. The popularization and broader application of high-efficiency water-saving irrigation technology is essential [1]. It is the best way to solve the problems encountered in the efficient use of water in crop production in water and soil fields. Under different irrigation conditions, the experimental plot's shape and the numbers of repetitions are the factors that are altered to determine the accuracy of results [2]. All regions of China have developed experimental irrigation stations since the mid-1950s. Irrigation experiments, which have been carried out for over 50 years, play a significant role in the development of agricultural irrigation technology [3].

Nevertheless, the standards employed in relation to water-saving irrigation regimes must be unified across regions. The representativeness and comparability of the results derived also differ, resulting in problems such as an insufficient overlap between the experiment results and actual production conditions. With the rapid development of informatization and intelligent industry, we will see a greater trend towards the informatization of farmland irrigation-related experimental datasets in the future [4]. In order to effectively integrate irrigation-related experiment data and give full play to the effects of the results on agricultural production indicators, the standardization of experimental data is essential. The standardization of these experiment data depends on the standardization of experiment plot areas and specifications. This will be essential to popularizing and broadly applying irrigation experimental results. Surface irrigation remains the most common kind of irrigation in China, while drip irrigation and other water-saving irrigation methods account for a small proportion [5]. When employing surface border irrigation, the spatial variability in soil water levels is vast; when this is coupled with the influence of the specific crop, the soil texture, and microclimate heterogeneity, the requirements become more stringent in relation to plot layout, soil water and crop water status monitoring, and water consumption measurement at different spatial scales. The reasonable planning and development of experiments, and the establishment of appropriate areas and specifications for the irrigation plots used comprise the premise of a series of studies on irrigation, as does the accurate acquisition and standardization of experimental data. Therefore, it is very important to scientifically determine the experiment plots' specifications, areas, and replication conditions when employing surface irrigation in order to standardize irrigation experiments in the future, and facilitate the large-scale application of the experimental results.

Regarding the practical problems that arise in relation to agricultural production, plot experiments are the most efficient way to solve big problems with little expense. The main question concerns establishing a plot size and area that is most representative of actual conditions, while maximizing cost savings. There is no uniform standard approach to irrigation experiments at present. The research on experimental plot areas is mainly focused on the relationship between the experimental plot's area and the coefficient of variation in the experimental data; that is, the coefficient of variation decreases with the increase in experimental plot area. The initial rate of decline is fast, and it then gradually slows down [6,7]. The maximum curvature method determines the optimal plot area that will ensure that the experimental data are representative [8–10]. Some scholars combined mathematical statistics formulae with Smith's empirical formula for soil heterogeneity, and thus developed a formula for determining the most appropriate area of the experiment plot, referred to as the Hatheway method, which takes the number of experimental repetitions and applies it to tomato, sunflower, cassava, papaya, and other crops [11–14]. Both methods have their advantages and disadvantages. The maximum curvature method is simple and widely applicable, but must more closely address the number of repetitions. Although the Hathaway method does consider the number of repetitions, it uses only the integral area method when calculating the soil heterogeneity index, and does not consider all combinations. Hence, the data utilization rate is low. Scholars in China have used two methods to determine suitable plot sizes based on the impact of crop yield [7,15]. Irrigation is the most effective way to ensure the sustainable development of agriculture. Irrigation uniformity is the most important factor when aspiring to reliability in the results derived for irrigation experiments. As such, soil water content should be used as the area of focus, and we should seek to establish the relationship between soil water variation coefficient and experimental plot area, in order to then determine the optimal plot area. The method proposed in this paper, and the results derived, can provide a reference for all kinds of agricultural experiments, thus laying the foundation for the standardization of irrigation experiments in the future. The integration of spatially variable and multi-scale irrigation experimental data is greatly important to the development of irrigation agriculture.

2. Materials and Methods

2.1. Experimental Site

Experiments were conducted during the period 2016.10–2017.6 at the Experimental Station of Farmland Irrigation Research Institute (35°19′ N, 113°54′ E, and 73.2 m altitude), located at Qiliying town, Xinxiang city, in Henan Province.

The area has a warm temperate continental monsoon climate, with a multi-year average temperature of 14.1 °C, a frost-free period of 210 days, 2398.8 h of sunshine, and a multi-year average precipitation level of 582 mm, with 70% to 80% of the annual precipitation occurring from July to September; it also has a multi-year average evaporation level of 2000 mm. The texture of the experimental soil was silty loam, with an average soil volume mass of 1.51 g/cm^3 in the 0–100 cm soil layer and a field water-holding rate of 20.5% (mass water content); the depth of groundwater burial is greater than 5 m. The experimental site is perennially cultivated land, where the soil texture changes little in the horizontal direction due to the deep tilling and leveling that take place all year round. The soil properties within the top 1 m are shown in Table 1 [16].

Table 1. Soil parameters at the experimental station.

Depth/cm	Clay/%	Silt/%	Sand/%	Wilting Point/(cm^3·cm^{-3})	Field Capacity/(cm^3·cm^{-3})	Saturated Water Content/(cm^3·cm^{-3})	Bulk Density/(g·cm^{-3})
0~20	6.75	69.72	23.53	0.16	0.34	0.45	1.58
20~40	6.41	66.91	26.69	0.16	0.29	0.40	1.60
40~60	10.19	69.96	19.85	0.18	0.32	0.42	1.55
60~80	10.16	73.44	16.41	0.18	0.30	0.36	1.42
80~100	8.22	75.74	16.05	0.17	0.31	0.38	1.45

2.2. Experimental Design

According to the characteristics of the surface irrigation water and the growth characteristics of winter wheat, this study on the most suitable size of experimental plots employed for the surface irrigation of winter wheat is divided into three parts: the core area, the lateral infiltration area, and the border effect area. The set-up of each stage of the experiment is as follows.

Core area: Two experimental treatments (105 mm and 75 mm) were designed according to the standard local irrigation quota. In this paper, we describe high- and low-water treatments as the winter wheat ground irrigation process. Each experimental plot was 360 m^2 (9 m × 40 m). Since data on soil water content per m^2 are required for the experiment, 360 × 5 = 1800 boxes of soil samples are required if we are to use their measured values, which will take a long time to sample and constitutes a vast workload. The experimental site was divided into 90 4 m^2 (2 m × 2 m or 1 m × 4 m) cells; the soil water content of every 4 m^2 area was obtained using gravimetric methods, while the soil water content per m^2 was calculated using the interpolation method based on experimental data. The soil water content was measured after 2–3 days of irrigation via the gravimetric method; soil samples were collected from the cells, with the positions shown in Figure 1. The soil samples were collected at distances of 20 to 100 cm from one another in each treatment. After collecting the soil, the holes were filled and compacted. After another application of water, soil was collected from different locations in the 4 m^2 cells. The two points of soil collection in each cell were always 1 m apart.

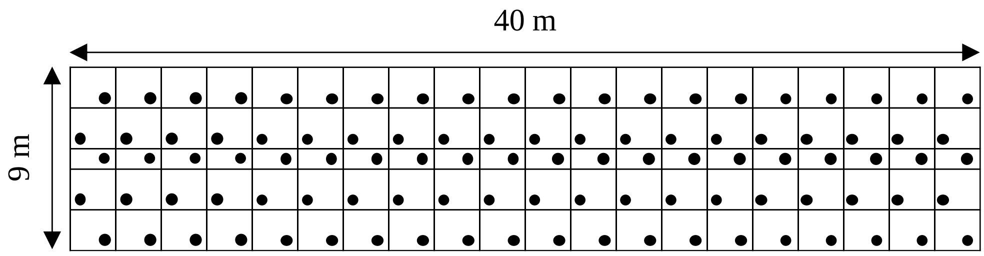

Figure 1. Location of ground irrigation sampling points for winter wheat.

Lateral infiltration area: We also studied the lateral infiltration of water after surface irrigation. Soil moisture sensors (S-SMC-M005) were embedded in the soil on both sides of the ridges in the plot after the emergence of winter wheat to monitor the movement of soil moisture. Two sets of water probes (1 and 2) were set inside the ridges (black triangle in Figure 2) laid out lengthwise in the experimental site. The second set of probes were set close to the edges of the ridges; the two sets were 100 cm apart, and four sets of water probes (3, 4, 5, and 6) were set on the outer side of the ridges, while the third set of probes were set close to the edges of the ridges. The fourth, fifth, and sixth groups of probes were respectively set at 30, 60, and 100 cm away from the third group of probes. Each group of probes comprised 5 water probes, buried 20, 40, 60, 80, and 100 cm from the surface, respectively. We used a total of 30 water probes. After irrigation, soil water migration was analyzed based on the patterns of change in the water data at each location, and the area of influence of lateral seepage was determined.

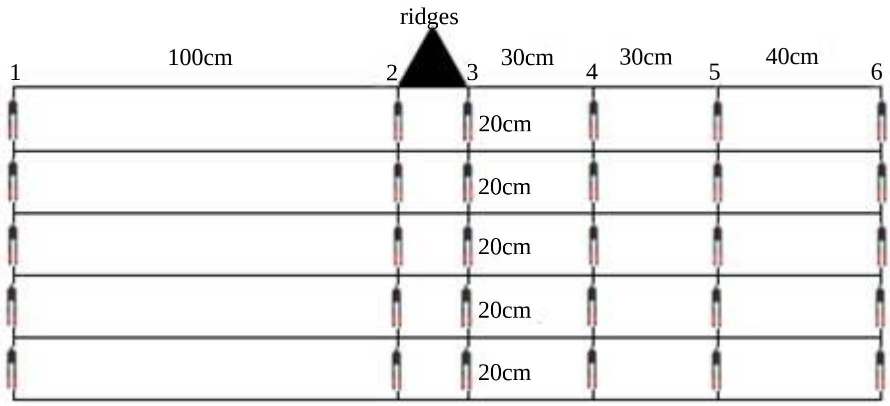

Figure 2. Layout of Hobo probe.

Border effect area: In the winter wheat's early growth stage, the rates of growth of 4 rows were continuously monitored, starting from the border row and moving inward. Each row was 1 m long, and the increases in plant height and leaf area were monitored; 2 rows showed the same rate of growth in the central area as the control. The two monitoring periods were set apart at an interval of 7 days, and the yield was also measured at harvest to determine the influence area of the border effect in winter wheat.

2.3. Experiment Items and Technical Methods

2.3.1. Soil Water Content

The soil moisture content in the core area was measured using the gravimetric method; soil samples were collected at 20 cm intervals to a depth of 100 cm in every treatment. After collecting the soil, the holes were filled and compacted. A soil moisture sensor was used to continuously monitor the soil water content in the lateral infiltration area.

2.3.2. Physiological Indexes of Crops

Plant height was measured as the distance from the base of the stem to the tip of the leaf before heading. After heading, we measured the distance from the base of the stem to the very top of the wheat ear.

Leaf area: The length and maximum leaf width of all leaves were measured with a ruler and calculated as leaf length × leaf width × 0.85 (conversion coefficient).

Yield: The yield of the border row was measured at the time of harvest, and the 1000-grain weight and average yield per plant were also measured.

2.3.3. Variation Coefficient of Soil Water Content

In the same plot, Formula (1) was used to calculate the variation coefficient of the soil water content among multiple treatments.

$$CV_x = 100 \times \frac{\mathrm{stdev}(\theta_1, \theta_2, \cdots\cdots \theta_n)}{\mathrm{average}(\theta_1, \theta_2, \cdots\cdots \theta_n)} \tag{1}$$

where CV_x is the coefficient of variation between treatments with area x; θ_1, θ_2, … θ_n refer to the soil water contents of each treatment in the same area; stdev and average are statistical functions in Excel; stdev is used to calculate the standard deviation of the soil water content under each treatment; average is used to calculate the arithmetic average of the soil water content in each treatment.

2.3.4. Improved Hatheway Method

Formula (2) elucidates the Hatheway method [17], wherein b is the soil heterogeneity index obtained via the Smith equation using the area integral fraction method. Due to the size of the experimental site, all possible combinations of shapes and sizes that can be employed still need to be fully considered. The data utilization rate under this approach is not high, meaning the relationship between soil water heterogeneity and the area of the experiment plot is unstable. Therefore, we calculated the coefficient of variation of the soil water content for all possible combinations of primary cells in the same area, and fitted the coefficient of variation in the treated area as a power function to obtain CV = ax^b, which was substituted into Cochran's [18] equation (Equation (3)) to obtain an improved Hatheway Formula (4):

$$x^b = \frac{2(t_1 + t_2)^2 \cdot c^2}{r \cdot d^2} \tag{2}$$

$$r = \frac{2CV^2(t_1 + t_2)^2}{d^2} \tag{3}$$

$$x_r = x = \left(\frac{rd^2}{2a^2(t_1 + t_2)^2} \right)^{\frac{1}{2b}} \tag{4}$$

where x_r is the area of the experimental plot employed; r is plural; d refers to the real difference between treatments that we can expect to detect (%); k is the number of treatments, which is related to d_f and thus affects t_1 and t_2; d_f is the error degree of freedom employed in the variance analysis, $d_f = k(r - 1)$; t_1 is the t value corresponding to the significance level, for which $\alpha = 0.05$ has been adopted; t_2 refers to the t value corresponding to $2(1 - p)$; p refers to the probability that the real difference between experimental treatments can be identified ($p = 80\%$); a and b are the parameters of the power function CV = ax^b fitted between the treatment area and the coefficient of variation of the soil water content between treatments.

3. Results

3.1. Suitable Plot Area of Core Area

The soil water content at, and corresponding coordinates of, the sampling points, laid out via the grid method, were input into the Sufer 10.2 software (Golden Software, Golden, CO, USA), and the soil water content per m^2 was obtained via Kriging interpolation. Each m^2 block in the experimental plot was taken as a basic cell. Adjacent basic cells were combined, and the new combined cells are referred to as the treatment. The areas subjected to different treatments and the corresponding soil water contents in these areas (the mean values of soil water content in the basic cells addressed in the treatment) were calculated. Formula (1) was used to calculate the coefficient of variation of soil water content among multiple treatments within the same area. The results of the calculation show that the irrigation quota was 105 mm, while the values of n and CV_1 were 360 and 5.22 for an area of 1 m^2; n and CV_2 were 671 and 5.21 for an area of 2 m^2; n and CV_3 were 2 and 0.18 for an area of 351 m^2; n and CV_1 were 1 and 0 for an area of 360 m^2. The coefficient of variation decreased with the increase in plot area.

With the treated area taken as the abscissa and the coefficient of variation of the soil water content between treatments used as the ordinate, a scatter plot was drawn, as shown in Figures 3 and 4. The power function CV = ax^b was used to fit it. We connected the variation coefficient point (1, 5.22) corresponding to the basic cell (1 m^2 cell) to the variation coefficient point (360, 0) corresponding to the combined maximum processing area (360 m^2). The equation used for determining the fitting line was y = kx + c, where k is the slope.

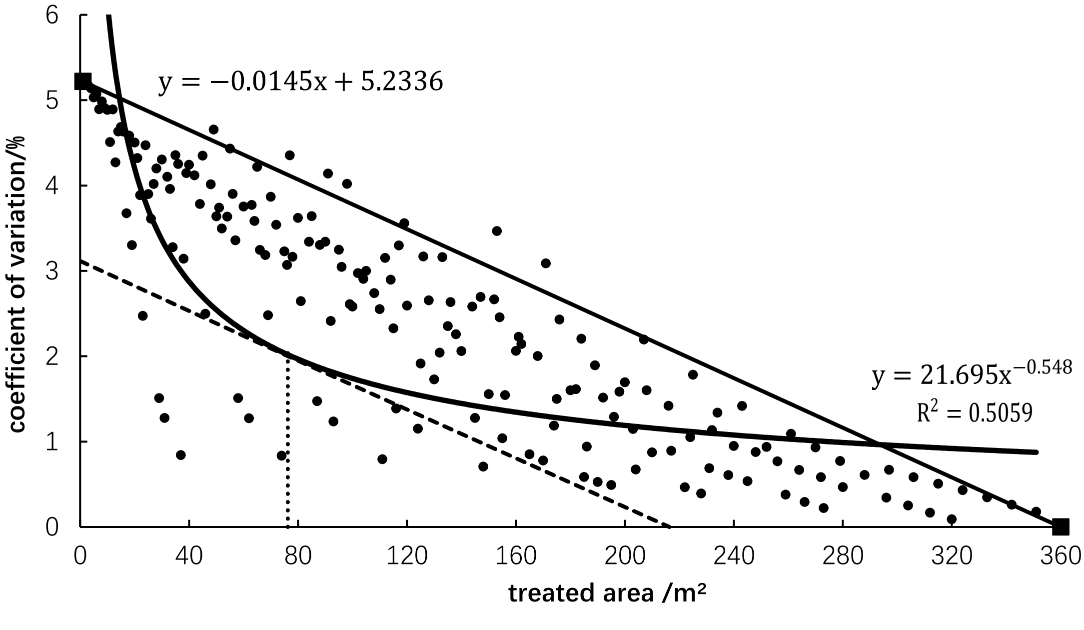

Figure 3. Relationship between treated area and coefficient of variation. Note: The solid line for the linear equation is Y = Ax + b, which is the line content the point (1, 5.22) and the point (360, 0). The dotted line is the tangent line for the curve, and has the same slope (−0.0145) with the solid oblique line. The bold dots are the value of the variation coefficient for the soil water content under different area combinations.

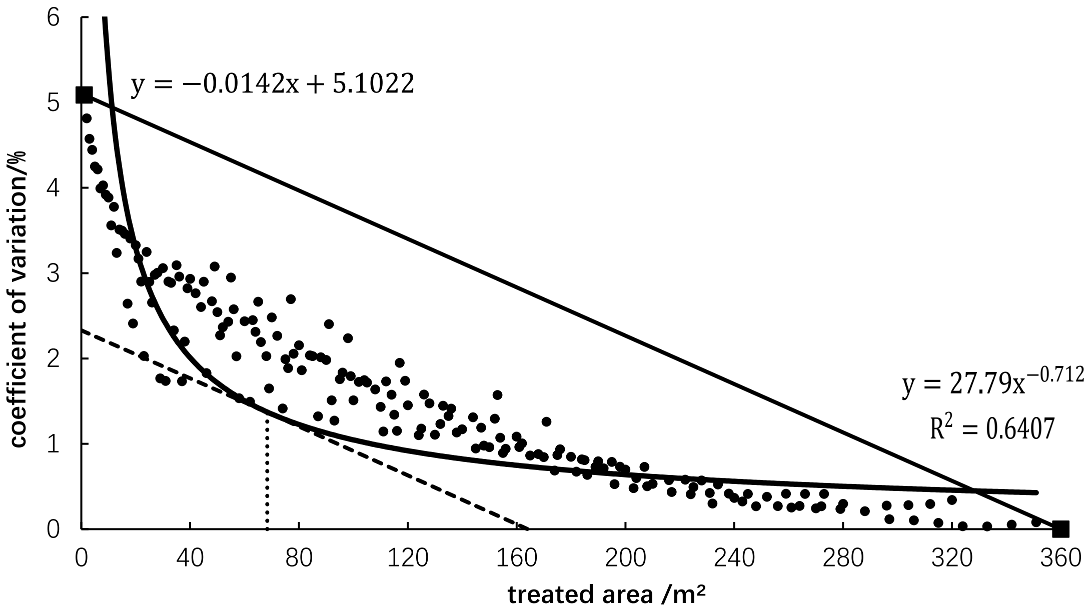

Figure 4. Relationship between treated area and coefficient of variation. Note: The solid line for the linear equation is Y = Ax + b, which is the line content the point (1, 5.09) and the point (360, 0). The dotted line is the tangent line for the curve, and has the same slope (−0.0142) with the solid oblique line. The bold dots are the value of the variation coefficient for the soil water content under different area combinations.

The curve CV = ax^b and straight line y = kx + c show different coefficients of variation for the same area being processed. The x coordinate at which the difference between these two is greatest is used as the most appropriate value for the area of the experimental plot. The maximum difference between the two functions is obtained via $|y - CV| = kx + c - ax^b$, and the derivative is kept at zero, that is

$$k - abx^{b-1} = 0 \Rightarrow k = abx^{b-1} \Rightarrow x = \left(\frac{k}{ab}\right)^{\frac{1}{b-1}} \quad (5)$$

The coefficients of the curve- and linear-fitting equations in Figures 3 and 4, respectively, are put into Equation (5). The most suitable area with the irrigation quota of 105 mm is 76.26 m^2, while the most suitable area with the irrigation quota of 75 mm is 68.64 m^2; the difference between the two is 7.62 m^2, which accounts for 10% and 11% of the high- and low-water treatment areas, respectively. This indicates that the area required for high-water treatment experiments is greater than that required for standard water treatment experiments, but the difference is only small. This is the minimum area required for the experiment. During actual operation, it can vary slightly, and 80 m^2 can be considered appropriate.

3.2. Appropriate Cell Area of the Core Area under Different Treatment Repetitions

The above-cited value of 80 m^2 refers specifically to the plot area that is appropriate under a single treatment and repetition. Under actual operation conditions, the number of experimental repetitions is often increased to ensure reliability in the results. The plot's area can be reduced appropriately when the number of repetitions increases.

The above parameters can be substituted into Formula (4) in order to calculate the most appropriate areas of both the plot and the total core experiment region under the two irrigation quotas with different treatments and numbers of repetitions, as shown in Table 2.

Table 2. Most suitable area of experimental plot with different levels, experimental parameters, and repetitions.

Irrigation Quota/m^3	a	b	Differences between the Treatments d	Number of Treatments k	Plural r	Degrees of Freedom d_f	t_1	t_2	x_r	Total Area X
70	21.695	−0.548	10	2	3	4	2.776	0.941	31.17	187.01
					5	8	2.306	0.889	14.83	148.34
				3	3	6	2.447	0.906	25.81	232.33
					5	12	2.179	0.873	13.64	204.61
			15	2	3	4	2.776	0.941	14.87	89.23
					5	8	2.306	0.889	7.08	70.78
				3	3	6	2.447	0.906	12.32	110.86
					5	12	2.179	0.873	6.51	97.63
50	27.796	−0.712	10	2	3	4	2.776	0.941	19.99	119.94
					5	8	2.306	0.889	11.29	112.88
				3	3	6	2.447	0.906	17.29	155.62
					5	12	2.179	0.873	10.58	158.74
			15	2	3	4	2.776	0.941	11.31	67.86
					5	8	2.306	0.889	6.39	63.87
				3	3	6	2.447	0.906	9.78	88.05
					5	12	2.179	0.873	5.99	89.82

As shown in Table 2, when a high quota of irrigation water is applied, the area of the experimental plot will be more significant than when a low-irrigation water quota is applied. Under the same conditions but with more repetitions, the area of the experimental plot decreases; however, the total area does not necessarily decrease. A small area can meet the experiment's requirements when the difference between treatments is significant. The minimum area was calculated and is given in the table above, the value of which can be approximated appropriately during practical operation.

3.3. Appropriate Specifications for the Core Area

Building on the results shown in Section 2.1, data points representing experimental areas between 60 and 80 m^2 were selected in this paper; the aspect ratio was used as the horizontal coordinate, and the coefficient of variation as the vertical coordinate, to draw a scatter diagram of the coefficient of variation in the soil water content between the treatments, as shown in Figure 5.

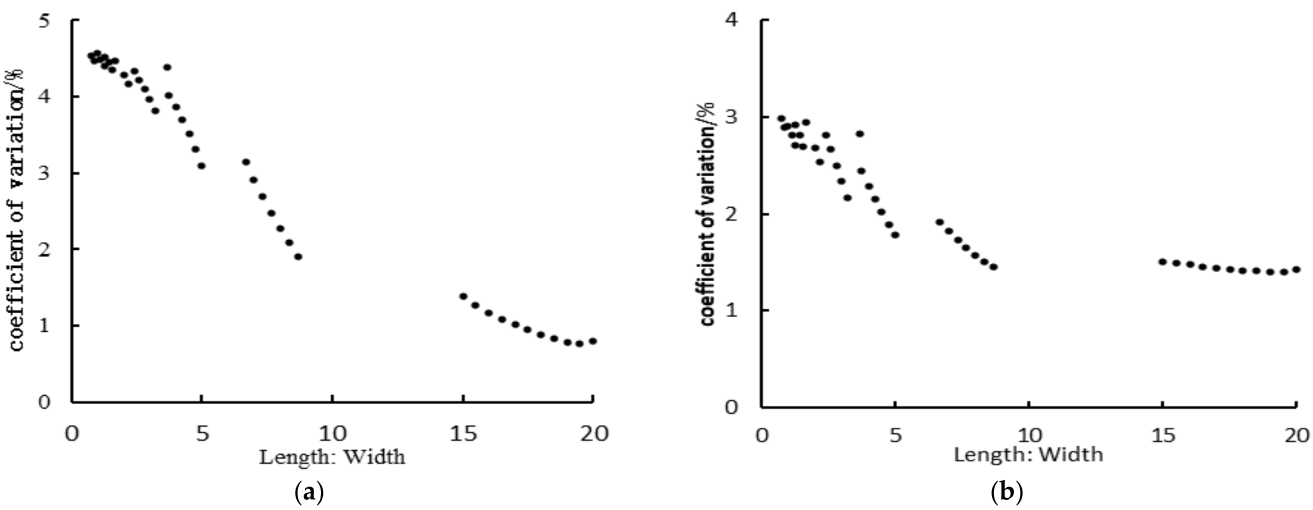

Figure 5. Variation coefficient of soil water content under different length and width ratios. (**a**) Irrigation water quota is 105 mm; (**b**) irrigation water quota is 75 mm.

As Figure 5 shows, the coefficient of variation decreases as the aspect ratio increases. When a high irrigation water quota is applied, the coefficient of variation will be slightly higher, but it will decrease rapidly with increases in the length–width ratio. With a low-irrigation quota, the coefficient of variation was slightly lower and changed only a little, especially when the length-to-width ratio was between 10 and 20. Generally speaking, the coefficient of variation remained stable. All the above indicates that the coefficient of variation in the soil water content in long and narrow experiment plots, oriented in the direction of water flow, is small. However, the potentially infinite increase in length in the direction of water flow must still adhere to planting requirements. Therefore, under practical conditions, the length of the experimental plot (in the direction of water advance) can be increased as long as the overall orientation of the plot (vertical direction of water flow advance) takes into account the number of crop rows planted.

3.4. Influence Area of Soil Water Lateral Permeability

Using the soil moisture data collected by water monitoring probes, the temporal and spatial changes in soil moisture at different locations after irrigation were plotted. The domain of influence for the lateral infiltration of soil moisture was determined by analyzing and comparing changes in soil moisture before and after irrigation at each measuring point. Under an irrigation quota of 105 mm, the incremental change in soil water content (volumetric water content) following irrigation (6 March 2017) at each of the measuring points assessed by the six groups of water probes was inferred by comparison with the value before irrigation, as shown in Figure 6.

As Figure 6 shows, the variations in the soil water content in each sample obtained at 100 cm and 0 cm inside the ridge were the same after irrigation. The soil water content in the 0–40 cm soil layer showed a noticeable trend of decreasing with time, while the content in the 40–60 cm soil layer showed a trend of increasing first and then decreasing, which was mainly caused by the infiltration of moisture in the 0–40 cm soil layer. After irrigation, the contents of water in the 0–20 cm and 20–40 cm soil layers in the 100 cm long ridge increased by 9.10% and 7.91%, respectively. The maximum increases in soil water content in the 0–20 cm and 20–40 cm soil layers in the 0 cm ridge were 4.90% and 5.20%, indicating that the lateral infiltration of soil moisture occurred in the 0 cm ridge, while it did not in the 100 cm ridge. The soil water content in the 60–80 cm soil layer increased and then decreased sharply within a short time after irrigation, after which it changed steadily. The soil water content in the 80–100 cm soil layer showed a trend of slowly increasing over time, which may be related to the upper soil retaining most of the water that infiltrated from above, and the water that was present in the layer was not sufficient to meet the soil demand, let alone have exosmotic effects.

After irrigation, the water contents in the 0–20 cm soil layer at positions 0 cm, 30 cm, 60 cm, and 100 cm outside the ridge showed trends of varying decline over time, represented on graphs as a wave, wherein the wave crest indicates water infiltration. Due to the significant rate of evaporation from surface soil, the water that infiltrated quickly evaporated, so the curve dropped rapidly. The curve at a location 60 cm outside the ridge fluctuated wildly, but a declining trend was evident after 5 days of irrigation. The curve at 100 cm outside the ridge fluctuated, but the amplitude of this fluctuation was small. The water content in the 20–40 cm soil layer increased marginally over time at a point 0 cm from the ridge, but it gradually decreased at other positions. The trend of decline in the curve at a position 60 cm outside the ridge was slower than that at 100 cm outside the ridge, and a clear trend of decline could be observed 6 days after irrigation. Therefore, it can be inferred that the curve measured at 60 cm outside the ridge may be affected by water infiltration, resulting in an insignificant downward trend. The soil water content in the 40–60 cm soil layers 0 cm and 30 cm outside the ridge increased gradually over time after irrigation, but little change was seen at 60 cm outside the ridge, and a noticeable decreasing trend was seen at 100 cm outside the ridge. The curves of the soil water content values in the 60–80 cm and 80–100 cm soil layers remained similar over time after irrigation, and all points within

100 cm of the outside of the buffer area were affected. However, the maximum change was only 0.13%, and the influence was negligible.

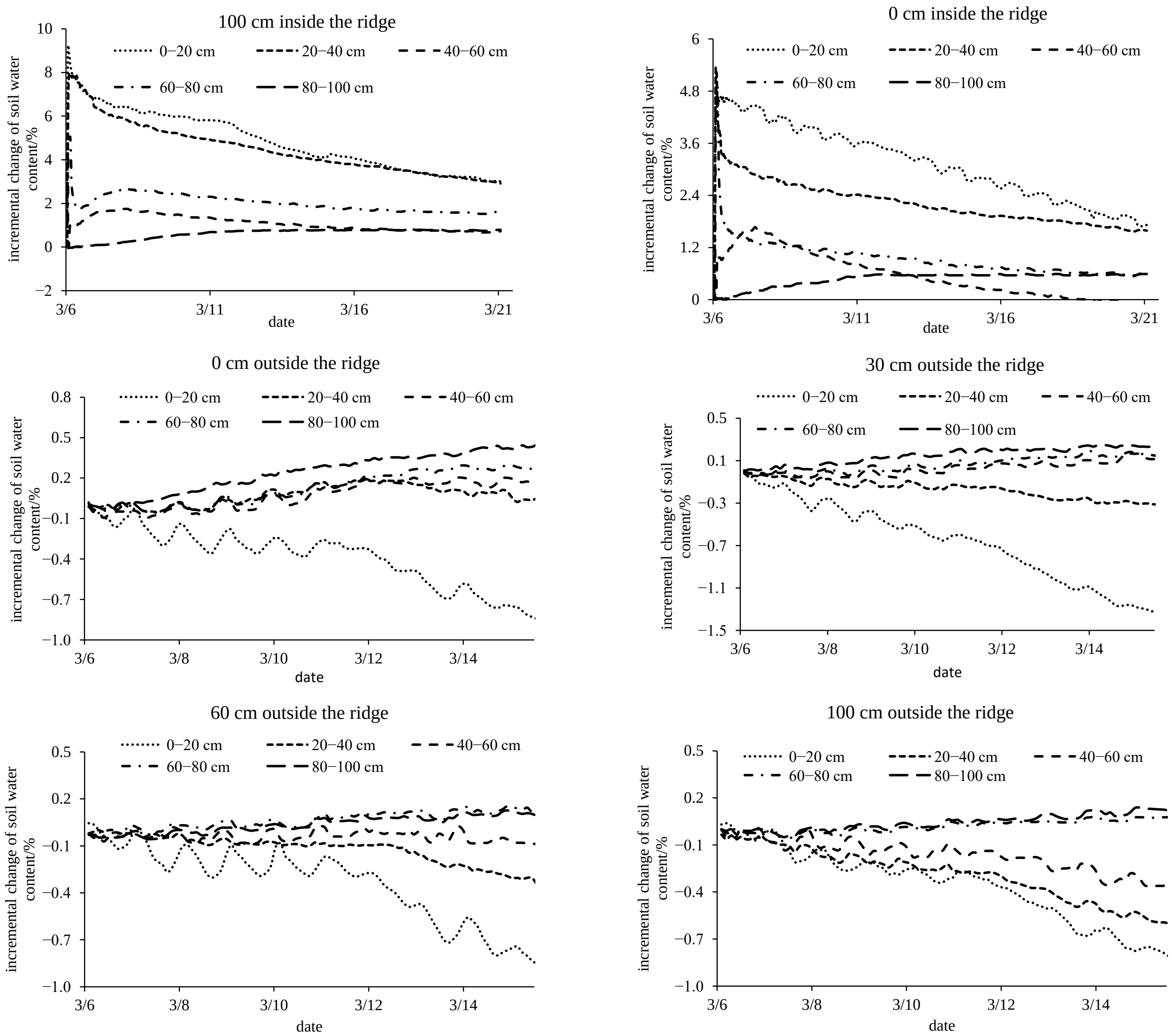

Figure 6. Change in soil water content at different soil layers inside and outside the ridge.

In summary, when a quota of 105 mm is used for the ground irrigation of winter wheat, the water will penetrate to 100 cm below the surface soil layer, and the lateral infiltration of the soil water will occur in the 0–80 cm soil layer close to the ridge. The main effects of the lateral infiltration of soil water on the soil outside the buffer area were seen in the 0–60 cm layer, and horizontal infiltration primarily occurred at points 60 cm away from the ridge.

3.5. Influence Area of Border Effect

3.5.1. Border Effects of Plant Height

Table 3 shows the results of plant height subjected to multiple comparative analyses in different stages of winter wheat growth.

Table 3. Significance analysis of interline plant height (cm) in different periods.

Row	Measured Date (Day/Month)					
	18/3	25/3	1/4	11/4	19/4	25/4
Border 1	32.41 a	37.51 a	43.23 a	57.21 a	69.13 a	75.31 a
Border 2	32.15 ab	37.31 a	43.34 a	56.76 a	67.80 ab	74.08 ab
Border 3	31.84 ab	35.08 b	42.18 ab	56.43 a	67.31 ab	73.46 ab
Border 4	31.48 ab	34.24 bc	40.30 bc	55.41 a	66.63 b	73.01 ab
Middle 1	31.06 ab	33.34 c	39.64 bc	55.03 a	66.73 b	72.21 ab
Middle 2	30.61 b	33.26 c	39.28 c	55.06 a	66.79 b	71.91 b

Note: The same letter after each data point indicates no significant difference in statistical analysis ($p > 0.05$).

As seen from Table 3, at the early stage of jointing (18/3) and the end of heading (25/4), except for the slight difference between border 1 and the middle row, there was little difference between the other rows and the middle row. At the end of jointing (11/4), all rows had no significant difference. At the early heading stage (19/4), there was a significant difference between the border 1 row and the middle row, but no difference between the border 4 row and the middle row. At the jointing stage (25/3–1/4), there was a significant difference between border 1 and 2 rows and middle rows, while there was a slight difference between other rows. Therefore, the border effect of plant height on the border 1 row existed in the whole growth period of winter wheat. The border effect had an excellent experiment effect on the border 3 row in the middle of jointing.

3.5.2. Border Effect of Leaf Area

Table 4 shows the results of multiple comparative analyses of interleaf area and different rows in different periods of winter wheat.

Table 4. Significant analysis of interline leaf area (cm^2) in different periods.

Row	Measured Date (Day/Month)					
	18/3	25/3	1/4	11/4	19/4	25/4
Border 1	52.09 a	55.67 ab	72.93 a	90.19 ab	114.92 a	110.14 a
Border 2	51.67 a	57.32 a	70.91 ab	92.24 a	115.89 a	109.00 a
Border 3	49.98 a	54.20 ab	66.60 abc	86.27 ab	113.76 a	110.81 a
Border 4	48.20 a	50.82 b	61.93 c	82.07 b	112.44 a	110.50 a
Middle 1	47.90 a	51.67 ab	62.21 bc	81.40 b	111.61 a	107.97 a
Middle 2	47.61 a	50.90 b	61.37 c	82.18 b	112.20 a	106.73 a

Note: Same letter after data indicates no significant difference in statistical analysis ($p > 0.05$).

As Table 4 shows, there were no significant differences in the areas of each row of leaves in the early growth stage, while the differences were significant in the jointing stage (25/3–11/4). After comparing the averages of the three measured values, we found no differences between the two middle rows and the four border rows; the values can be ranked as two border rows > one border row > three border rows > four border rows. There were no significant differences between the rows during the heading stage (19/4–25/4). Therefore, the border effect of the winter wheat leaf area mainly manifested in the jointing stage, and this mainly affected the plots with one border and two rows. The border effect in the plots with three rows also showed advantages over the middle row, but these were insignificant.

3.5.3. Border Effect of Production

A statistical analysis was performed on the factors affecting yield between rows of winter wheat (Figure 7). As can be seen from Figure 7, the 1000-grain weight and average yield per plant in plots with one and two rows were higher than those with one; specifically, the 1000-grain weight and average yield per plant in plots with one row were 2.3 g and 0.15 g/plant greater than those in other plots. Therefore, the border effect of winter wheat yield affected rows with one and two borders, but mainly manifested in the row with one border.

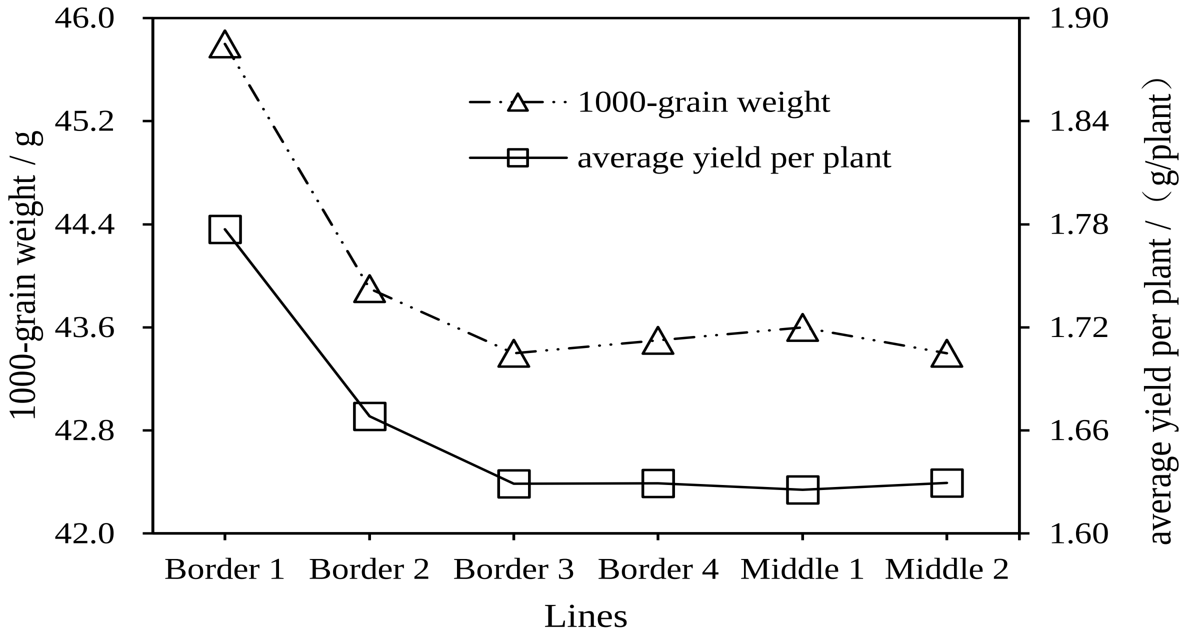

Figure 7. Relationship between 1000-grain weight of winter wheat, average yield per plant, and interline.

4. Discussion

Many factors, such as soil type, irrigation method, crop type, and experimental area, determine the selection of the optimal plot size. In conclusion, this paper only discusses the determination of the most suitable plot size under conditions of surface border irrigation with silty loam soil in northern Henan Province. The findings thus could not be directly applied to areas with different soil types and different irrigation methods. However, they can be used in setting out the zones of irrigation experiments in soils with the same textures in other areas.

Research on experimental plot areas has focused on tea tree, sorghum, Chinese cabbage, corn, sunflower, etc. The main methods used include the maximum curvature method and the Hatheway method, which are both based on the relationship between the coefficient of variation and the area of the plot. The difference with this study is that the analysis of the coefficient of variation here considers soil moisture, not soil fertility or grain yield [19–22]. In relation to this, Su Jiakai has described in detail the determination of the area of experimental plots' forage grass in several papers published in *Acta Agrestia Sinica*; they concluded that the small experimental plots used in many articles led to under-representative results, but the methods of determining plot area are limited to information in college textbooks, industry standards, and various industry texts [23], and there is no standard scientific method. The method proposed in this paper seeks to make up for this deficiency.

Our results show that the area of the experiment plot should be directly proportional to the irrigation quota. For example, with a high irrigation quota (105 mm), the amount of water applied may be too much, leading to short-term flooding after the water reaches the end of the bed. In such cases, the water layer may not be deep enough to water flow back, causing the water to accumulate at the end of the bed, and resulting in significant deep leakage [24,25]. On the other hand, with a small quota (75 mm), the variation in soil moisture between opposite ends of the bed will be considerable, meaning the area of the experimental plot must be increased. However, the difference in this case is not significant.

The calculated difference in the area is 7.62 m^2. During real-world use, the experimental results can be applied reliably with a degree of appropriate flexibility.

Li Yongning's sampling survey of Trollius chinensis yield showed that rectangular plots are the best, followed by square plots, and circular plots are the worst, which coheres with our finding that the core area should be rectangular, as is also consistent with the surface irrigation method [7]. The side of the plot that is longest in the direction of water flow can feature more spatial variation, allowing the experimental data to be more representative. The same conclusions have also been reached elsewhere [26–29].

Because of the large water-receiving area and high irrigation quota, lateral seepage of the water is inevitable after irrigation. Accurately estimating the distance and depth of lateral water infiltration after irrigation, and setting reasonably sized protected areas, can prevent the reliability of results between lateral irrigation treatments from wavering. The distance and depth of lateral infiltration are related to the quantity and method of irrigation, as well as soil properties. Liu Qunchang' s research on border irrigation showed that with an irrigation quota of 60 mm, the greatest distance of lateral infiltration in loam is 48 cm [30]. Wang Shaohua found that with an irrigation quota of 90 mm, in clay loam, horizontal seepage will occur up to 50 cm outside the ridge, and vertical seepage will reach 60 cm [31]. Although our wheat experiments employed border irrigation, the treatment locations were generally separated by ridges. After irrigation, infiltration occurred in both horizontal and vertical directions outside the ridges, which implies two-dimensional infiltration, similar to what occurs with ridge and furrow irrigation. Zhang Rui used soil box experiments, and found that the distance of horizontal lateral infiltration reached 35 cm, while vertical infiltration reached 60 cm, when the soil bulk density was 1.3 g/cm^3 and there was no furrow irrigation [32]. Jia Ruiqi studied the infiltration of soil moisture in jujube forest land when applying furrow irrigation. He found that when the irrigation amount was 90 mm, horizontal infiltration could reach 100 cm, and lateral infiltration could reach 80 cm. This study found that when the irrigation quota was 105 mm, for silty loam, internal and external seepage in the 0–60 cm soil layer reached as far as 60 cm from the ridge edge, while external seepage reached 100 cm from the ridge edge in the 60–100 cm soil layer, but the quantity of water was small. Considering the differences in soil factors, experimental conditions, bare soil, and crops, the conclusions of this study are essentially consistent with those of various other scholars. For the irrigation of winter wheat in northern Henan Province, in this study, a quota of 105 mm was considered as high-water treatment. Therefore, it will be possible to isolate the treatment cells by placing a 60 cm deep vertical water barrier, or impervious membrane, in the center line of the ridge, or by setting up a protected area no less than 60 cm wide between the two plots. This method would only be applicable to silty loam in the north of Henan Province, when the irrigation quota is 105 mm or less. When other irrigation quotas are used, or the areas and soil properties change, we can refer back to our results, and adjust or re-test via our method.

Due to the influence of light and wind speed, the physiological shapes and the yields of crops on the boundary of the experimental plot will be different from those inside the plot. The significance of this difference will be related to crop planting density and crop height. In a study on the marginal effects of densely planted dwarf crops such as wheat, Chen Yuhai found that the edge advantage of winter wheat is only derived with a border of one row [33]. Luo Zhaoxia believed that the area of marginal influence of spring wheat's yield and other related traits is within the border of two rows [34]. Galezewski L found that the marginal effects of grain yield traits will be most significant with a border of one row, but this advantage disappears with a border of four rows [35]. Ma Hongliang 's research on the strip-planting of wheat showed that the yield of a plot with a border of two rows will be the highest [36]. Due to the different planting and management methods employed, the conclusions of scholars differ. Taking an overarching view and considering the results of this study, we conclude that, when there is an area of bare land next to the wheat in the experimental area, the influence range of the marginal effect will extend to the border of the second row, while if there is a protected area outside the experimental plot, the influence range of the marginal effect will extend to the border of the first row.

5. Conclusions

Using silty loam soil in northern Henan as an example, this study outlines a method for determining the most appropriate size and area of an experimental irrigation plot. This method can be referred to for similar soils in other areas. The experimental plot should comprise a core area and a buffer area. Therefore, the area of the experimental plot should be calculated as the core area plus the area of the buffer. After the size and shape of the core area have been determined, the buffer area can be calculated as the distance between the boundary of the core area and the center of the core area; that is, the area of the buffer can be taken as the area of the frame surrounding the core.

The area of the core varies according to the stage of the treatment, the number of repetitions, and the differences between treatments. The most suitable area of the experiment plot is 60–80 m^2 at level 1, with one repetition; at treatment level 2 with a difference in soil moisture between the treatments $\geq$15%, the plot can be arranged with two replicates and with 40 m^2 per replicate, or three replicates with 20 m^2 per replicate; at treatment level 2 and a difference in soil moisture between treatments of 10–15%, two replicates can be arranged, with 80 m^2 per replicate, or three replicates with 30 m^2 per replicate; at treatment level 3 with a difference in soil moisture between treatments of $\geq$15%, two replicates can be used with 30 m^2 per replicate, or three replicates with 20 m^2 per replicate; at treatment level 3 and a difference in soil moisture between treatments of 10–15%, two replicates can be arranged with 50 m^2 per replicate, or three replicates with 30 m^2 per replicate.

The core area should be rectangular; the long border should be that which is oriented in the direction of water flow, and the shorter border should be that which is oriented in the direction of vertical water flow. This layout will firstly ensure that the overall orientation of the experiment site (the direction of vertical water flow propulsion) takes into consideration the number of crop rows planted, and that the length of the experimental site can be appropriately increased (along the direction of water flow propulsion). A length-to-width ratio of 5:1–7:1 is appropriate, and we do not recommend exceeding 10:1.

The width of the buffer area should be greater than 60 cm to preclude the influence of the border seepage of irrigation water between treatment.

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