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Effects of Planting Density on Root Spatial and Temporal Distribution and Yield of Winter Wheat

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Abstract: The root system is the only vital organ for plants to connect with soil moisture and nutrients and obtain feedback information. This research aimed to explore the response of different spike type winter wheat varieties to plant and row spacing configurations. Multi-spike and large-spike winter wheat varieties were used as materials. By setting different plant row configurations and planting densities, the spatial and temporal distribution of root length density, root diameter, root dry weight density, and the main control factors of root growth and development of winter wheat during the whole growth period were studied. The results showed that the root system was the most widely distributed and the root diameter was the largest in the 0–40 cm soil depth, with an average root system diameter of more than 0.5 mm. The root length density and root diameter peaked at the heading stage, decreased at the maturity stage, and the root dry weight density peaked at the jointing stage. The jointing stage and heading stage are the most vigorous periods of root growth in winter wheat, when the center of gravity of root growth in winter wheat is gradually moving down. Therefore, the rapid growth and elongation time of a root system can be effectively prolonged at the jointing stage and heading stage, and the root growth rate can be improved. Promoting root thickening can effectively meet the needs for water and nutrients, for the formation and filling of aboveground plants and grains, in the later stage, which is conducive to the formation of aboveground dry matter production and final yield. The root distribution was greatest in the 0–60 cm soil depth, accounting for 95.13–97.84% of the total root length. After the heading stage occurs, the upper roots begin to decline in large quantities. Thus, the jointing stage and heading stage require fertilization and other farmland management operations to increase root nutrients for the ground parts and dry matter accumulation to provide sufficient nutrients so that the number of effective panicles, grain weight, and the number of spike grains coordinate to achieve the highest grain yield. Results showed that the highest yield can be achieved with the planting pattern X2M1. A comprehensive analysis showed that the genetic characteristics of winter wheat varieties were different, and there were some differences in the correlation between wheat yield and root system at the different growth stages. The correlation between the root parameters and yield of multi-spike winter wheat during the overwintering-jointing stage was obvious. For large-spike type winter wheat in the jointing stage, the yield correlation is most obvious.

Keywords: farming practices; productivity; root system; uniform planting; winter wheat

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1. Introduction

Wheat is one of the major food crops in the world. In recent years, the instability of global wheat production has increased due to climatic and other natural disasters. According to the report released by the U.S. Department of Agriculture in August 2021, global wheat production was 776.4 million tons in 2021 [1,2]. Although this is 1.07 million tons more than in 2020, it is 1549 million tons less than the forecast in October 2021. It is estimated that this year's consumption will be 786.7 million tons [3]. The annual data concerning the global wheat inventory at the end of the year reduced to 279 million tons; this is the lowest level since 2017, and the global wheat supply and demand pattern is gradually tightening. By the middle of this century, the global population may stabilize at about nine billion, and by that time, global food production will have to increase by 50% to meet needs [4–7]. To this end, how to improve wheat yield is a hot topic in agricultural research today.

Wheat yield is not only controlled by genetic characteristics but also affected by cultivation measures [8,9]. It is of great practical significance to explore the morphological characteristics of the wheat root system and its growth and distribution dynamics within soil to optimize root configuration and improve wheat yield potential. Plant roots' structure distribution and dynamic growth have always been essential topics in root research.

In recent years, research on wheat roots has mainly focused on the effects of tillage measures, water, fertilizer conditions, irrigation techniques, and growth redundancy on the spatial and temporal distribution of wheat roots. The effects of soil water stress on root morphology, architecture and the physiological indexes of wheat have been explored [3,8,10]. The distribution of winter wheat roots is closely related to the soil type. Roots are found more in lower layers and less in areas with clay [11,12]. At the same time, the distribution of cumulative root weight and root length in different soil layers of the winter wheat root zone conform to hyperbolic function distribution [13]. With the development of agricultural technology, it was found that the root length density and root diameter first increased and then decreased. The root diameter reached its maximum at the returning green stage and its minimum at the mature stage, while the root length density was different. The root length density was smallest at the overwintering stage, and increased rapidly from the jointing stage to the heading stage until it reached its peak [8,9]. There is a positive correlation between root growth and soil moisture, which is affected by environmental factors. Appropriate control of the nitrogen supply can improve soil fertility, and the local application of nitrogen fertilizer has a local stimulation effect on root growth and can change root growth patterns. Root growth and physiological activity are affected by temperature [14]. According to other studies [15,16], the optimum temperature for wheat root growth is 16–20 °C, and growth is very slow at 0–2 °C. The root growth is inhibited when the temperature is higher than 30 °C. Reasonable planting density plays a vital role in coordinating wheat growth and environmental conditions. The root density of wheat decreases with a decrease in population density, and the number of roots and secondary roots per plant increase with a decrease in density. The decline gradually increases with the delay of the growth period [17,18]. Duan found that the deep roots of winter wheat increased with an increase in density from the overwintering stage to the jointing stage, and the denser the root system at maturity, the deeper the recession depth [19–21].

It can be seen that there are many factors affecting the growth and development of crop roots. Currently, research on the uniform sowing technology of winter wheat primarily focuses on the aboveground part of winter wheat and the planting pattern. There are few studies on the underground part of uniform sown wheat. The study area is located in the warm temperate extreme continental arid desert climate zone. The study of the spatial and temporal distribution of uniform sown winter wheat planting density on the root system helps to explore the effects of plant and row spacing on dry matter accumulation, post-anthesis assimilation and translocation, and grain yield and its components in winter wheat; this provides a theoretical basis for the application of uniform sowing technology for winter wheat. At the same time, we anticipate that this case can provide a reference for surrounding areas with similar planting environments in Central Asia.

2. Materials and Methods

2.1. The Experimental Site

The experiment was carried out at the experimental agronomy station of Tarim University in Alar City, Xinjiang (40°32′20′′ N, 81°17′57′′ E) from 2019 to 2020. Varieties were sowed on 2 October 2019 and harvested on 18 June 2020. The experimental area is situated on the Tarim Basin's northern edge. The average annual temperature is 10.8 °C, the average annual precipitation is about 50 mm, the altitude is 1015 m, and the frost-free period is 220 d.

It is a warm temperate extreme continental arid desert climate zone. The previous crop was soybean, and the soil texture was loam. The soil organic matter content was 7.81 g/kg^{-1}, available phosphorus was 18.3 mg/kg^{-1}, available potassium was 112 mg/kg^{-1}, alkali hydrolyzed nitrogen was 33.5 mg/kg^{-1}, and pH was 7.9 (Figure 1).

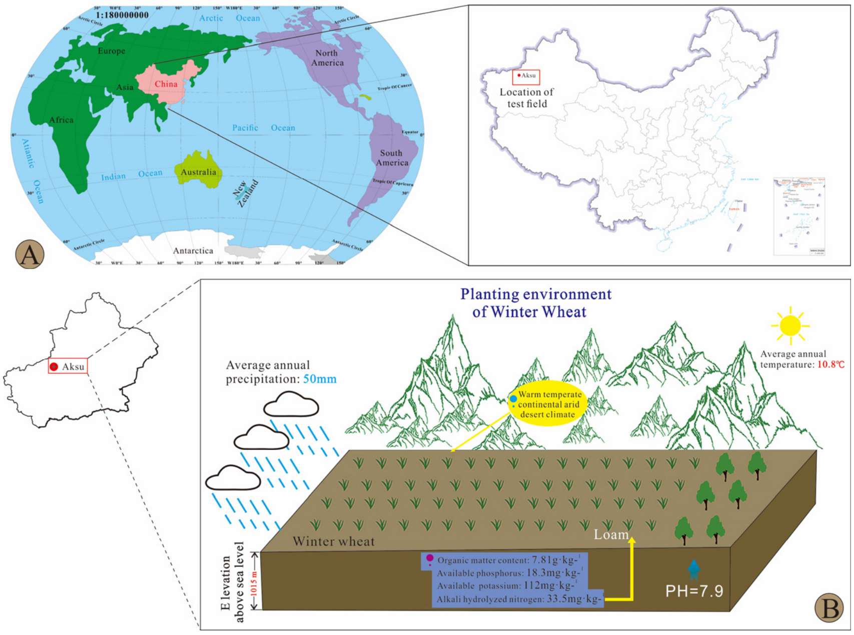

Figure 1. Introduction of Test Field. (**A**) The geographical location of the study area. (**B**) Growth environment model of winter wheat.

2.2. Materials and Methods

The tested winter wheat varieties were of the multi-spike variety (XD22) and large-spike variety (XD50) (cultivated and provided by Agricultural Science Research Institute of the Seventh Division of Xinjiang Production Construction Corps and Xinjiang Jinfengyuan Seeds Co., Ltd., respectively). The split-plot design was used in this experiment, and the varieties were at the following main plots (X): XD22 (X1) and XD50 (X2); the density was the sub-region (M), and the row spacing was established as follows: 5 cm × 5 cm (M1), 3.3 cm × 7.5 cm (M2), 2.5 cm × 10 cm (M3), 2 cm × 12.5 cm (M4) and 1.7 cm × 15 cm (M5). Five-row spacing treatments were used to plant the multi-spike variety XD22 (X1) and the large-spike variety XD50 (X2). Root length density, surface area, root diameter, and dry weight were evaluated at the overwintering stage (until 22 November 2019), jointing stage (until 11 April 2020), heading stage (until 27 April 2020), and maturity stage (until 12 June 2020). Each treatment took 3 sample points with the plant as the center point, and each sample point was divided into levels 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm.

A root drill with a length of 20 cm and a drill diameter of 9 cm was used to select a plot as a fixed sampling area in each treatment. In the fixed sampling region of each treatment, one central sample point was chosen at random, and three drill points were obtained for each sample. A total of 5 samples were taken from a point, from a total of 300 samples according to different treatments; different soil layers were placed into 200 mesh nylon bags, washed outdoors, and a large amount of soil was taken to the laboratory after picking the roots. The selected root samples were placed neatly on the scanning disc of the root scanner according to different soil depths. The root samples were analyzed using Win RHIZO 2008 (Produced in Regent, Canada) root analysis software to obtain root length and diameter. Then, the roots were dried with absorbent paper and placed in an oven at 85 °C to a constant weight, and the root dry was obtained by weighing them (Figure 2).

$$\text{Root dry weight density (RDWD, g/m}^3\text{)} = \text{M/V} \times 10^6$$

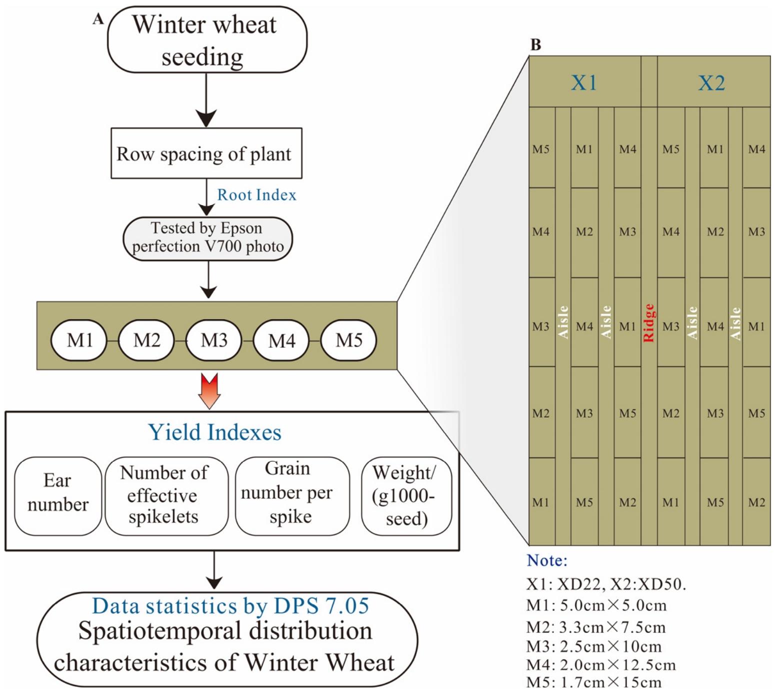

Figure 2. Experimental method Technical route. (**A**) Experimental design and process framework. (**B**) Split-plot experimental design.

M is the root mass (g) after drying at different soil depths, and V is the root-soil volume.

Root growth characteristics: A root scanner systematically measured the changes in root length and root diameter in soil depth during the critical period of wheat growth and development.

$$\text{Root length density (RLD, cm/cm}^3\text{)} = L/V$$

L is the root length (cm) obtained using a software analysis of root samples measured in different soil layers, and V is the volume of root soil.

$$V = \pi r^2 h$$

In this experiment, r = 4.5 cm, h = 20 cm, 20 cm soil depth volume is 1271.7 cm^3.

2.3. Statistical Analysis

The growth stage, soil depth, and various treatments were used to categorize the root trait characteristics of large-spike and multi-spike winter wheat. Using Data Processing System 9.5 software (Produced in Zhejiang, China), the classified data were tested according to the least significant difference (LSD) method to detect differences between pairs of means. Pearson's correlation analysis and two-tailed test were calculated using IBM SPSS Statistics 22 software (IBM, Inc., Armonk, NY, USA) to determine the correlation between root traits and winter wheat yield. Statistical comparisons were significant when $p < 0.05$.

3. Results

3.1. Temporal and Spatial Distribution Characteristics of Root Length Density

The root length density of multi-spike wheat shows a tendency of initially growing and then dropping with the progress of the development process under various plant row configurations. It decreased after reaching the peak at the heading stage. In addition, the root length density of each growth period decreased first and then increased with the increase in soil depth. The root length at 0–40 cm soil depth accounted for 83.44% of the total root length. The root length density at 0–20 cm soil depth was the largest. The root length at the jointing and heading stages accounted for 22.75% and 47.85% of the total root length. It is important to note that root length density in the 0–100 cm soil layer peaked at the heading stage. At maturity, the plant spacing, row spacing, and root length density all decreased more quickly when plants were further from one another. At the mature stage, M3's root length density does, however, decline rapidly. The reduction range is also significant, so it is unfavorable for the dry matter accumulation in the root (Figure 3A). For large-spike varieties, the root length density decreased gradually with the increase in soil depth at each growth stage. The root length at 0–40 cm soil depth accounted for 91.58% of the total root length, the root length at 0–20 cm soil depth accounted for 65.13% of the total root length, and the root length density was the largest. The root length at the jointing and heading stages accounted for 23.06% and 57.16% of the total root length, respectively. The distribution characteristics of root length density in 0–100 cm soil depth of winter wheat at different growth stages were quite different. With the advancement of the growth process, the root length density increased first and then decreased, and reached the peak at the heading stage and then decreased at the maturity stage (Figure 3B).

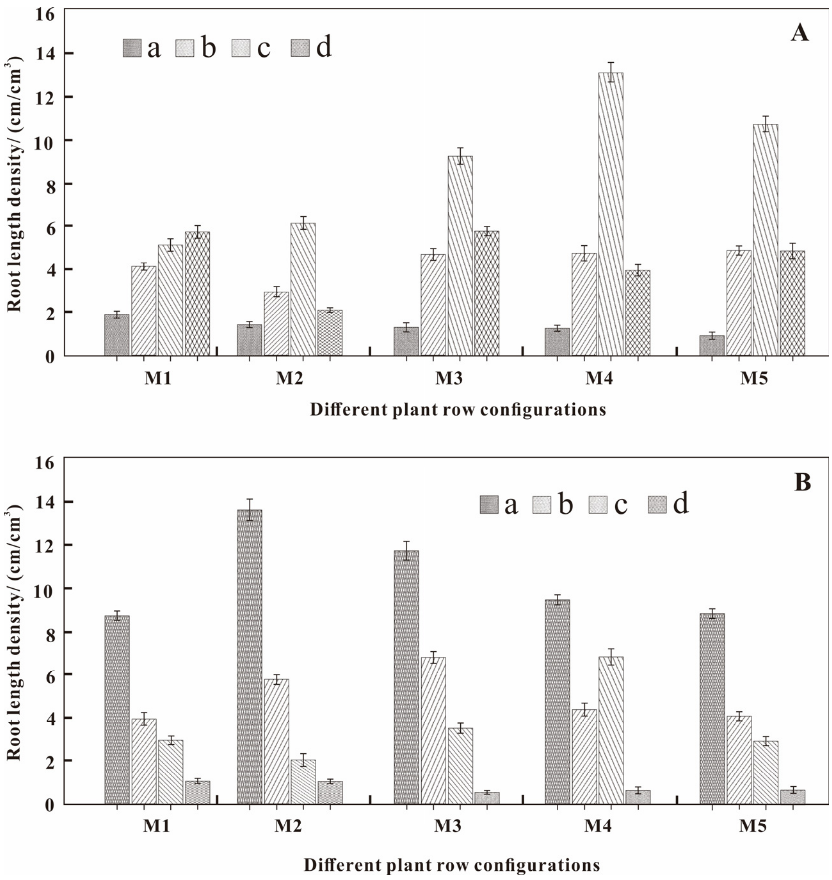

Figure 3. Distribution characteristics of root length density at different growth stages (a: Overwintering, b: Jointing, c: Heading, d: Ripening). (**A**) Multi-spike wheat. (**B**) large-spike wheat.

3.2. Spatiotemporal Distribution Characteristics of Root Diameter

The variation characteristics of root diameter in 0–100 cm soil depth of multi-spike winter wheat at different plant row spacing and different growth stages showed that the root diameter decreased with the increase in row spacing in the overwintering period, with M1 > M2 > M3 > M4 > M5 (Figure 4A). The root diameter of winter wheat treated with row spacing at the jointing stage was similar. Other treatments, particularly the M1 treatment, led to a quick decline in root diameter, except for the M5 treatment, in which the root diameter slightly rose. In contrast to the wintering stage, the root diameter rose during the heading stage. After attaining its maximum diameter at M4, the root diameter steadily declined after the row spacing was reduced. At maturity, the root diameter shrank significantly, particularly in the M4 and M5 treatments. The root diameter at a 0–100 cm soil depth of winter wheat at the same growth period under different row spacing showed that the root diameter increased first and then decreased with the increase in row spacing; that is, M2 > M5 > M4 > M3 > M1 (Figure 4B). At the jointing stage, each treatment's root diameter increased rapidly, the root diameter of M3 increased the most, and the root diameter of M2 reached the maximum. The root diameter increased at the heading stage, the maximum increase in M1 reached the maximum and the minimum increase was observed in M3′s root diameter. The mature root diameter decreased rapidly; with the increase in row spacing, root diameter decreased, that of M1 decreased to the greatest extent, and that of M4 decreased the least.

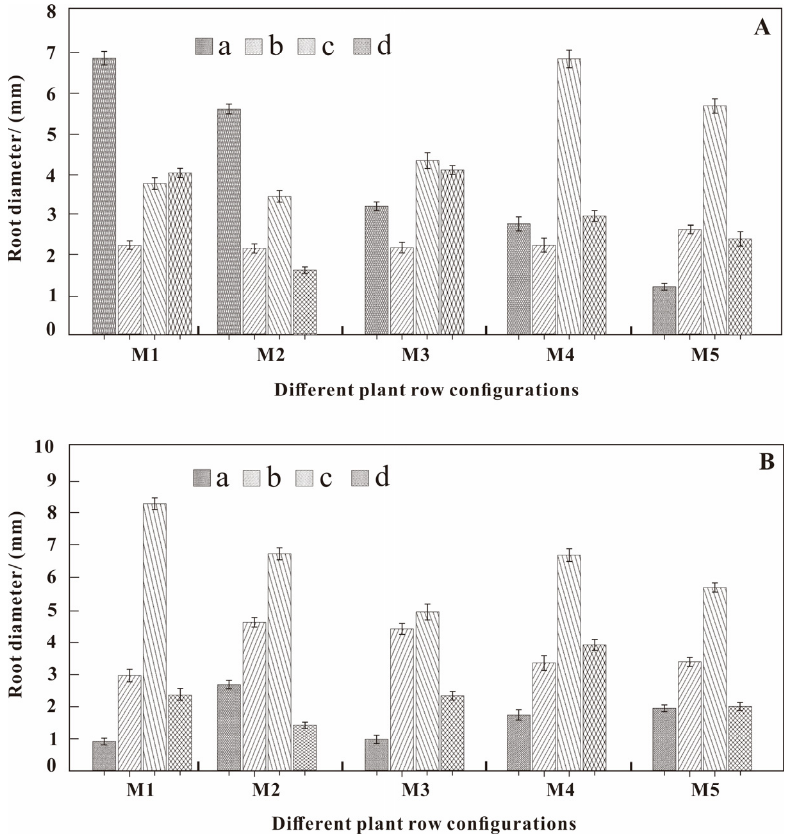

Figure 4. Distribution characteristics of root diameter area at different growth stages (a: Overwintering, b: Jointing, c: Heading, d: Ripening). (**A**) Multi-spike wheat. (**B**) large-spike wheat.

3.3. Spatial and Temporal Distribution Characteristics of Root Dry Weight Density

With increasing soil depth, the vertical distribution features of root dry weight of multi-spike winter wheat at various growth stages decreased. The root dry weight at 0–40 cm soil depth accounted for 90.39% of the total root dry weight, and the root dry weight at 0–20 cm soil depth accounted for 67.67% of the total root dry weight. The root dry weight density at the jointing and heading stages accounted for 37.20% and 32.77% of the total root dry weight density, respectively. With the advancement of the growth process, the root dry mass density increased first, then decreased, reaching the peak at the jointing and heading stages (Figure 5A).

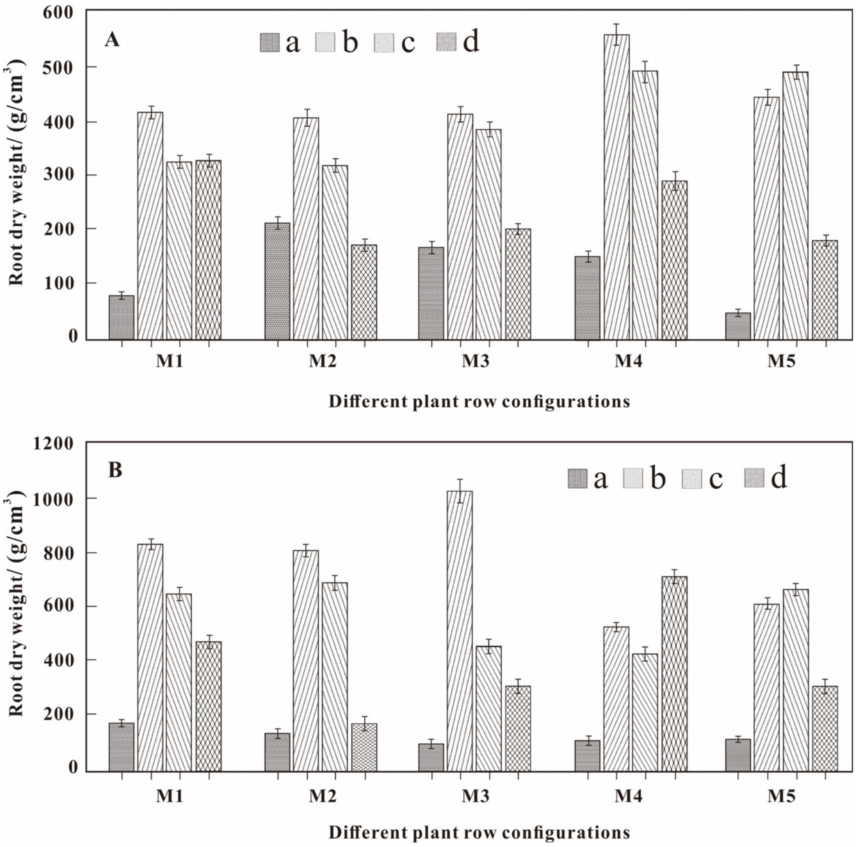

Figure 5. Distribution characteristics of root dry weight density at different growth stages. (a: Overwintering, b: jointing, c: heading, d: ripening). (**A**) Multi-spike wheat. (**B**) Large-spike wheat.

With the advancement of the growth process, the root dry weight density of the large-spike varieties increased first and then decreased, similar to the multi-spike type. While at the jointing stage, the root dry weight density increased rapidly to the peak of the whole wheat growth period, and M3 reached the maximum. Root dry weight density decreased slightly at the heading stage, and M3 decreased the most. The root dry weight density decreased rapidly at the mature stage, the root dry weight density of M4 continued to increase, and M2 decreased the most (Figure 5B).

4. Discussion

4.1. Effect of Plant Row Configuration on Temporal and Spatial Distribution of Winter Wheat Roots

The root length density and diameter increased as the development process progressed, peaked at the heading stage, and subsequently reduced at the maturity stage. The root dry mass density increased first, then decreased, reaching the peak at the jointing stage and then decreasing. The smaller plant spacing in the overwintering period benefits the growth of roots. The larger plant spacing and the smaller row spacing benefit the growth of roots in winter wheat's jointing and heading stages. The phase between the jointing and heading stages is the most robust for root development. The roots can better water and provide nutrients in the soil, and the roots rapidly decay at the mature stage to better retain the nutrients in the soil. Therefore, in actual production management, farmland management operations such as fertilization at the jointing stage and heading stage can increase the root nutrients to provide sufficient nutrients for the dry matter accumulation of the aboveground part.

More than 80% of the root distribution occurs in the 0–40 cm soil depth range and 0–20 cm root distribution root growth is the most extensive. The maximum values of root length density, root diameter, and root dry weight density were all at 0–20 cm soil layer depths. As soil depth increased, the diameter of the surface root increased, the diameter of the intermediate root decreased, and the diameter of the bottom root expanded. At the jointing and heading stages, the M1 treatment outperformed other treatments. The root length density and root diameter of M1 and M2 also attained their greatest values at these stages, along with the deep root growth state and a lower maturity value. Combined with the yield situation (Table 1), one may infer that the smaller plant spacing and larger row spacing for X2 are more suitable for root growth and development; the root growth and development of X2 were better than X1. At the same time, X1M1, X1M2, and X1M3 had different degrees of lodging at the heading stage due to the large population at the jointing stage, which was unfavorable to production. X2 did not appear to be lodging. This experiment's best row spacing configuration was found for the X2M1 treatment (Figure 6).

Table 1. Yield measurement data of winter wheat under different plant row configurations.

Time	Treatment	Ear Number	Number of Effective Spikelets	Grain Number Per Spike	Weight/ (g1000-Seed)	Yield/(kg/hm^2)
2 October 2019–18 June 2020	X1M4	633.67 bA	15.9 bAB	32.05 aA	54.07 aA	8933.75 abAB
	X1M3	642.67 aA	16.15 abAB	31.95 aA	53.69 abA	9180.65 aA
	X1M2	631.67 bA	16.5 aA	31.1 abAB	53.42 bA	8779.65 bB
	X1M1	608.00 cB	15.65 bBC	30 bcAB	52.34 cB	7881.65 cC
	X1M5	583.67 dC	15 cC	29.05 cB	51.5 dC	7295.15 dD
	X2M4	375.67 dD	21.2 aA	55.67 aA	50.56 aA	8527.25 dD
	X2M3	393.33 dCD	20.97 abA	54.03 bAB	50.5 aA	8710.15 dCD
	X2M2	412.67 cBC	20.47 abA	53.1 bcBC	50.21 aA	8985.6 cBC
	X2M1	433.67 bB	20.37 bA	52.13 cdBC	50.19 aA	9267.2 bAB
	X2M5	467 aA	20.3 bA	50.97 dC	49.29 aA	9599.65 aA

Note: Uppercase and lowercase letters imply significance below 0.05 and 0.01, respectively. Different letters indicate significant differences at different levels.

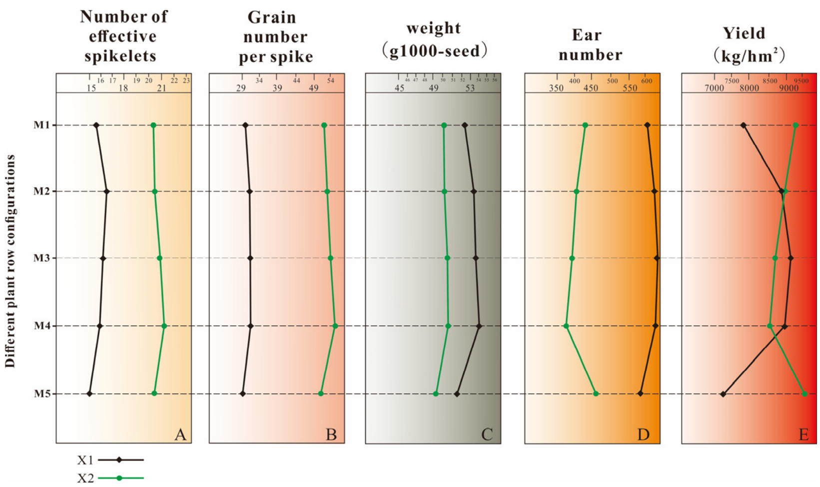

Figure 6. Yield measurement of winter wheat treated with different varieties and densities. (**A**) Number of effective spikelets, (**B**) Grain number per spike, (**C**) weight, (**D**) Ear number, (**E**) Yield.

4.2. Correlation Analysis of Root Index and Yield

There is a close relationship between the root index of winter wheat and the yield of wheat fields, but the correlation is different because of the different genetic characteristics of different varieties [8,22]. The Pearson correlation test studied the relationship between root traits and yield-related traits of winter wheat under different treatments.

From the early to middle growth stage, the root length density and root dry weight of X1 showed a strong correlation with the yield of a wheat field, especially in the overwintering stage. The relationship between root dry weight and yield was the most significant. The root length density and root dry weight of X2 was significantly correlated with a yield at the mature stage (Table 2). In addition, the root dry weight of the surface layer (40–60 cm soil layer) and the root length density of the deep layer (80–100 cm soil layer) of X1 were significantly correlated with yield. The root dry weight of the deep (60–100 cm) roots of X2 and the root length density of the roots in the 40–100 cm soil layer were most significantly correlated with yield. This indicates that the roots are vertically distributed in descending order in the soil profile [23–25]. However, for multi-spike varieties, in the early growth period, the overall growth of the root system is better than the large-spike type, especially at the jointing stage, and heading stage root growth can better absorb soil moisture and nutrients. The advantage of large-spike varieties is that the middle-deep roots grow better. After reaching maturity, the aging rate of root length density is accelerated, further alleviating the competition between aboveground and underground elements and is conducive to the formation of grain yield. Therefore, in production management, fertilization and other farmland management operations can be carried out at the jointing stage and heading stage to increase root nutrients and provide sufficient nutrients for the accumulation of dry matter above ground.

Table 2. Correlation analysis between root index and yield of different winter wheat varieties at different growth stages.

Correlation		X1	X2	X1	X2	X1	X2	X1	X2	X1	X2
		0–20 cm		20–40 cm		40–60 cm		60–80 cm		80–100 cm	
Root length density	Winter period	−0.335	0.466	0.502	0.4	0.931 **	0.021	0.901 **	−0.238		
	Jointing stage	−0.217	−0.195	0.524 *	−0.222	−0.026	−0.694 **	−0.226	−0.695 **	−0.634 *	−0.955 **
	Heading stage	−0.064	0.268	0.487	−0.13	−0.202	−0.056	−0.48	0.903 **	−0.624 *	0.28
	Mature stage	0.258	−0.582 *	−0.383	−0.317	−0.407	−0.807 **	0.243	−0.085	−0.13	−0.597 *
Root diameter	Winter period	−0.179	0.302	0.222	0.139	0.857 **	0.146	0.888 **	−0.286		
	Jointing stage	−0.461	−0.147	0.383	−0.212	−0.704 **	−0.323	0.043	−0.407	0.236	−0.454
	Heading stage	−0.229	0.016	0.413	−0.678 **	0.048	−0.248	−0.638 *	0.768 **	−0.613 *	0.714 **
	Mature stage	0.256	−0.337	−0.383	0.332	0.066	−0.005	0.381	−0.302	0.504	−0.439
Root dry weight density	Winter period	0.829 **	0.462	0.796 **	−0.209	0.481	0.153	0.871 **	−0.139		
	Jointing stage	−0.022	0.037	0.699 **	0.042	0.054	−0.143	0.028	−0.892 **	−0.324	−0.858 **
	Heading stage	−0.333	0.618 *	0.616 *	0.078	−0.703 **	0.423	−0.497	0.876 **	−0.924 **	0.012
	Mature stage	0.032	−0.266	−0.327	0.163	−0.540 *	−0.556 *	−0.098	−0.527 *	0.2	−0.603 *

Note: X1: multi-spike; X2: large-spike. * and ** denote significant differences at 0.05, 0.01 probability levels.

4.3. Relationship between Root Spatial Distribution and Yield

Under different planting densities, the effective tillers of winter wheat increased with the increase in density, while the grain number per spike and grain weight per spike decreased with the increase in density. By dividing the root length density, root dry weight, and planting density, the value of root system per plant, root length density, and root dry weight density per plant were obtained. From the over-wintering stage to the heading stage, the root length density and root dry weight density increased with the increase in density, which assisted in the formation of an adequate panicle number. In the soil profile, the root length density of winter wheat increased with the increase in wheat planting density, and the root length density of wheat per plant also increased with the increase in planting density. The rate of increase with planting density was the highest at the heading stage, followed by the jointing and maturity stages. The root dry weight density and root length density of wheat were consistent at jointing, heading, and maturity stages; that is, the root length density and root dry weight density per plant increased with the increase in planting density, but the rate of increase with the decrease in density was the highest at the jointing stage, followed by the maturity stage and heading stage.

The higher the root length density and dry weight density per plant, the stronger the water and nutrient capacity absorbed by the root system and the higher the yield per plant. In the period of effective panicle formation after the jointing stage, sufficient nutrients and water can promote the formation of effective panicles [26–28]. In the critical period of yield formation after the heading and filling stage, the greater the availability of water and nutrients, the higher the grain weight and grain number per spike [29–31].

With the increase in planting density, the root length density of wheat per plant increased to ensure water absorption and nutrition. The increase in the senescence rate of root length density from heading to the maturity of wheat per plant can alleviate the competition between aboveground and underground elements [32–35], which is beneficial to grain yield formation. Although the root senescence rate under high density was higher than that under low density, the root indexes of the single plant under high density were still higher than those under low density until the mature stage, which proved important for the later yield formation.

5. Conclusions

The root growth index of the X2M1 treatment was very prominent in the whole experiment. In this experiment, the best treatment for variety, row spacing configuration, and density was X2M1, and the yield of large varieties was higher than that of multi-panicle varieties.

The overwintering stage is not the critical period for determining wheat yield. The jointing and heading stages are winter wheat roots' most vigorous growth periods. Therefore, in the jointing stage and heading stage, roots' rapid growth and elongation time can be effectively prolonged, the growth rate of roots can be improved, root volume may be raised, root thickness can be encouraged, and the process of root senescence can be postponed. It can effectively meet the needs of water and nutrients for the formation and filling of aboveground plants and grains in the later stage, which is conducive to producing aboveground dry matter and forming the final yield. Therefore, we suggest that winter wheat irrigation and fertilization management can be appropriately strengthened in the actual planting process.

In the late heading stage of winter wheat, the upper root system began to decline, but the lower root system still experienced a certain degree of growth until the mature stage. It can be seen that the deep root system was the functional root system of winter wheat. Reasonable cultivation measures should be adopted in production to promote the deep root system of winter wheat. Here, the root system of winter wheat was distributed deeply and widely, which was of great significance to prolonging the functional period of leaves and ensuring grain filling and prominent grains.

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Data Availability Statement: The entire set of raw data presented in this study is available upon request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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