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Effects of Different Drip Irrigation Rates on Root Distribution Characteristics and Yield of Cotton under Mulch-Free Cultivation in Southern Xinjiang

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Abstract: In order to study the effects of different irrigation amounts on the root characteristics and yield of cotton without film mulching (abbreviated as filmless cotton) under drip irrigation in Southern Xinjiang, five irrigation amounts of filmless cotton (300, 375, 450, 525 and 600 mm, represented by W1, W2, W3, W4 and W5) and one irrigation amount of cotton with film mulching (abbreviated as filmed cotton) (450 mm, represented by WCK) were set. The effects of irrigation amount on root length density (RLD), root surface area (RSA), root average diameter (RAD), root volume (RV), root weight density (RED) and yield of filmless cotton were analyzed. The results of the two-year experiment showed the following: (1) The indexes of cotton root growth reached the maximum at the flowering and bolling stage, and the growth of soil root in the periphery (30 cm from the main root) and the lower layer (40–60 cm soil layer) reached the peak at the flowering and bolling stages, respectively; (2) The average value of root growth index of film-free cotton in each treatment was W2 > W3 > W4 > W5 and W1. The RLD of W2 and W3 increased by 19.41–106.67% and 13.66–84.22% in the peripheral and lower soil layer, and the proportion of RSA in the peripheral and middle soil layer (20–40 cm soil layer) increased by 1.64–3.41% and 0.49–4.09% compared with other treatments. The RAD, RV and RWD after W2 treatment were relatively large at various distribution points in the soil, followed by W3 treatment; (3) The average root indexes of WCK were not significantly different from those of W3, but the indexes of the lower soil layer were the smallest, at only 29.18–66.84% of the average value of the non-film mulching treatment, while the root indexes of the surface layer (0–20 cm soil layer) and the surrounding soil were larger, with an increase of 11.43–102.17% and 29.60–111.57%, respectively, compared with the non-film mulching treatment; (4) The seed cotton yield of W3 was the highest in the non-film mulching treatment, reaching 4833.25 kg·hm^{-2}, but was still lower than that of WCK by 27.79%. Conclusion: An appropriate water deficit is conducive to root growth and increases the uniformity of its distribution in the soil layer. The irrigation amount of 375–450 mm for filmless cotton in Southern Xinjiang can promote root growth, prevent senescence and increase yield, which can be used as a reference in production.

Keywords: film-free cotton; irrigation quantity; root growth index; spatial distribution; yield

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1. Introduction

Cotton is an important cash crop. In 2020, the world's cotton planting area was 32.27 million hectares, with a total output of 24.59 million tons, accounting for 21.3% of the world's fiber trade [1]. Therefore, cotton, as a natural fiber material, has important strategic significance in international trade and economic value. In 2023, China's cotton planting area was 2788.1 khm^2, with a total output of 5.618 million tons, of which Xinjiang's planting area was 2369.3 khm^2, with a total output of 5.112 million tons, accounting for 84.98% and 90.99% of the country's total, respectively. Xinjiang has become an important cotton planting area in China [2]. In Xinjiang, cotton planting mainly adopts the policy of "short, dense and early", with a high level of mechanized management, and mainly film mulching [3]. Because the cotton field is covered with plastic film for a long time and cannot be effectively recovered, the residual film pollution is serious [4], the soil is damaged [5] and the cotton yield is reduced [6]. This has caused an inevitable trend of popularizing cotton planting without film mulching (abbreviated as filmless cotton). Southern Xinjiang is rich in light and heat resources. Scientific and reasonable irrigation is the key to ensuring efficient water use, a high yield and the quality of filmless cotton. The amount of irrigation directly affects the growth structure, physiological function and water absorption capacity of cotton roots, which are some of the key measures for yield formation. Hu et al. [7] believed that different soil moisture levels had a significant impact on the growth rate of cotton roots. When the soil moisture was 75% θf (field capacity), the root growth rate and final root weight were the largest, so was the appropriate water content for root growth; 90% θf of soil moisture exceeded the suitable range of soil moisture for cotton roots. When the soil moisture is between 60–75% θf and 75–90% θf, there is a certain water stress, which inhibits the growth of cotton roots at the flowering and bolling stage, and the root length, root surface area and root volume are significantly reduced compared with using an appropriate level of water [8]. Chen et al. [9] believe that the activity centers of cotton roots in the soil layer are different during different periods. The root length density in the middle and shallow soil layers is higher at the flowering and boll setting stage, while after boll opening, it is distributed more in the deep roots and between the rows far away from the cotton row. Since Yu et al. [10] selected and bred the varieties of filmless cotton, filmless cotton has been planted in Southern Xinjiang. Because the soil moisture ecology of filmless cotton was significantly different from that of film-covered cotton (abbreviated as filmed cotton) [11], the effect of the irrigation amount on the root system was quite different. At present, there are many studies on the growth and development, root characteristics and yield formation of cotton with film mulching under the control of irrigation amount, but less on cotton without film mulching [8,12]. Taking the main cultivar 'Zhong619' of filmless cotton in Southern Xinjiang as the material, this paper set five irrigation amounts of filmless cotton and one suitable irrigation amount of filmed cotton as the control treatment, and studied the spatial distribution characteristics of root growth and yield components of filmless cotton under drip irrigation in Southern Xinjiang under different irrigation amounts, so as to provide technical support for the scientific irrigation of filmless cotton in Southern Xinjiang.

2. Materials and Methods

2.1. Overview and Management of the Experimental Site

The test was conducted at the agricultural ecological water-saving test station of Tarim University, which is located at the northwest edge of the Tarim Basin (40°33′ N, 81°16′ E, with an altitude of 1012.2 m). It is a typical extremely arid desert area. The annual average temperature is 11.2 °C, the accumulated temperature at 10 °C is 4760 °C, the annual average precipitation is 53.6 mm, the annual evaporation is 1988.4 mm and the annual relative humidity is below 55%. It is a typical warm temperate inland climate (Table 1). In order to ensure the normal growth of crops, a small amount of repeated irrigation is required during production. The soil of the test site is sandy loam, the soil bulk density of 0–40 cm soil layer is 1.32 g·cm^{-3}, the field water-holding capacity is 23.8% (weight water content), the groundwater level is about 8.0 m, the soil organic matter content is 10.25 g·kg^{-1}, the total nitrogen is 0.09%, the alkali hydrolyzable nitrogen is 49.27 mg·kg^{-1}, the available phosphorus is 32.01 mg·kg^{-1} and the available potassium is 214.10 mg·kg^{-1}.

Table 1. Meteorological conditions in the test area.

Year	Month	Average Temperature /°C	Average Relative Humidity/%	Average Pan Evaporation/ (mm d^{-1})	Average Wind Speed/ (m·s^{-1})	Average Sunshine Hours/ (h·d^{-1})	Rainfall/ mm	Reference Crop Evapotranspiration ET_0/mm
2022	April	18.3	28.5	5.9	2.6	7.1	0.0	149.3
	May	24.4	31.9	8.0	2.9	7.3	0.1	196.7
	June	25.3	39.4	7.6	2.3	8.5	0.4	165.4
	July	26.9	44.7	7.8	2.6	7.8	17.9	172.4
	August	22.9	65.7	4.7	2.2	5.3	33.9	97.2
	September	22.2	47.1	5.7	1.8	9.2	0.0	108.0
	October	11.8	48.2	3.5	1.6	7.4	0.0	48.9
2023	April	15.3	27.5	5.4	2.5	6.1	0.0	123.1
	May	19.6	33.0	7.1	3.0	8.6	0.5	168.6
	June	26.8	33.7	8.4	2.5	9.6	5.2	196.7
	July	27.1	44.7	7.3	2.3	7.9	4.5	162.2
	August	25.3	47.0	5.9	2.1	8.6	0.4	141.5
	September	20.4	49.4	5.5	2.0	8.9	11.9	103.1
	October	13.4	48.9	3.0	1.3	8.6	0.0	45.6

The test plot was sown on 9 April 2022 and 11 April 2023. The 'Zhong 619' (Breeding by the Chinese Academy of Agricultural Sciences, provided by the Xinjiang Academy of Agricultural Reclamation Sciences, Shihezi, China) was selected as the test material, and the wide and narrow row planting mode of non-film deepening and spot sowing (sowing depth of 3.5 cm) was adopted. The wide row spacing was 66 cm, the narrow row spacing was 10 cm, the plant spacing was 10 cm, and the theoretical number of holes was 239,200 holes·hm^{-2}. The drip irrigation belt was placed in the middle of the narrow row and buried shallowly at 3 cm. The emitter spacing was 30 cm, and the emitter flow was 2.8 L·h^{-1}. Before sowing, 180 mm alkali compression irrigation was used to store soil moisture. An amount of 600 kg·hm^{-2} of NPK compound fertilizer (19-17-6) was evenly applied before artificial plowing, and the depth was 25 cm. Before sowing, 33% pendimethalin EC (Shandong Lebang Chemical Co., Ltd., Jinan, China) was sprayed with 2.25 L·hm^{-2} and mixed with soil for 3 cm to control weeds. During the growth period, urea 600 kg·hm^{-2}, high-phosphorus ternary compound water-soluble fertilizer (10-30-10 + TE) 300 kg·hm^{-2} and high-potassium ternary compound water-soluble fertilizer (12-8-30 + TE) 225 kg·hm^{-2} were applied with water drops. The top was topped on July 15, and the chemical control was carried out three times at the full bud stage, the first flowering stage and the full flowering stage; the dosage of 98% mepiquat chloride wettable powder (DPC, Dezhou Huisheng Agricultural Technology Co., Ltd., Dezhou, China) was 22.5 g·hm^{-2}, 37.5 g·hm^{-2} and 120 g·hm^{-2}, respectively. Other field management practices were the same as those of the local field.

2.2. Experimental Design

In arid areas, the normal growth of crops can be ensured through irrigation. When irrigation meets 100% of evapotranspiration (ET_C), crops can give full play to their maximum production performance. However, in actual production, water is limited. In order to ensure high water-use efficiency, deficit irrigation is often required. In Southern Xinjiang, drip irrigation of 450 mm is generally used to save water and achieve a high yield. In order to explore the root development characteristics of filmless cotton under different water supplies, a single-factor randomized block experiment based on crop evapotranspiration was carried out. The area of each plot was 10 m × 4.5 m = 45 m^2. Five drip quotas were set for the treatment without film mulching: 300 mm, 375 mm, 450 mm, 525 mm and 600 mm, respectively, representing different water stress degrees. Relative to 100% water demand (ET_C) of cotton, these are 0.46 ET_C, 0.63 ET_C, 0.74 ET_C, 0.85 ET_C and 1.00 ET_C in 2022, and 0.44 ET_C, 0.60 ET_C, 0.71 ET_C, 0.82 ET_C and 0.97 ET_C in 2023, respectively, with 450 mm drip irrigation under film (0.80 ET_C in 2022 and 0.77 ET_C in 2023) as the control. The above water treatments are represented by W1, W2, W3, W4, W5 and WCK, respectively. There were 6 treatments and 18 cells in total, which were repeated 3 times. Each plot was separated by impermeable board (PVC polyester board) with an isolation depth of 80 cm to prevent leakage. Due to the use of non-film mulching cultivation, the soil water was dispersed and lost rapidly. According to the characteristics of water consumption by cotton stage, during the growth period, there were 9 occasions of drip irrigation in the proportion of 0.1:0.1:0.1:0.12:0.12:0.14:0.12:0.1:0.1:0.1:0.1, respectively, at triple leaf stage, pregnant bud stage, initial bud stage, full bud stage, initial flower stage, full flowering stage, late flowering stage, initial boll stage and full boll stage (Table 2).

Table 2. Stage water demand (ET_C), drip irrigation time and its setting.

Phenological Phases	Time Ranges/(M/D)		ET_C/mm		Water Treatment/mm					
	2022	2023	2022	2023	W1	W2	W3	W4	W5	WCK
TLS	21 April–15 May	24 April–17 May	63	51	30	37.5	45	52.5	60	45
PBS	15 May–28 May	18 May–31 May	59	62	30	37.5	45	52.5	60	45
IBS	29 May–14 June	1 June–15 June	80	75	30	37.5	45	52.5	60	45
FBS	15 June–1 July	16 June–30 June	71	88	36	45	54	63	72	54
IFS	2 July–11 July	1 July–13 July	74	55	36	45	54	63	72	54
FFS	12 July–24 July	14 July–26 July	69	87	42	52.5	63	73.5	84	63
LFS	25 July–4 August	27 July–6 August	63	59	36	45	54	63	72	54
FBoS	5 August–18 August	7 August–21 August	55	76	30	37.5	45	52.5	60	45
FBoS	19 August–15 September	22 August–17 September	61	83	30	37.5	45	52.5	60	45
	21 April–15 September	24 April–17 September	595	636	300	375	450	525	600	450

Note: TLS, PBS, IBS, FBS, IFS, FFS, LFS, IBoS and FBoS represent triple leaf stage, pregnant bud stage, initial bud stage, full bud stage, initial flower stage, full flowering stage, late flowering stage, initial boll stage and full boll stage, respectively. ET_C is 100% of crop evapotranspiration [13], and its calculation formula is $ET_C = ET_0 \times K_C$, where ET_0 is the reference crop evapotranspiration ($mm \cdot d^{-1}$), which is calculated by FAO Penman–Monteith equation. According to FAO 56 [14], the K_C of cotton in the initial stage (0–25 days), development stage (26–70 days), boll development stage (71–120 days) and maturity stage (121 days before harvest) are 0.45, 0.75, 1.15 and 0.70, respectively. W1, W2, W3, W4, and W5 represent irrigation of 300, 375, 450, 525, and 600 mm for filmless cotton, and WCK represents irrigation of 450 mm for filmed cotton.

2.3. Measurement Items and Methods

2.3.1. Root Index

In the critical period of cotton growth and development (bud stage, full bloom stage, boll stage and boll opening stage), the soil drilling method was used to take roots. Root drills were drilled at 10 cm, 20 cm and 30 cm away from the cotton plant in each plot. Root soil in 0–20 cm, 20–40 cm and 40–60 cm soil layers was drilled. The roots were washed with clean water in a 200-mesh gauze and selected. The roots were carefully placed on the glass plate with tweezers, scanned into TIF images with a WanShen LA-S root scanner and morphological characteristics, such as root length (RL), root surface area (RSA), root volume (RV) and root average diameter (RAD), were extracted using the image analysis software of the root scanner. Finally, the roots of each layer were put into the drying oven, killed at 105 °C for 0.5 h, dried at 65 °C to constant weight, and the dry weight was weighed. The root length density (RLD) and root weight density (RWD) were calculated according to the following formula [15]:

$$\text{Root length density (RLD, } mm \cdot m^{-3}) = L/V \quad (1)$$

$$\text{Root weight density (RWD, } g \cdot m^{-3}) = g/V \quad (2)$$

where L is the total length of root system (mm), g is the dry weight of root system (g) and V is the volume of soil drill (cm^3).

2.3.2. Yield Index

In the early frost period (25 October), cotton was tested. The number of harvested plants and total effective bolls in each plot were counted, and the number of bolls per plant and the number of harvested plants (10,000 plants·hm^{-2}) were calculated. The number of effective bolls of 20 cotton plants in total was counted in 2 rows side by side, with 10 plants in each row in the representative point. All the seed cotton of the sample plant that had opened bolls was picked and weighed, the single boll weight (g) was calculated, and the lint percentage (%) was determined. The seed cotton in the plot was collected, and the actual yield was counted together with the sample plant seed cotton, and the final yield (kg·hm^{-2}) was determined.

2.4. Data Processing

The data from two years were averaged, and the data were analyzed by Microsoft Excel 2007 and SPSS 27.0 statistical software. The SigmPlot 12.0 software was used to draw a graph. The LSD method was used to test the significance of the difference between the treatments. The significance level was set as $\alpha = 0.05$.

3. Results and Analysis

3.1. Effect of Different Irrigation Amounts on Root Growth Characteristics of Filmless Cotton

3.1.1. Effect on RLD

It can be seen from Figure 1 that the RLD was the highest at the boll stage, followed by the full flowering stage, and the smallest at the bud stage and boll opening stage. Except for the flowering period, the RLD of each treatment decreased rapidly with the deepening of the soil layer. Compared with other periods, the root system in the surface layer of the bud stage and boll opening stage was the highest, and the RLD in the 0–20 cm soil layer increased by 50.71–53.86% compared with the average RLD. At the flowering stage, the RLD increased first and then decreased with the depth of the soil layer. The average RLD of the 20–40 cm soil layer was the largest, with an increase of 19.34–31.58% compared with the average RLD. The root growth reached its maximum at the boll stage, and the number of deep roots increased. The RLD of the 40–60 cm soil layer at this stage was 68.99% of the average RLD, which was 17.41%, 23.40% and 23.18% higher than at the bud stage, full bloom stage and boll opening stage. In the horizontal distribution, the RLD of cotton decreased with the increase in the distance from the main root, which was 10 cm > 20 cm > 30 cm, and the RLD in the periphery of the flowering period was higher than that in other periods.

The average RLD in the whole period among all treatments of filmless cotton was W2 > W3 > W4 > W5 > W1 (Figure 2). The RLD of W2 was larger at each distribution point, and the RLD at a soil layer of 30 cm and 40–60 cm away from the main root increased by 24.57–106.67% and 13.66–84.22% compared with other treatments, followed by the W3 treatment, which increased by 19.41–65.91% and 21.45–62.08% compared with other treatments (except W2). The RLD of W1 was the lowest at all points. The results showed that a mild water deficit and suitable water (W2 and W3) could promote root growth, while excessive drought (W1) was disadvantageous to root growth. The average RLD of WCK was larger than that of W3, but its root distribution decreased rapidly with the deepening of the soil layer and the increase in distance from the main root. At the full bloom stage, the RLD of the 40–60 cm soil layer and 30 cm from the main root was only 77.75% and 29.14% of that of the W2 treatment.

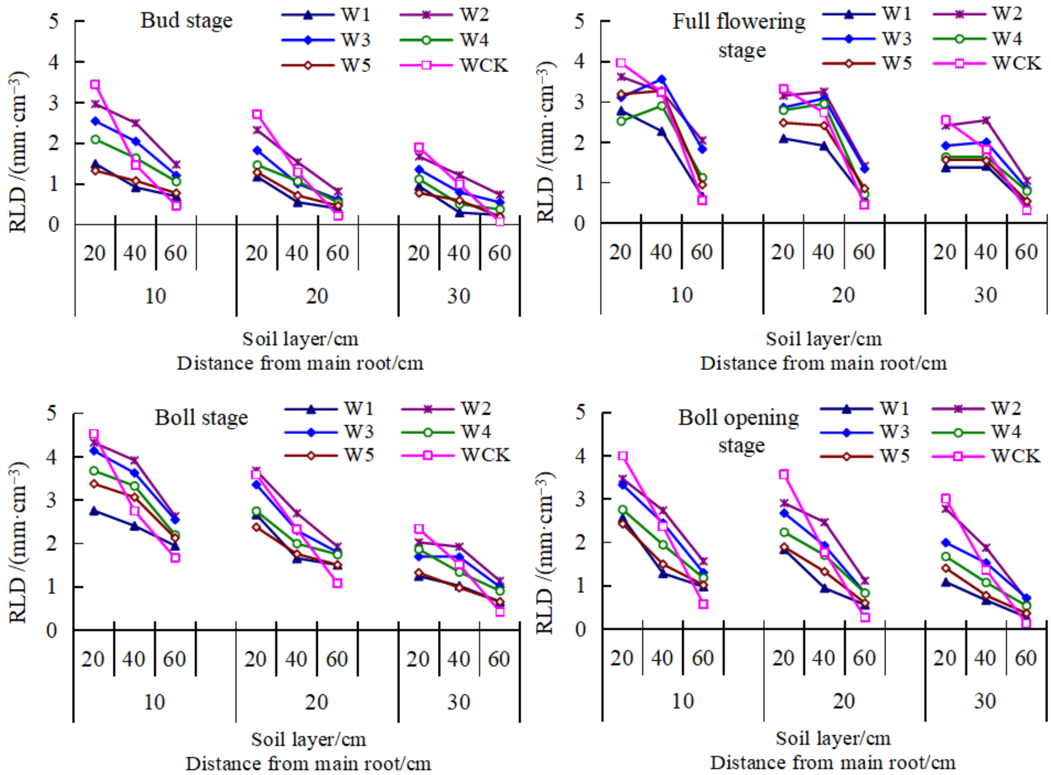

Figure 1. Spatial distribution of RLD of non-film cotton at different irrigation levels and stages. W1, W2, W3, W4 and W5 represent irrigation of 300, 375, 450, 525 and 600 mm for filmless cotton, and WCK represents irrigation of 450 mm for filmed cotton.

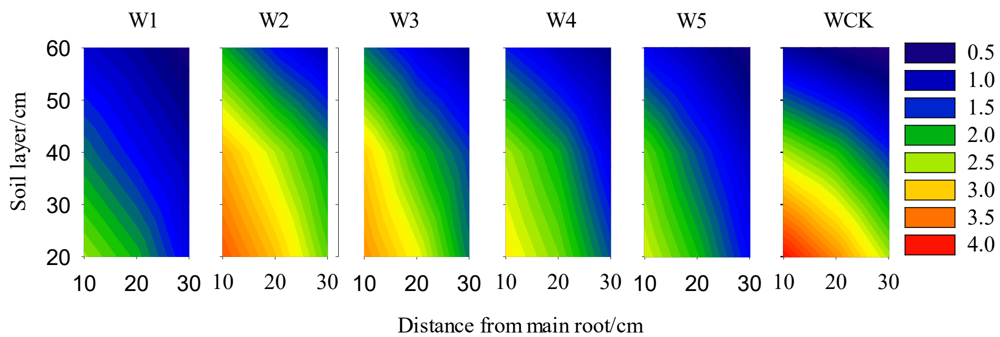

Figure 2. Spatial distribution of average RLD of non-film cotton under different irrigation amounts. W1, W2, W3, W4 and W5 represent irrigation of 300, 375, 450, 525 and 600 mm for filmless cotton, and WCK represents irrigation of 450 mm for filmed cotton.

3.1.2. Effect on RSA

It can be seen from Figure 3 that the RSA increased first and then decreased with the advance of the growth period, reaching its maximum at the boll stage and full bloom stage, with an average of 1592.9 cm^2 and 1472.3 cm^2, followed by 1041.4 cm^2 at the boll opening stage and 817.6 cm^2 at the bud stage. At the full flowering stage, the RSA of filmless cotton in 0–20 cm and 20–40 cm soil layers at 10 cm from the main root showed little difference. In addition, the RSA of filmless cotton in each treatment stage showed a rapid downward trend with the deepening of the soil layer.

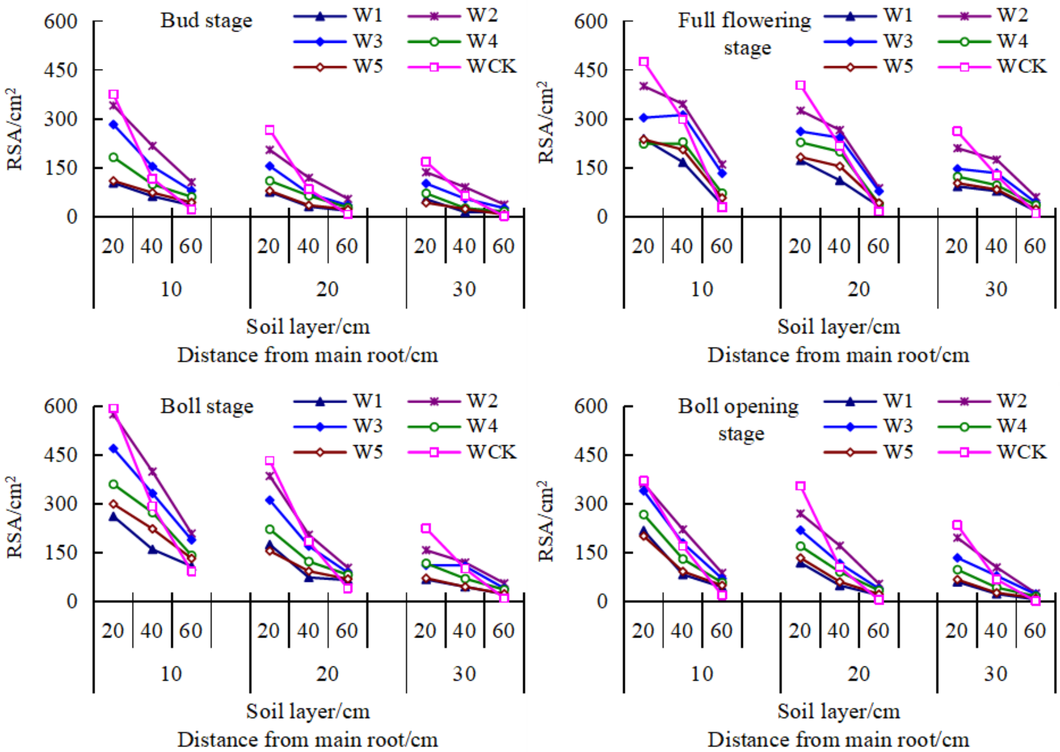

Figure 3. Spatial distribution of RSA of non-film cotton at different irrigation levels and stages. W1, W2, W3, W4 and W5 represent irrigation of 300, 375, 450, 525 and 600 mm for filmless cotton, and WCK represents irrigation of 450 mm for filmed cotton.

At the boll stage, the root distribution was deeper, and the RSA of the underlying soil decreased slightly. The RSA in the 40–60 cm soil layer accounted for 15.94% of the total RSA, which increased by 3.29% and 6.42% compared with the bud stage and boll opening stage. In the horizontal distribution, the peripheral roots were more distributed at the full flowering stage, and the RSA 20 cm and 30 cm away from the main root accounted for 34.74% and 20.71% of the total RSA, which increased by 1.99–4.70 and 1.08–5.66 percentage points compared with other periods.

The average total RSA in the whole period of each non-mulched treatment was W2 > W3 > W4 > W5 > W1 (Figure 4). The average total RSA during the whole period of W2 was 1766.07 cm^2, which was 24.80%, 65.76%, 112.39% and 137.42% higher than that of W3, W4, W5 and W1, respectively.

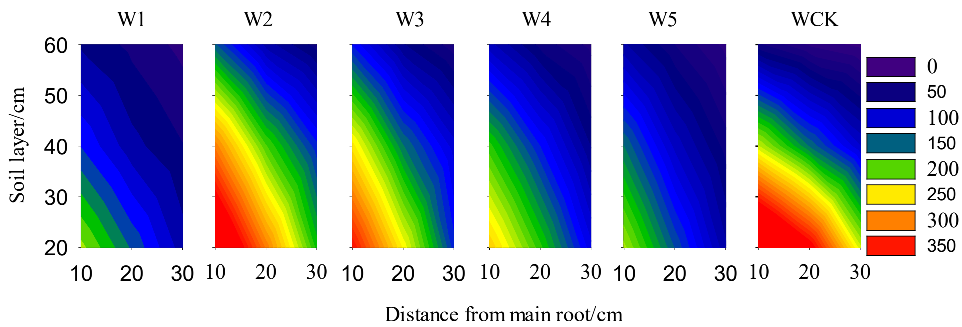

Figure 4. Spatial distribution of average RSA of non-film cotton under different irrigation amounts. W1, W2, W3, W4 and W5 represent irrigation of 300, 375, 450, 525 and 600 mm for filmless cotton, and WCK represents irrigation of 450 mm for filmed cotton.

The ratio of the average RSA in the periphery (30 cm from the main root) and middle layer (20–40 cm soil layer) of the W2 treatment to the total RSA increased by

1.64–3.41 percentage points and 0.49–4.09 percentage points compared with other treatments, while the ratio of the average RSA in the deep layer (40–60 cm soil layer) of the W3 treatment to the total RSA increased by 1.25–2.78 percentage points compared with other treatments. In addition, the total RSA of WCK was second only to that of the W2 treatment, and its surface layer (0–20 cm soil layer) accounted for the largest proportion of RSA, which was 11.50–16.31% higher than that of the non-film mulching treatment. However, with the increase in the soil layer, the RSA of WCK decreased rapidly. The total RSA of the 40–60 cm soil layer accounted for the smallest proportion of the total RSA, but the total RSA of its periphery (30 cm from the main root) was the largest, at 4.62–26.82% higher than that of the non-film mulching treatment. It can be seen that an appropriate water deficit can promote an increase in total RSA and RSA in the middle and lower layers of film-free cotton, while film mulching can promote an increase in RSA in the surface layer and periphery.

3.1.3. Effect on RAD

It can be seen from Figure 5 that, with the development of the growth period, RAD increased first and then decreased, with the peak flowering period first, followed by the boll stage, the third bud stage and the smallest boll opening stage. With the deepening of the soil layer, RAD decreased rapidly. The coefficient of variation (CV) of RAD in each soil layer was 23.74%, 24.47%, 28.13% and 35.44% at the bud stage, full bloom stage, boll stage and boll opening stage, respectively, indicating that the decline of RAD in deep soil accelerated with the advance of the growth stage. In the horizontal distribution, RAD decreased with the increase in distance from the main root. The full-term RAD of 10 cm from the main root was 0.92 mm, which was 20.25% and 44.31% higher than that of 20 cm and 30 cm. The maximum RAD was 1.03 mm at the distance of 10 cm from the taproot at the boll stage, and it also decreased fastest with the increase in the distance from the taproot.

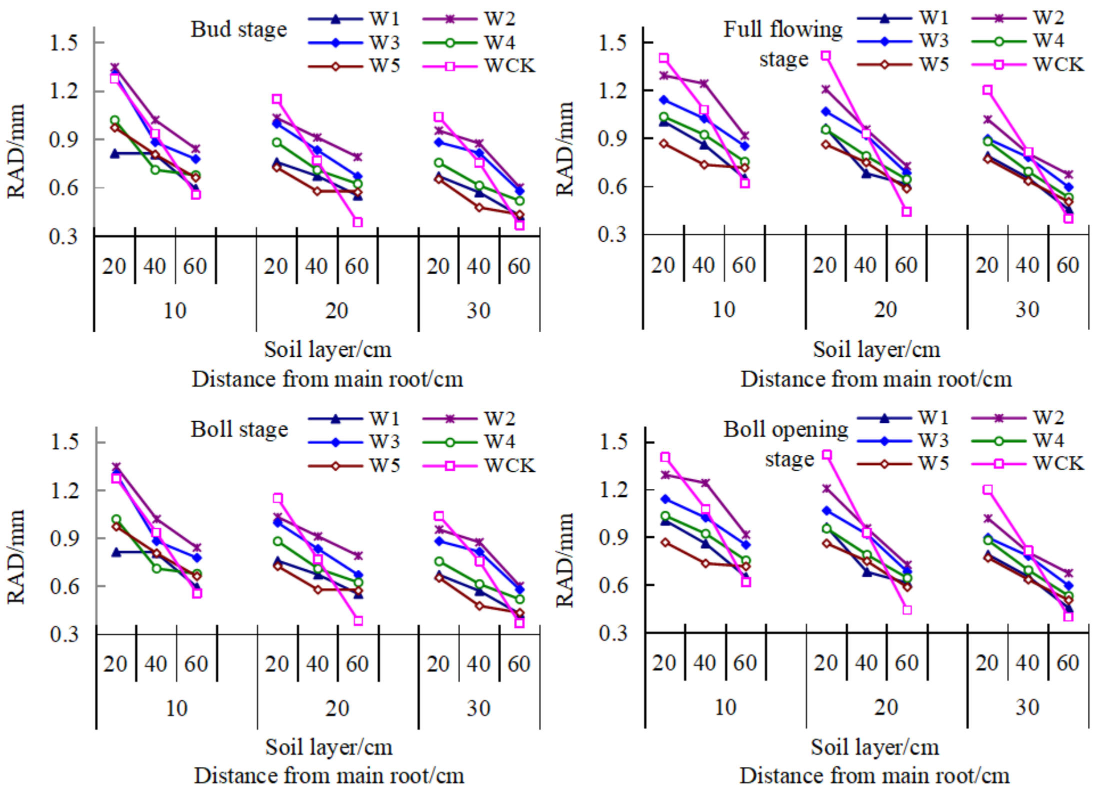

Figure 5. Spatial distribution of RAD of non-film cotton at different irrigation levels and stages. W1, W2, W3, W4 and W5 represent irrigation of 300, 375, 450, 525 and 600 mm for filmless cotton, and WCK represents irrigation of 450 mm for filmed cotton.

The RAD of each non-mulched treatment at each stage was W2 > W3 > W4 > W1 > W5 (Figure 6), and the RAD of the whole period of W2 treatment was 0.92 mm, which was 9.58%, 24.14%, 38.43% and 38.67% higher than that of W3, W4, W1 and W5, respectively, and the RAD of each soil layer and different distances from the main root was also the largest, followed by W3 treatment. The RAD of WCK was second only to W3, and its RAD in the 0–40 cm soil layer, the 20–40 cm soil layer and at each distance from the main root was second only to W2, while the RAD in the 40–60 cm soil layer was the smallest, only 58.82% of W2. That is to say, the appropriate water supply of filmless cotton can promote the uniform distribution of roots in all layers of soil, while the deep root of filmed cotton becomes thinner.

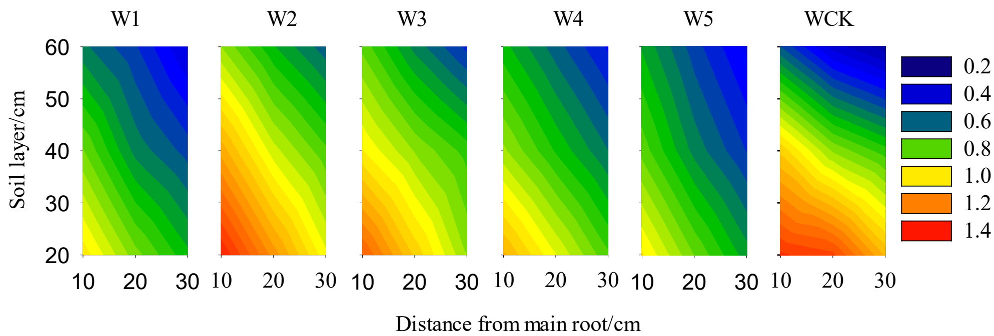

Figure 6. Spatial distribution of RDA of non-film cotton under different irrigation amounts. W1, W2, W3, W4 and W5 represent irrigation of 300, 375, 4500, 525 and 600 mm for filmless cotton, and WCK represents irrigation of 450 mm for filmed cotton.

3.1.4. Effect on RV

It can be seen from Figure 7 that the RV increases first and then decreases with the growth period, and the overall performance was as follows: boll stage > full bloom stage > boll opening stage > bud stage. With the deepening of the soil layer, the RV rate decreased, and the proportion of RV to total RV in the 0–20 cm soil layer at the boll opening stage, the 20–40 cm soil layer at the flowering stage and the 40–60 cm soil layer at the boll setting stage was the largest compared with other soil layers. In the horizontal distribution, the further away from the main root, the smaller the RV. The RV at 20 cm and 30 cm away from the main root in the flowering and boll stage and 10 cm away from the main root in the boll opening stage were the highest. It can be seen that at the boll stage of filmless cotton, the roots gradually extended downward and outward to expand the absorption area. After the boll opening, the lower and peripheral roots began to decline, and the proportion of upper and inner roots increased.

The average RV of each period among the treatments without film mulching was W2 > W3 > W4 > W5 > W1 (Figure 8). The average RV of W2 was 47.33 cm^3, which was 36.78%, 105.33%, 193.60% and 219.68% higher than that of W3, W4, W1 and W5, respectively. The average RV of W2 in each soil layer and at different distances from the main root was also the largest, followed by W3, and W1 was the smallest. The average RV of WCK in the whole period reached 44.98 cm^3, second only to W2. The RV of WCK at 10 cm from the main root and in the 20–40 cm soil layer was second only to W2. The RV of WCK at 20 cm and 30 cm from the main root and in the 0–20 cm soil layer was the largest, while the RV of the 40–60 cm soil layer was the smallest. It can be seen that the W2 and W3 treatments can expand the distribution range of the root system of film-free cotton in the soil, while film mulching planting mainly promotes the development of the root system on the surface and periphery of cotton.

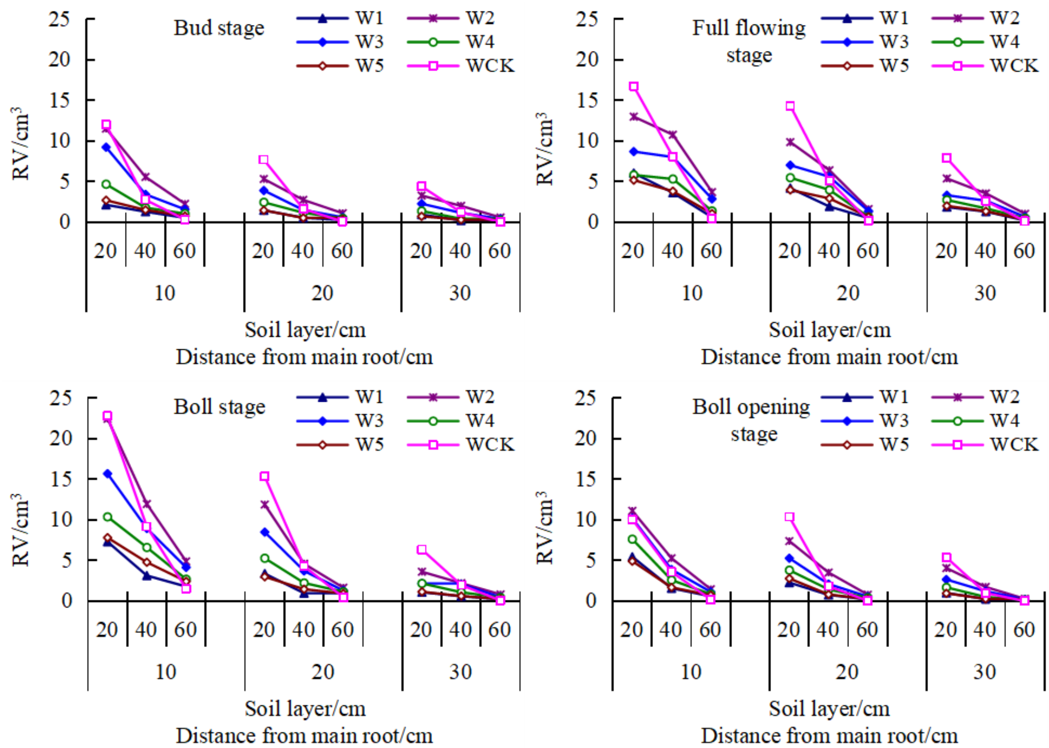

Figure 7. Spatial distribution of RV of non-film cotton at different irrigation levels and stages. W1, W2, W3, W4 and W5 represent irrigation of 300, 375, 450, 525 and 600 mm for filmless cotton, and WCK represents irrigation of 450 mm for filmed cotton.

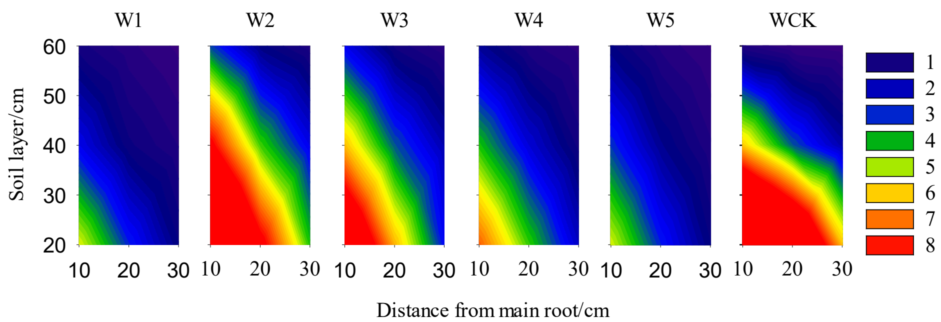

Figure 8. Spatial distribution of average RV of non-film cotton under different irrigation amounts. W1, W2, W3, W4 and W5 represent irrigation of 300, 375, 450, 525 and 600 mm for filmless cotton, and WCK represents irrigation of 450 mm for filmed cotton.

3.1.5. Effect on RWD

It can be seen from Figure 9 that the RWD increases first and then decreases with the growth period, reaching the maximum at the peak flowering stage, followed by the boll stage, and the minimum at the boll opening stage. With the deepening of the soil layer, the RWD decreased rapidly, and the CV value of average RWD in each soil layer was 26.72%, 26.91%, 32.27% and 40.15% at the bud stage, full bloom stage, boll stage and boll opening stage, respectively, indicating that the average RWD in deep soil decreased rapidly with the growth stage. The RWD of the 0–20 cm soil layer at the boll stage and the 20–40 cm and 40–60 cm soil layers at the flowering stage were the largest compared with other treatments. Under the horizontal distribution, the RWD decreased with the increase in the distance from the main root, and the RWD at 10 cm from the main root at the boll stage and 20 cm and 30 cm from the main root at the full bloom stage was the highest, and the RWD at the boll opening stage was the lowest. It can be seen that the full bloom stage is the key period for root expansion, and then the root gradually aged, the peripheral root decreased and the RWD decreased.

The average RWD of each period among the treatments without film mulching was W2 > W3 > W4 > W1 > W5 (Figure 10), and the average RWD of W2 was 0.2619 g·cm^{-3}, which was 10.85%, 27.32%, 43.88% and 45.30% higher than that of W3, W4, W5 and W1, respectively, and its average RV in each soil layer and at different distances from the main root was also the largest, followed by W3 and W5. The average RWD of WCK in the whole period reached 0.2368 g·cm^{-3}, second only to W2. The WCK's spatial distribution difference in RWD compared with other treatments was consistent with the RV, indicating that the appropriate water treatment promoted the root expansion of filmless cotton and increased the RWD while increasing the peripheral and deep RV.

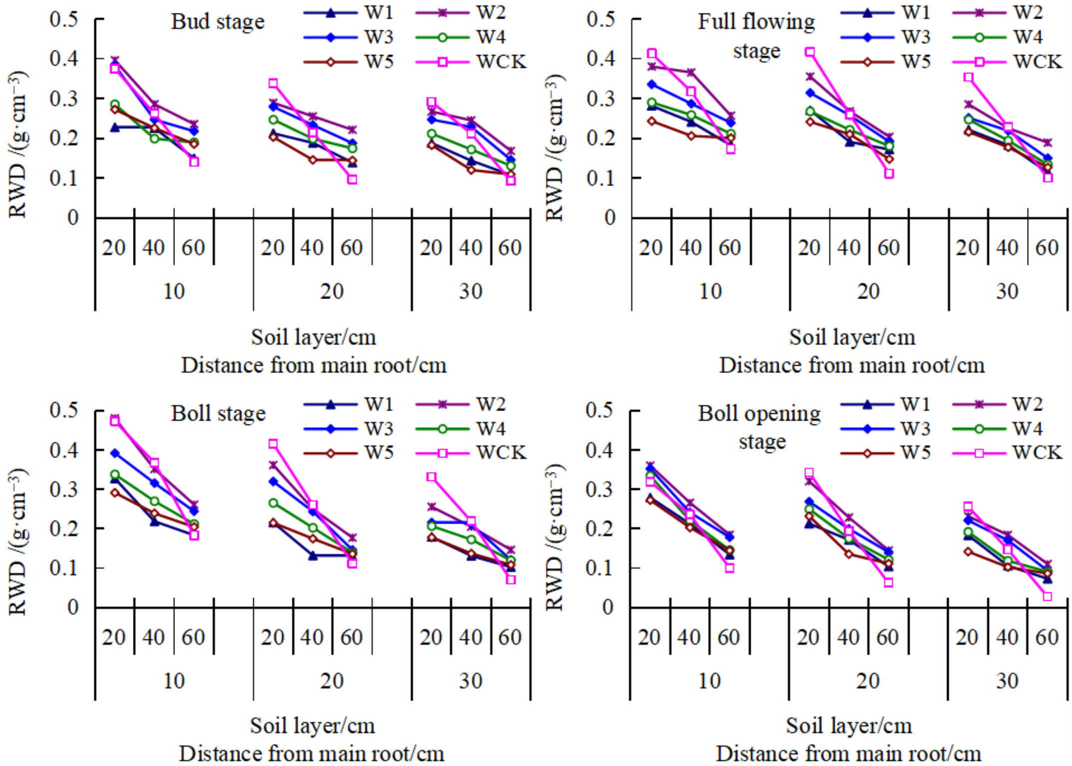

Figure 9. Spatial distribution of RWD of non-film cotton at different irrigation levels and stages. W1, W2, W3, W4 and W5 represent irrigation of 300, 375, 450, 525 and 600 mm for filmless cotton, and WCK represents irrigation of 450 mm for filmed cotton.

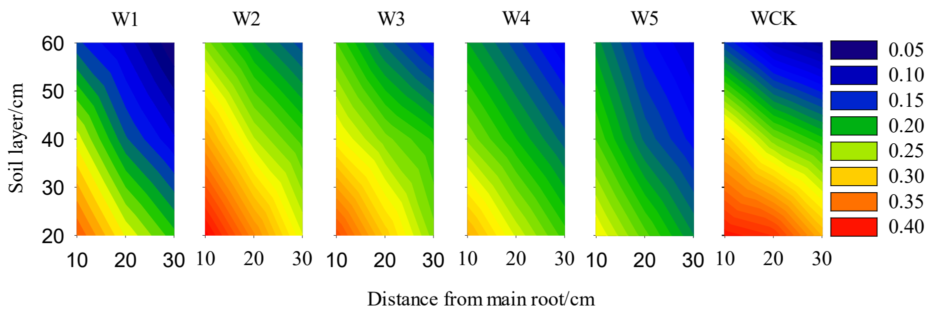

Figure 10. Spatial distribution of average RWD of non-film cotton under different irrigation amounts. W1, W2, W3, W4 and W5 represent irrigation of 300, 375, 450, 525 and 600 mm for filmless cotton, and WCK represents irrigation of 450 mm for filmed cotton.

3.2. Effect of Different Irrigation Amounts on Yield and Yield Components of Filmless Cotton

It can be seen from Table 3 that the single boll weight and boll number per plant of filmless cotton increased first and then decreased with the increase in irrigation water. The single boll weight, boll number per plant and seed cotton yield of W3 were the largest, reaching 5.06 g, 5.07 and 4833.25 kg·hm^{-2}, respectively. The single boll weight was not significantly different from W4 and W5, but it was significantly different from W1 and W2. The boll number per plant of filmless cotton was significantly higher than that of other non-mulched treatments, while the seed cotton yield was significantly different from other non-mulched treatments except W4. In addition, too little irrigation also affected the number of harvested plants, and the number of harvested plants in W1 was significantly lower than that in other treatments. It can be seen that an appropriate irrigation amount is beneficial to increase the number of harvested plants of filmless cotton, promote the development of yield factors and improve the boll weight and boll number per plant. The yield was the highest when the irrigation amount was 450 mm, followed by 525 mm. From the comparison of the yield of filmless cotton and filmed cotton, the yield of filmless cotton was significantly lower than that of film-covered cotton, and W3 was 38.48% lower than that of WCK, which was mainly reflected in a 33.53% lower number of bolls per plant compared to WCK, with a significant difference, and the difference in single boll weight was not significant. It can be seen that whether film mulching was performed or not mainly affected the effective boll setting of cotton plants, followed by boll weight. In addition, the results of variance analysis showed that different irrigation amounts had no significant effect on lint percentage.

Table 3. Changes in yield and constituent factors of non-film cotton under different irrigation amounts.

Treatment	Single Boll Weight/g	Bolls per Plant	Number of Harvested Plants/($\times 10^4$·hm^{-2})	Seed Cotton Yield/(kg·hm^{-2})	Lint Percentage/%
W1	4.53 ± 0.27 b	3.91 ± 0.19 d	17.85 ± 1.16 a	2901.45 ± 268.25 e	39.76 ± 1.38 a
W2	4.61 ± 0.21 b	4.48 ± 0.27 c	18.17 ± 1.10 a	3701.66 ± 170.56 d	39.86 ± 1.79 a
W3	5.06 ± 0.25 a	5.07 ± 0.25 b	19.09 ± 0.85 a	4833.25 ± 237.14 b	41.03 ± 1.62 a
W4	5.04 ± 0.22 a	4.66 ± 0.13 c	19.72 ± 1.02 a	4589.14 ± 246.06 bc	40.61 ± 1.70 a
W5	5.04 ± 0.23 a	4.53 ± 0.12 c	19.14 ± 1.23 a	4303.34 ± 166.27 c	40.02 ± 1.07 a
WCK	5.13 ± 0.14 a	6.77 ± 0.33 a	19.67 ± 0.99 a	6693.25 ± 211.28 a	41.62 ± 1.71 a

Note: W1, W2, W3, W4 and W5 represent irrigation of 300, 375, 450, 525 and 600 mm for filmless cotton, and WCK represents irrigation of 450 mm for filmed cotton. The data in the table are observation values ± SD. Different lowercase letters within columns indicate significant differences indicated by LSD's test at $p < 0.05$.

The quadratic polynomial regression analysis of yield and irrigation volume was as follows:

$$Y = -0.0451W^2 + 45.4669W - 6764.8251\ (R^2 = 0.9393,\ p < 0.01) \quad (3)$$

where Y is the yield (kg·hm^{-2}) and W is the irrigation amount (mm).

By deriving the equation, the maximum yield reached 4707.01 kg·hm^{-2} when the irrigation amount was 504.62 mm (Figure 11).

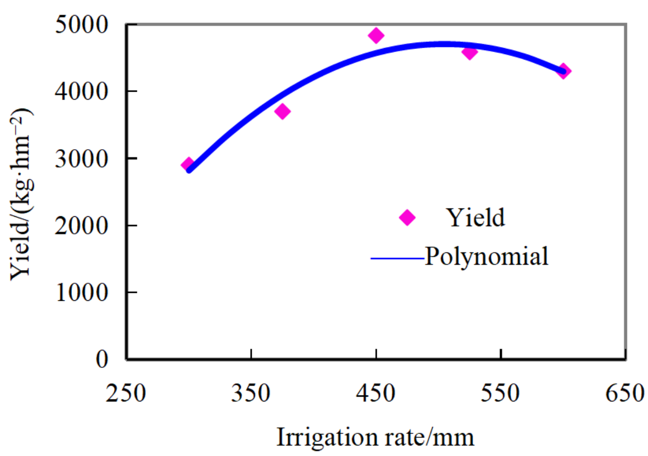

Figure 11. Yield dynamics of filmless cotton under different irrigation amounts.

3.3. Correlation Analysis between Irrigation Amount and Root Index and Yield Index

In order to further understand the relationship between irrigation amount and root index and yield index, a correlation analysis was used to analyze each index. It was found (Figure 12) that irrigation amount was negatively correlated with RLD, RSA, RV, RAD and RWD, but not significantly. The irrigation amount was positively correlated with single boll weight, boll number per plant, number of harvested plants, seed cotton yield and lint percentage, and was significantly positively correlated with single boll weight, number of harvested plants, and seed cotton yield. The depth of the soil layer is significantly negatively correlated with RLD, RSA, RV, RAD and RWD, meaning that the deeper the soil layer, the smaller the RLD, RSA, RV, RAD and RWD. The distance from the main root was negatively correlated with RLD, RSA, RV, RAD and RWD, and significantly negatively correlated with RLD, RSA and RAD. The root index was positively correlated with the boll number per plant, seed cotton yield and lint percentage, but only RWD was significantly correlated with the boll number per plant. It can be seen that the appropriate reduction in irrigation amount can promote the root growth of filmless cotton, and the root growth was inhibited when the amount of irrigation was too high. There was a weak positive correlation between the root distribution index and the yield index of filmless cotton, and the seed yield of filmless cotton could be improved by appropriately increasing the amount of irrigation. It can be seen that determining the appropriate amount of irrigation and coordinating the balance between root growth and yield formation are the keys to improving the yield of filmless cotton.

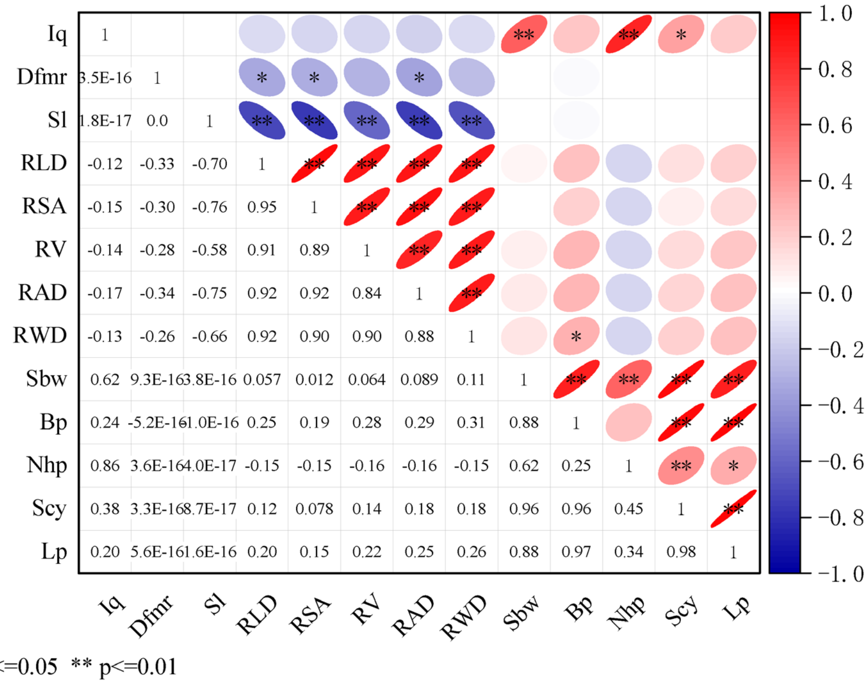

Figure 12. Correlation analysis of root system indicators and yield indicators of non-film cotton. In the above figure, Iq: irrigation quantity, Dfmr: distance from main root, Sl: soil layer, RLD: root length density, RSA: root surface area, RV: root volume, RID: root average diameter, RWD: root weight density, Sbw: single boll weight, Bp: bolls per plant, Nhp: number of harvested plants, Scy: seed cotton yield, Lp; lint percentage.

4. Discussion

Plant leaf senescence is coordinated with root growth [16], and canopy growth directly reflects the quality of root growth. In this experiment, the leaf area index (LAI) of the population at each stage of filmless cotton was in the order of boll stage > full bloom stage > boll opening stage > bud stage, and its root index showed a corresponding trend. The peak of RLD, RSA, RAD and RV were all in the boll stage, which was later than that of filmed cotton [17]. The characteristic peak of the root system of filmed cotton was in the full bloom stage, which was larger than that of filmless cotton, but the characteristic value of the root system at the boll opening stage was smaller than that of filmless cotton, which may be related to the different effects of film mulching on its growth [12].

A total of 85% of cotton roots are distributed in the 0–40 cm soil layer, and their nutrient and water absorption are also in this area [18]. When a water deficit occurs, the shallow roots in the soil decrease and the roots are rooted down. With the aggravation of the water deficit, the coordination ability of roots to actively adapt to the environment decreases, resulting in the reduction in RL, RSA and RV, and the growth and development of roots are inhibited [19]. Li et al. [8] showed that water stress inhibited the growth of cotton roots at the flowering and bolling stage, their RL, RSA and RV were significantly lower than those in normal water conditions and the root length and distribution ratio in the 0–40 cm soil layer were the most affected, resulting in the root being rooted and growing deep under the soil. This test result also reflected this feature. It is generally believed that [7,20], under certain water stress, the crop root system will produce stress-resistant growth, the root system will become larger, the root layer will deepen and the RLD, RSA, RAD, RV and RWD will increase but that a deep drought will inhibit the growth of the cotton root system. When the amount of irrigation is too much, the water will arrive too late to be consumed, the soil permeability will become poor, the root system will induce water-repellent growth [21,22] and the root volume will reduce or even die. In this study, the roots under the W2 and W3 treatments developed well and were widely distributed in the soil, and the root indexes were large, indicating that appropriate drought or appropriate water promoted the root development of filmless cotton, while too little water (W1) or too much water (W5) significantly affected the root growth and its spatial distribution in the soil was reduced, which was not conducive to the development of root function [23,24]. The RLD, RSA, RAD, RV and RWD of cotton were the largest in the 0–20 cm soil layer and 10 cm away from the main root, which shows a significant downward trend with the deepening of the soil layer and the increase in the distance from the main root, which is consistent with the results of previous studies [25,26]. The difference is that the vertical decline of the root index of filmless cotton is significantly less than that of filmed cotton, while the horizontal decline is greater than that of filmed cotton. That is to say, the root system of filmless cotton is highly distributed in the deep soil and less distributed around the surface, which is also one of the reasons why the root system of filmless cotton is deeper and less prone to premature senescence in the later stage [27,28].

The effect of water on cotton yield follows the law of diminishing returns. Either too much or too little water will reduce the weight of cotton bolls and the number of bolls per plant, resulting in cotton yield reduction. The effect of a water deficit on cotton yield and its components is greater than that of excessive water [29]. In this study, the differences in the coefficient of variation between water deficit treatment and excessive water treatment are 1.24% for single boll weight, 7.61% for bolls per plant and 12.59% for seed cotton, which are lower than that of filmed cotton [30]. It can be seen that the effect of water stress on cotton yield and its components under cultivation without film mulching was less than that under cultivation with film mulching, which may be related to the deeper root distribution and slower senescence in the later stage of cotton without film mulching [31]. In addition, this study found that the final yield under the W2 treatment with better root growth and spatial distribution was lower than that under the W3 treatment, which may be related to the fact that water stress promoted root development and rooting, resulting in the "redundant" growth of roots [32,33] and reducing the proportion of total biomass to the aboveground part.

Like film-covered cotton [34,35], the yield of the film-free cotton and irrigation amount had a peak line change relationship in the polynomial equation, and the yield of moderate water in the W3 treatment was the highest. The difference is that the suitable irrigation amount of filmless cotton in Southern Xinjiang was 450 mm, and the irrigation amount of the simulation equation for the maximum yield was 504.62 mm, while the economic irrigation amount of filmed cotton is generally 370 mm [36]. Compared with film-covered cotton, the yield of filmless cotton increased by 21.62–33.53%, which is similar to the research results of Wang [37], because the film-free mulching increases the field evaporation and decreases the water-holding capacity of the root zone. In addition, the yield of each irrigation treatment of filmless cotton was significantly lower than that of the filmed treatment, WCK. It can be seen that film mulching cultivation has indeed improved the ecological environment of cotton roots and crowns [3], which is conducive to the coordinated growth of cotton, while film-free cultivation has a certain role in promoting the development of roots in deep and peripheral soil layers. In production, it is necessary to pay attention to reasonable water and fertilizer management and the application of scientific control technology and give full play to the characteristics of film-free cotton roots, such as efficient utilization of deep soil water and nutrients and no premature root senescence in the later stage, so as to further improve the yield.

In view of the occurrence of weeds in cotton fields, film mulching can effectively inhibit their growth, while no film mulching may lead to weed damage. In this experiment, herbicide soil treatment and drip irrigation point source water supply were used before sowing. In addition, the climate in the experimental area was dry and the rainfall amount was low, so there was no overgrowth of weeds in the field.

5. Conclusions

Moderate drought could promote the root growth of filmless cotton, with the treatment of 375 mm having the best effect, and the root distribution in deep and peripheral soil layers was significantly increased compared with the treatment of film mulching. The maximum yield of seed cotton was observed in the treatment of 450 mm, which showed that the effect of water on root growth and yield of filmless cotton was inconsistent. The yield of filmless cotton was significantly lower than that of film-covered cotton. Under the condition of an appropriate irrigation amount (450 mm), a higher yield could be obtained through scientific regulation, giving full play to the advantages of root growth of filmless cotton, promoting the accumulation and optimal distribution of effective substances and bringing improvements in chemical weeding.

Author Contributions: J.W. and Y.W. initiated and designed this study. Y.W., W.L. and B.W. conducted experiments and collected data. Y.W., W.L. and F.S. analyzed the data and wrote the manuscript. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Data are available from the first author or the corresponding author on reasonable request.

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