Response of spatial structure of cotton root to soil-wetting patterns under mulched drip irrigation

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Abstract: The matching relationship between the spatial structure of cotton cluster root systems and soil-wetting patterns under mulched drip irrigation forms the theoretical basis for the technical design of mulched drip irrigation. A 2-year field experiment was conducted, in which different soil-wetting patterns were produced by setting different emitter discharge rates. The envelopes of cotton cluster root length densities were derived using the topological methodology and used to examine the effects of different soil-wetting patterns on the spatial structure of root systems and water uptake capacity within row spaces. The results showed that the root systems in rows of cotton grown under narrower and deeper soil-wetting patterns exhibited a single-peak distribution, while those under wider and shallower soil-wetting patterns exhibited a two-peak distribution. Furthermore, cotton rows grown near mulch edges experienced lower moisture stress, and wider and shallower soil-wetting patterns contributed to greater root growth rates in the vertical direction and resulted in more even potential water uptake capacities. The findings of this study revealed that wider and shallower soil-wetting patterns were more desirable for mulched drip irrigation of cotton and should be considered in the technical design of drip irrigation systems.

Keywords: mulched drip irrigation, soil-wetting pattern, envelopes of cotton cluster root length densities, soil matrix suction, potential root water uptake capacity

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1 Introduction

The root system of crops is a major organ for supplying the water and nutrients necessary for growth and serves as an important support for securing growth stability[1]. Thus, the reasonable root system architecture is a fundamental factor for securing the growth of crops. In the case of drip irrigation, in which the soil is only locally wetted, soil-wetting patterns serve as a constraint on root system architecture[2] and affect the growth of the aboveground parts of crops. Therefore, drip irrigation, and more specifically the soil-wetting patterns, should be designed according to the root system architecture required for crop growth[3]. The water uptake of a crop generally depends on crop root length density[4], the root length density distribution of individual plants or clusters of plants at a given stage of growth has typically been described using contour maps of root length density[5]. Alternatively, the variation in root length density in relation to the root growth depth of individual crop plants during reproduction can be described using a negative exponential function[6,7]. However, for crop plant clusters, the root length density distribution is uneven in horizontal space, and also varies as root growth depth increases. Accordingly, the changes in root length density cannot be completely represented using contour maps of root length density or a negative exponential function. However, the topological method can be used to describe both the spatial distribution and temporal variation process (with increasing root growth depth) of the root length density of crop clusters, and this method can also closely reflect water uptake capacity[8] and characterizes the stability[9] of crop clusters. The concept of the root length density envelope of cotton clusters has been proposed in the former study. It was taken as the basis to analyze the root length density distribution of cotton clusters under mulched drip irrigation. Moreover, the variations in root growth depth were also assessed concerning the soil-wetting patterns produced by drip irrigation.

The spatial structure of the root could illustrate the shape of the root system and its changing characteristics with the soil environment. The adaptability of roots to the environment is reflected by the architecture of root systems, and in this regard, a number of notable advances have been made in recent years in terms of our understanding of the relationships between crop root length density and soil-wetting patterns[10-12]. The growth-development process of root systems is closely related to soil moisture distribution[13]. Fang et al.[2] pointed out that, under drip irrigation, soil matrix suction is closely related to emitter flow rate, crop roots are markedly constrained by the soil-wetting

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patterns, and roots grow toward soil with higher moisture contents under emitters. Wang et al.[14] and Li et al.[15] obtained different soil-wetting patterns by controlling the emitter flow rate and found that, for cotton clusters under mulched drip irrigation, the root system is uniformly distributed if the soil-wetting pattern is wider and shallower, whereas it is mainly distributed under the drip irrigation line if the soil-wetting pattern is deeper and narrower. These results indicated the marked differences in water accessibility between different rows of cotton in a field[16,17]. A change in soil moisture content initially results in a change in root system physiology and when the change in soil moisture content reaches a certain degree, results in a change in the spatial structure of root systems[18]. Quantification of the root system architecture and analysis of the topological structure of root systems can be combined with water investigation. Such an approach was able to show the different root phenotypic traits in response to low water availability[19]. It is helpful to understand the distribution of root structure[20,21] and its mechanism of extension to changes in soil moisture environment[22].

Xinjiang Region is China's largest production base of upland cotton and has a high potential for production yield increases owing to its unique advantages in terms of light, climate, and land resources. In 1996, the Xinjiang Production and Construction Cooperation started developing and promoting the technique of mulched drip irrigation of cotton in order to cope with water resource shortages and to safeguard major agricultural product and strategic material security in Xinjiang[23]. The popularization of drip irrigation under mulch technology led to the rapid growth of cultivated land and development land in the watershed[24]. But owing to financial constraints, when irrigating, farmers in Xinjiang tend to minimize the number of emitters, using a single drip irrigation line to irrigate several rows of cotton. This arrangement results in a soil-wetting pattern that is too small to effectively cover the space required for the root systems of several cotton rows, which tends to be inconsistent with the technical perspective of the local irrigation design[25]. To date, no design theories for the soil-wetting patterns of drip irrigation of cotton have been reported in the literature. In this study, a topological theory was proposed and demonstrated to describe the evolution of the spatial structure of cotton cluster root systems irrigated under different soil-wetting patterns, analyze the impact on the water uptake capacity of the cotton root system, and suggest design criteria for the mulched drip irrigation of cotton. The findings of this study are expected to contribute to improving the existing design theory for mulched drip irrigation.

2 Materials and methods

2.1 Experimental site

A two-year experiment (from April 2010 to October 2011) was carried out at the water-saving irrigation experimental station (85°59′E, 44°19′N) of Shihezi University. According to data collected at the Shihezi Meteorological Station, over the past 30 years, the experimental site has had annual mean hours of sunshine of 2865 h, frost-free period of 170 d, and annual evaporation of (1342±413) mm (small evaporation pan). For the years 2010 and 2011, the annual precipitation was 114.7 mm and 122.4 mm, respectively. The soil at the experimental site is a light loam, with a physical clay (particle size<0.01 mm) content higher than 20%, a soil bulk density of 1.52 g/cm^3, an average porosity of 41.71%, a field water-holding capacity of 31.92% (moisture content by volume), and an initial salt content of 1.21 g/kg. The depth of the water table at the experimental site is greater than 8 m.

2.2 Experimental design

The experimental field was planted with cotton (Huiyuan 710) (seeded on May 1 and April 17 in 2010 and 2011, respectively). Four rows of cotton were covered with mulch, with a wider space between the inner two rows (60 cm) and a narrower space between the two side cotton rows and the two inner cotton rows (30 cm). Plant spacing was 11 cm. A labyrinth thin-wall drip irrigation line (produced by Xinjiang Tianye (Group) Co., Ltd.) was used for irrigation. The emitters were spaced at 30 cm intervals and designed with a discharge rate of 2.8 L/h and a working pressure of 10 mH_2O. Different soil-wetting pattern distributions were obtained using a previously described method[26].

In an experiment conducted in 2010, two combinations with one and three irrigation lines were respectively placed along the central line of the wider row space (as shown in Figure 2), with the emitters of lines being aligned for each combination. By increasing the number of working emitters at the water discharge points, the discharge rates could be adjusted to obtain different soil-wetting patterns. As a reference, an emitter arrangement was also examined by comprising of two drip irrigation lines placed along the central line of each narrower row space. Three emitter discharge rates were used in the experiments: 1.54 L/h (W154), 3.14 L/h (W314, reference pattern), and 5.93 L/h (W593). Similarly, three combinations with one, two, or three irrigation lines were respectively placed along the central line of the wider row space in 2011 by using three discharge rates: 1.69 L/h (W169), 3.46 L/h (W346), and 6.33 L/h (W633). Each of the soil-wetting patterns was repeated five times. Irrigation scheduling was maintained at a constant level across the different soil-wetting patterns. Table 1 shows the amount and frequency of irrigation for the different stages of cotton reproduction. In 2010 and 2011, the experimental field was fertilized with 705 kg/hm^2 and 780 kg/hm^2 of urea and 112.50 kg/hm^2 and 311.25 kg/hm^2 of potassium dihydrogen phosphate, respectively. The fertilizers were administered through the irrigation water in several doses.

Table 1 Irrigation regime for mulched drip irrigation (2010–2011)

Reproductive stage	Seedling stage	Bud stage	Early flowering stage	Peak flowering stage	Boll-opening stage
Irrigation amount /m^3·hm^{-2}	405.0	303.7	486.0	344.2	300.0
Irrigation frequency (number of times)	1	2	4	2	1

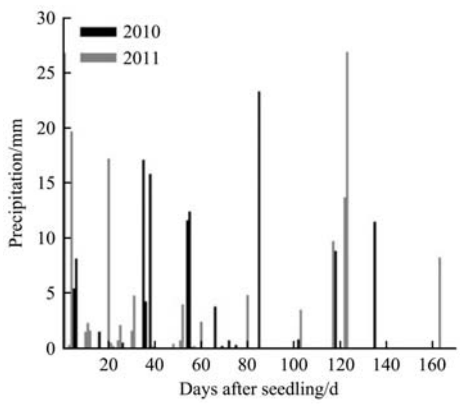


Figure 1 Precipitation recorded at the study site in 2010 and 2011

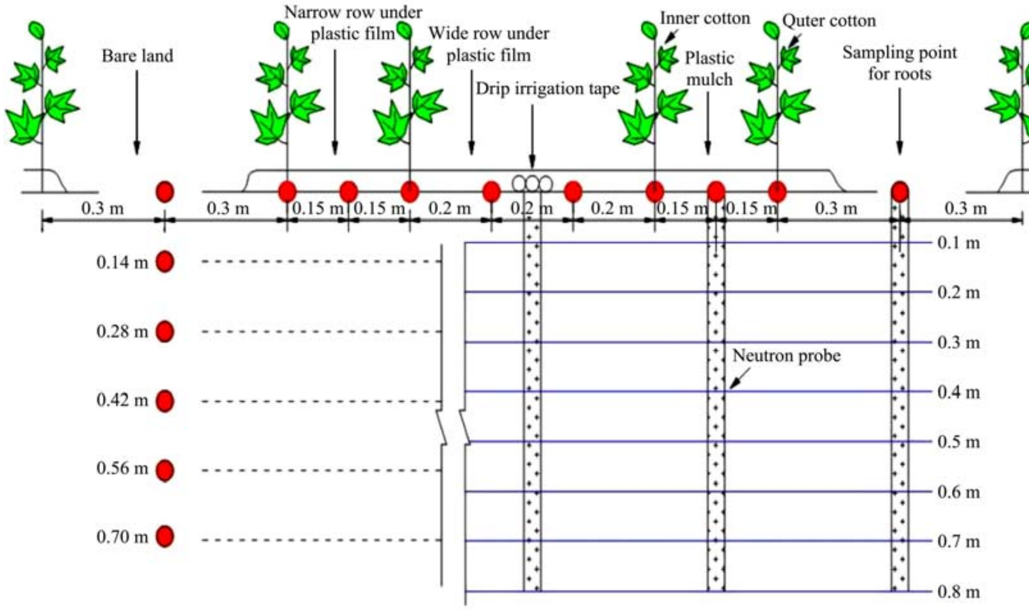


Figure 2 Schematic diagram of cotton cultivation mode under mulched drip irrigation

2.3 Sample collection

Soil moisture content was measured using the oven drying method. Before the seedlings stage, measurements were made for the upper-most 60 cm soil layer, with a sample collected for each 10 cm layer at 6 d intervals. After the seedlings stage, the moisture content in the top 30 cm of soil layer was measured by the oven drying method, using a sample collected for each 10 cm layer. The moisture content in soil layers with depths in the range of 30-130 cm was measured using a 503DR.9 neutron moisture detector, with a reading taken for each 10 cm soil layer at 3 d intervals. Five neutron detector tubes were installed for each of the soil-wetting patterns as follows: one along the central line of each of the two narrower row spaces, one along with the central wider row space, and one along the central line of bare land on either side outside the mulched area. After irrigation at the boll-opening stage, the number of neutrons in the soil layers from 30 cm to 130 cm in depth was calibrated using the oven drying method, with samples collected by soil layer at sites located 20 cm from the nearest detector tube. Fitting was performed using neutron number measurements and the corresponding soil moisture contents. Equations (1) and (2) were obtained as the calibration equations for 2010 and 2011, respectively:

$$\theta_v=0.0034N-0.4693 \qquad R^2=0.8009, n=116 \tag{1}$$

$$\theta_v=0.0033N-3.3112 \qquad R^2=0.816, n=82 \tag{2}$$

where, θ_v is the moisture content by volume, %; N is the number of neutrons.

Samples of cotton root systems were collected according to the root system distribution characteristics at different stages of cotton growth, using a root drill with a diameter of 10 cm and a depth of 14 cm. The sampling points are shown in Figure 2. Table 2 shows the detailed sampling schedule. Root system samples were collected at the following stages of cotton growth: seedling (sampling depth: 0-14 cm), bud (0-28 cm), early flowering (0-42 cm), peak flowering (0-56 cm), and boll-opening (0-70 cm, 2010; 0-84 cm, 2011). The sampling was repeated three times. The cotton roots collected were immersed in water for 24 h and then screened using a sieve with a 0.5-mm mesh diameter. The sieved roots were transferred to an oven using a pair of forceps and heated at 65°C to a constant weight. The dried roots were spread over a sheet of white paper marked with 20 cm reference lines and imaged. Root length was computed using R2V (Able Software Corp) and Photoshop, and root length density of different growing stages (corresponding depths), was computed using the following equation:

$$RLD=RL/SV \tag{3}$$

where, RLD is the root length density, m/m^3; RL is the root length, m; SV is the soil volume, m^3.

Table 2 Root system sampling schedule

Date of sampling	Seedling stage	Bud stage	Early flowering stage	Peak flowering stage	Boll-opening stage
2010	June 18	June 29	July 23	August 15	September 5
2011	June 8	July 1	July 22	August 12	September 2

Given that root systems compete with soil for access to water, an increase in soil matrix suction compounds the difficulty that root systems experience in obtaining sufficient amounts of water required for growth. Accordingly, root systems tend to develop via hydrotropism toward areas with lower soil matrix suction. Therefore, the soil matrix suction was measured in this study to characterize the environmental stress associated with root system growth. Following the completion of the reproductive stage in 2011, undisturbed soil samples were collected from the 20-30 cm soil layer, the moisture contents of which were measured using a 1500F1 bar pressure plate extractor. A soil moisture characteristic curve was subsequently fitted using soil matrix suction as follows:

$$S=635915.76e^{-36.812456\theta_v} \qquad R^2=0.997 \tag{4}$$

where, S is the soil matrix suction, kPa; θ_v is the soil moisture content by volume (ratio).

2.4 Statistical analysis

The data of Root length density were analyzed using Microsoft Excel 2010, and graphic representations of the data were produced using Surfer 10 and Matlab 6.0.

3 Results

3.1 Soil matrix suction

When the soil moisture content reaches a level that results in fractured capillaries, the water uptake capability and growth of the crop root system will be restrained. Hillel[27] found that, in most cases, the soil moisture content at capillary fracture is less than

60% of the field water-holding capacity. Under drip irrigation, different soil-wetting patterns result in different areas being subjected to capillary fracture. The soil matrix suction at capillary fracture was 0.55 MPa, which was computed according to the field water-holding capacity measurements and Equation (4). Analysis of the soil matrix suction distribution during the interval between the two irrigation applications for the flowering stage (Aug 5, Aug 13 in 2010 and July 19 and 28 in 2011) revealed that the W154 soil-wetting pattern, which did not restrain the root system growth of cotton clusters, was characterized by a narrower and deeper pattern, whereas the W593 soil-wetting pattern had a wider and shallower soil-wetting pattern.

When the different soil-wetting pattern measured during the same periods were analyzed with respect to soil matrix suction at capillary fracture, it was found that, for W154 and W593 (2010), the inner cotton rows received effective soil moisture contents, whereas the side cotton rows had inadequate soil moisture contents on the right side (as shown in Figure 3). On August 6 and 12, the average soil matrix suctions on the right side of the side cotton rows were higher than the soil matrix suction at capillary fracture by 81.6% and 23.3%, respectively, thereby restraining the water uptake of the cotton root systems.

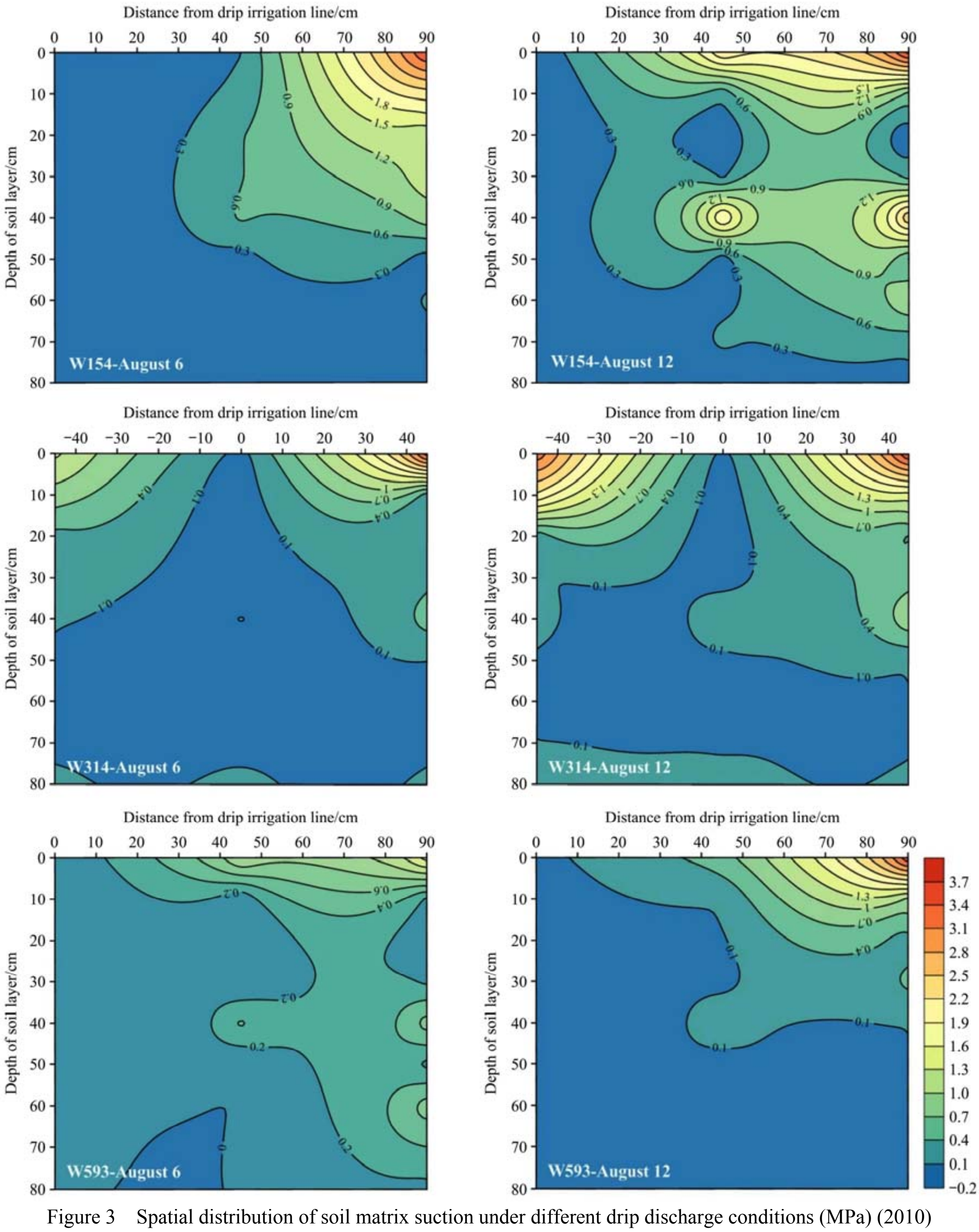


Figure 3 Spatial distribution of soil matrix suction under different drip discharge conditions (MPa) (2010)

For the W314 reference configuration, both the inner and side rows of cotton plants received adequate moisture after irrigation on August 6, whereas both these rows received inadequate moisture after irrigation on August 12, with the inner cotton rows experiencing inadequate water moisture on the left side and the side cotton rows experiencing inadequate water moisture on the right side, and with soil matrix suction being higher than the soil matrix suction at capillary fracture by 32.6% and 50.8%, respectively.

For configurations W169 and W346 (2011), the inner cotton rows experienced effective soil moisture after the irrigation on July 20, whereas the side cotton rows experienced inadequate water moisture on the right side (as shown in Figure 4). Compared with the soil matrix suction at capillary fracture, the average soil matrix suctions on the right side of the side cotton rows in the two configurations increased 191.6% and 188.1%, respectively. On July 27, the inner and side cotton rows experienced inadequate water moisture on both left and right sides, with the averages soil matrix suctions (measurements made in the wider and narrower row spaces in the mulch and bare land outside the mulched area) were higher than the soil matrix suction at capillary fracture by 161.7% and 153.5%, respectively. For configuration W633, only the side cotton rows experienced inadequate water moisture on the right side, and the degree of water moisture stress was considerably lower than that determined for any of the other configurations, with the average soil matrix suction on the right side of the side cotton rows (measurements made on July 20 and 27) being higher than the soil matrix suction at capillary fracture by 27.8%. These observations reveal that a wider and shallower soil-wetting pattern in the mulch results in lower soil matrix suction, and thereby facilitates water uptake by the cotton root system.

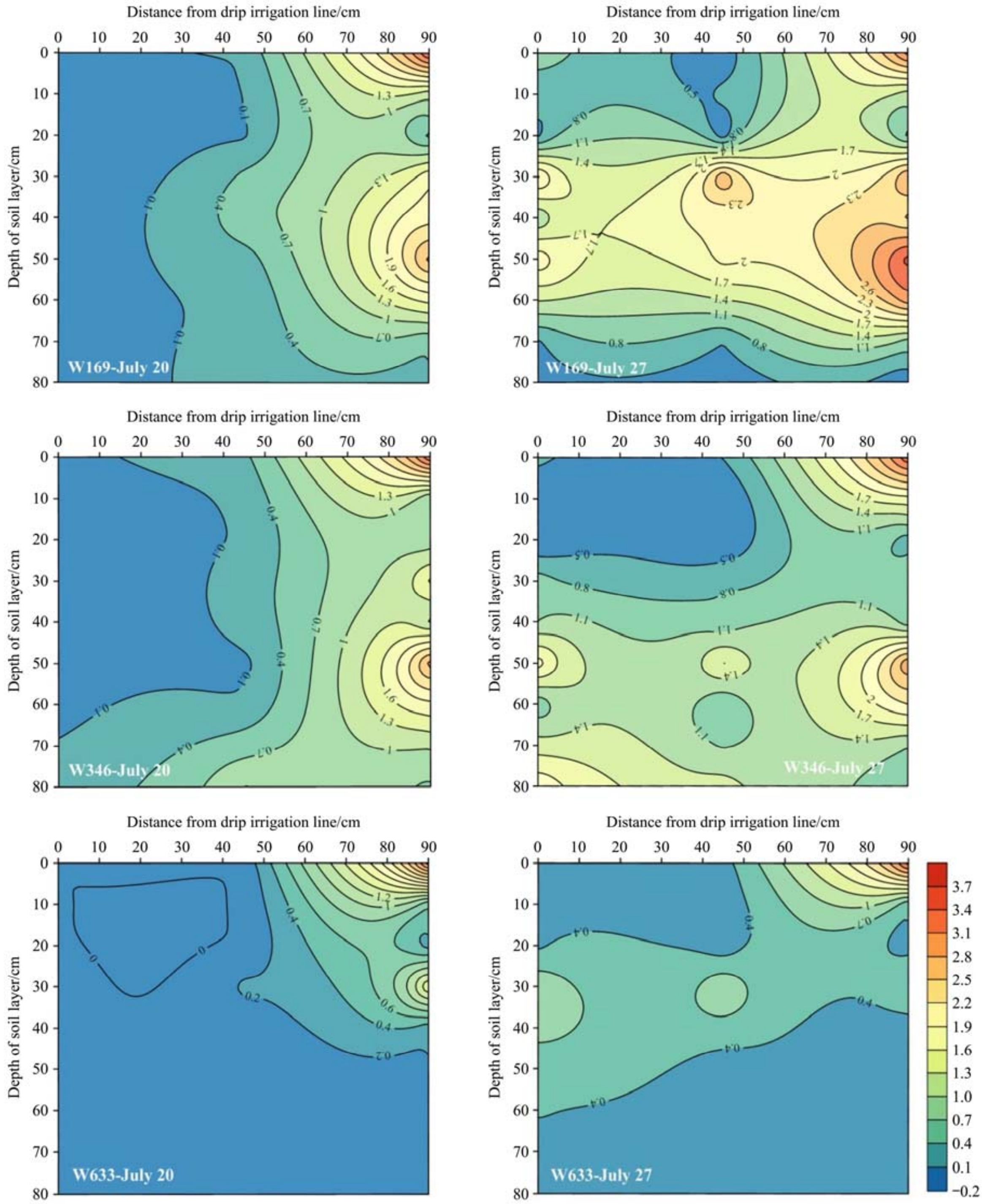
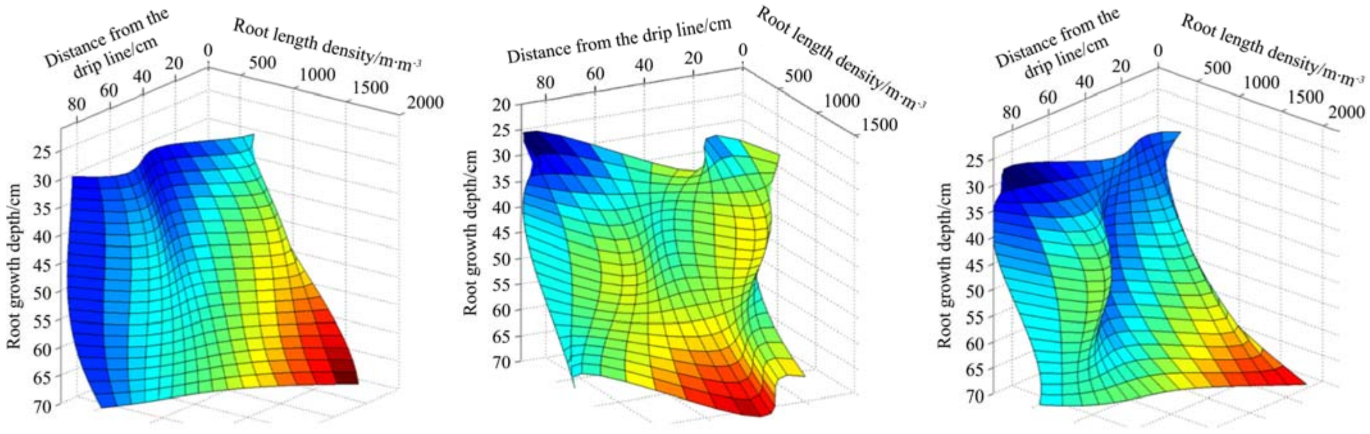


Figure 4 Spatial distribution of soil matrix suction under different drip discharge conditions (MPa) (2011)

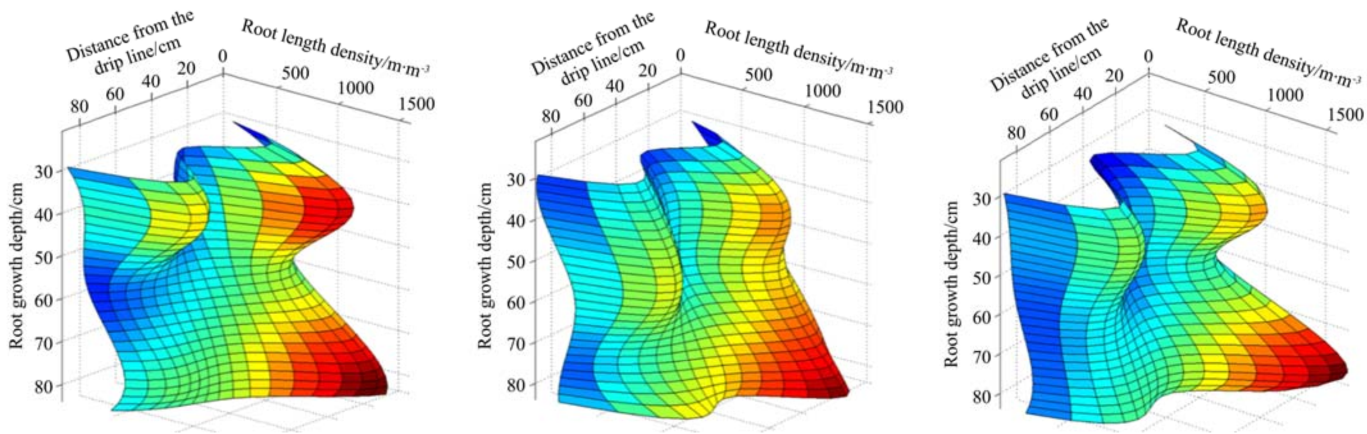
3.2 Root length density distribution

As a cotton plant grows, its root length density and root distribution shape change with an increase in root growth depth. In the present study, in order to characterize the three-dimensional distribution of the cotton root system at different growth stages, the root length density envelopes of cotton clusters were derived by determining the relationship between root densities at different sampling points and the effective depth of the root system, to obtain the envelope of root length and density at different growth stages (corresponding depths), and to construct models for root length density envelopes of cotton clusters at the different growth stages (Figures 5 and 6). The average rate of increase in the root densities of cotton in the inner and side rows at different growth stages was used to characterize the temporal changes in root system growth depth. As shown in Table 3, a change in the soil-wetting pattern does not alter the growth rate of the cotton root system in the vertical direction, and the growth rate was higher during the bud and peak flowering stages and was lower or even decreased during the early flowering and boll-opening stages. In contrast, different soil-wetting patterns resulted in different rates of increase in cotton root length density. More specifically, the average rates of increase in root length density in the vertical direction under configurations W154, W314, and W593 (2010) during the bud and peak flowering stages were 46.1%, 84.4%, and 99.7%, respectively, whereas those of configurations W169, W346, and W633 (2011) were 46.4%, 54.1%, and 66.0%, respectively. These findings according reveal that wider and shallower soil-wetting patterns facilitate water and nutrient uptake by the root system in deep layers of soil, thereby resulting in more reasonable distributions of root systems within the soil.



W154 W314 W593

Figure 5 Models of cotton cluster root length density envelopes under different soil-wetting pattern (m/m^3) (2010)



W169 W346 W633

Figure 6 Models of cotton cluster root length density envelopes under different soil-wetting pattern (m/m^3) (2011)

Table 3 Rates of root length density increase (%)

Reproductive stage	2010			2011		
	W154	W314	W593	W169	W346	W633
Seedling-bud stage	80.6	112.6	116.0	60.2	88.8	92.5
Bud–early flowering stage	15.5	12.0	18.4	–15.9	–1.9	–18.6
Early flowering-Peak flowering stage	11.5	56.1	83.4	32.6	19.4	39.5
Peak flowering-boll opening stage	7.1	–15.5	–12.1	2.8	25.8	2.5

The experimental results also showed that, for the different soil-wetting patterns, the maximum root length density in horizontal space occurred mainly in the wider row spaces and peak values were detected in the mulch at the root axes of the inner and side cotton rows (with the distances to the drip irrigation line being 30 cm and 60 cm, respectively). However, different soil-wetting patterns were found to promote different root length density distributions at these axes. For configuration W154, the root length densities of the inner cotton rows were invariably very large, whereas those of the side cotton rows were very small. Furthermore, during the seedling and bud stages, the root length density peaked at the root axes of the inner and side cotton rows, showing a two-peak distribution pattern, whereas, with continued cotton plant growth, the root length density distributions in the horizontal direction changed from a two-peak pattern during the early growth stages to a single-peak pattern, with a single peak in the inner cotton rows and a non-significant peak in the side cotton rows. The average difference between the root length densities of the inner and side cotton rows of configuration W154 was 257.7 m/m^3 (p=0.009).

For configuration W593, both the inner and side cotton rows showed significant peaks of root length density, with the difference between the root length densities of the inner and side cotton rows being 148.4 m/m^3 (p=0.56). For configuration W314, the narrower and wider row spaces had slightly different root length density distributions, with peak values mainly occurring in the inner cotton rows and the narrower row spaces, although the difference between the root length densities of the inner and side cotton rows was smaller (104.2 m/m^3, p=0.78). The patterns detected in the 2011 experiment were found to be similar to those observed in the 2010 experiment, with the differences between the root length densities of the inner and side cotton rows of configurations W169, W346, and W633 being 334.3 (p=0.014), 224.7 (p=0.22), and 216.2 m/m^3 (p=0.28), respectively. These root system distribution observations thus indicate that wider and shallower soil-wetting patterns contribute to an improved physiological architecture and a more even distribution of the root system.

3.3 Potential water-uptake capacity of root systems

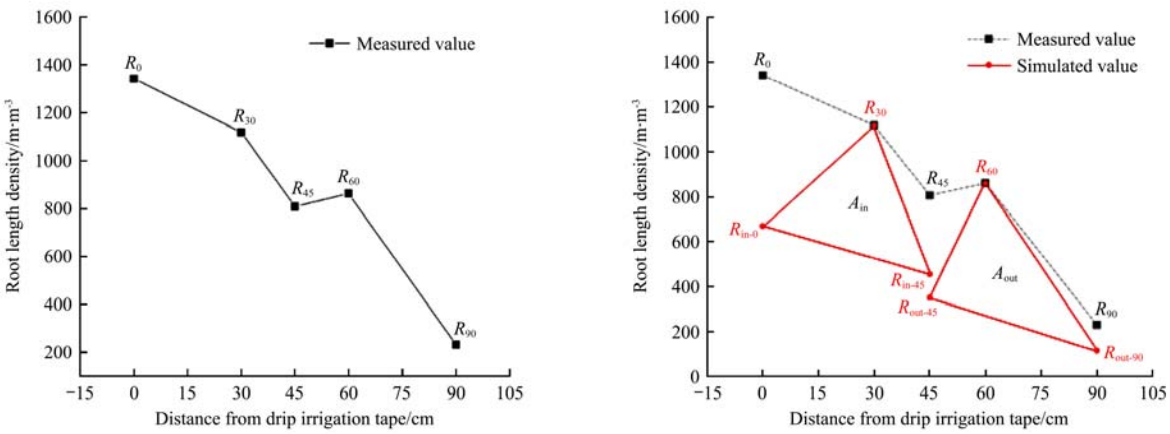
The potential water uptake capacity of a crop root system is positively related to root length density, as described in the following equation:

$$S_{\max}(t)\alpha\int_0^{L_r(t)} RLD(z,t)dz \tag{5}$$

where, $S_{\max}(t)$ is the potential water-uptake flux of the crop root system; $L_r(t)$ is the root growth depth, cm.

The model derived for the cotton cluster root length density envelope in relation to root growth depth can be integrated to indicate the maximum water uptake capacity of the cotton root system. In order to analyze the potential water uptake capacities of the inner and side cotton rows and take into account the discrete nature of the measurement data, the root length densities of the inner and side cotton rows were integrated separately.

When the spatial distribution of soil moisture is even, the single cotton root system exhibits an umbrella-shaped overall distribution[12] (Figures 5 and 6); that is, the root length distribution is symmetrical around the root axis, but its root length density and the shape of root distribution change with an increase in root growth depth. For example, on the basis of an analysis of the root length densities at distances from the drip irrigation line of 0 cm (the central wider row space), 30 cm (inner cotton rows), 45 cm (narrower row spaces), 60 cm (side cotton rows), and 90 cm (bare land outside the mulch) (designated as R_0, R_{30}, R_{45}, R_{60}, and R_{90}, respectively), the horizontal distribution of the root length density of configuration W633 (sampled on September 2, 2011) peaked at the root axes of the inner and side cotton rows (with distances from the drip irrigation line being 30 cm and 60 cm, respectively). It was found that the root systems of the cotton clusters overlap, and thus to analyze the root length density of individual cotton plants through integration of root length density, the overlapping root length densities need to be separated. For example, root sampling points are located symmetrically on both sides of drip irrigation lines. The water environment of inner and side cotton rows is basically the same in the central wider row space and bare land outside the mulch. Total root length densities measured in the wider space under the mulch and the bare land outside the mulched area (designated as R_0 and R_{90}, respectively) are the overlapping root length densities of the two inner cotton rows and two side cotton rows, respectively. Therefore, the arithmetic average method was used to simplify the computation of this separation. Thus, the root length density of the inner row at a distance of 0 cm from the irrigation line can be expressed as $R_{\text{in-0}}=R_{0/2}$, and the root length density of the side cotton rows at a distance of 90 cm from the irrigation line can be expressed as $R_{\text{out-90}}=R_{90/2}$. As the root systems of the inner and side cotton rows compete for growth at a distance of 45 cm from the irrigation line, according to the assumption that the root architecture of a single cotton plant exhibits a triangle shape, the root length density at the intersection point (R_{45}) is linearly separated proportionately to the root length density at the two highest points of the triangle (R_{30}, R_{60}), the overlapping root densities at this distance (R_{45}) can be separated by the ratios of the root length densities in the inner (R_{30}) and side cotton rows (R_{60}) to the total root length density of the inner and side cotton rows. The overlapping root density of the inner cotton rows at 45 cm from the irrigation line can thus be expressed as $R_{\text{in-45}}=(R_{30}/(R_{30}+R_{60}))\times R_{45}$, $R_{\text{out-45}}=R_{45}-R_{\text{in-45}}$. Accordingly, two triangular areas ($R_{\text{in-0}}$, R_{30}, and $R_{\text{in-45}}$; $R_{\text{out-45}}$, R_{60}, and $R_{\text{out-90}}$) can be obtained as shown in Figure 7b. These triangular areas can be used to indicate the integral root densities of the inner and side cotton rows in the horizontal direction at a given root growth depth, or the potential root water uptake capacities at given root growth depths. The model derived for cotton cluster root length density envelopes shows that the root length density of the cotton rows varies according to root system growth depth, which in turn varies with time. Thus, the accumulative A_{in} and A_{out} of the root system growth depth (or in growth time) can indicate temporal variations in the potential root water uptake capacities of the inner and side cotton rows, respectively (as shown in Figures 8 and 9).



a. Measured value of horizontal distribution of cotton root length density

b. Simulation value of horizontal distribution of cotton root length density

Figure 7 Illustration of the computation of root water uptake capacity according to root length

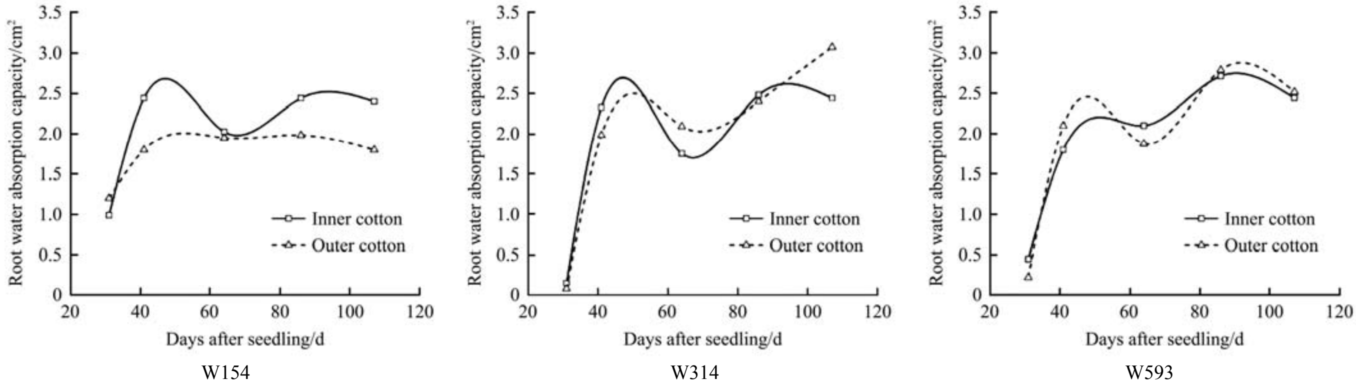


Figure 8 Water uptake capacity of cotton root systems (cm^2) (2010)

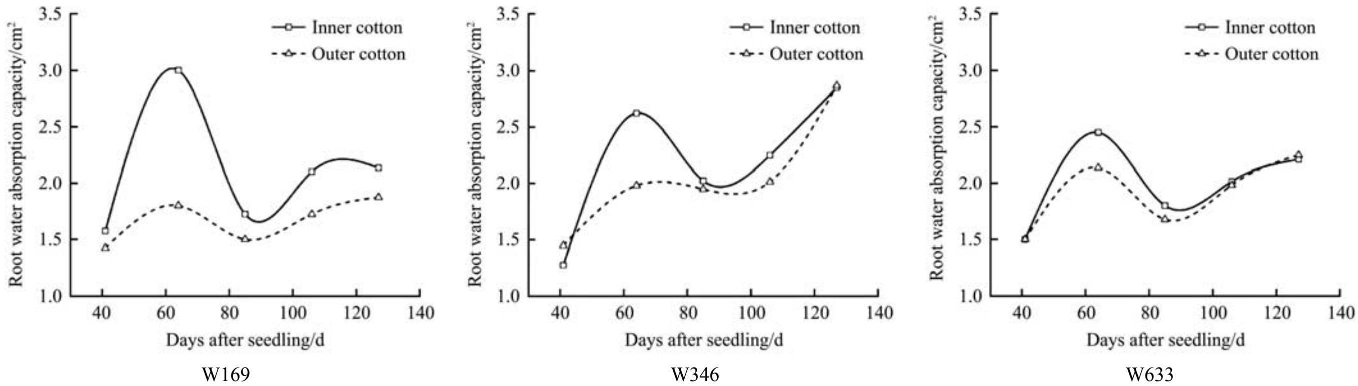


Figure 9 Water uptake capacity of cotton root systems (cm^2) (2011)

The results showed that for the two soil-wetting patterns, the potential water uptake capacity of the root system of the side cotton rows was smaller than that of the inner cotton rows. However, for the wider and shallower soil-wetting patterns, the difference between the potential water uptake capacities of the side and inner cotton rows diminishes. In the 2010 experiment, the difference between the potential water uptake capacities of the inner and side cotton rows of configuration W154 was 0.31 cm^2 (p=0.047), whereas the differences for configurations W314 and W593 (0.09 m^2 and 0.02 cm^2, p=0.30, 0.41, respectively) were non-significant. In the 2011 experiment, the differences between the potential water uptake capacities of the side and inner cotton rows of configurations W169, W346, and W633 were 0.39 cm^2, 0.15 cm^2, and 0.10 cm^2 (p=0.026, 0.16, 0.13, respectively), respectively. These findings revealed that the wider and shallower soil-wetting patterns not only result in an even root system distribution but also a non-significant difference between the root water uptake take capacities of cotton rows, thereby indicating that the soil-wetting pattern plays a significant role in regulating cotton root system growth.

4 Discussion

Data from two seasons of field experiments were used to investigate the matching relationship between the spatial structure of cotton cluster root systems and soil-wetting patterns under mulched drip irrigation, and the matching relationship is the theoretical basis in the technical design of mulched drip irrigation in Xinjiang, China. Although Hu et al.[28] found that the different soil-wetting patterns generated by drip irrigation result in different root system distributions, previous studies of root length density variations in the vertical or horizontal direction have mainly focused on individual cotton plants[2,7], and thus provided only limited insight for drip irrigation design (soil-wetting pattern and space between drip irrigation lines). In this study, models of the spatial distribution of cotton cluster root length density envelopes and root system growth depth were derived to characterize the response of the spatial structure of cotton cluster root systems to different soil-wetting patterns generated by drip irrigation and to analyze temporal variations in the potential root water uptake capacities in the mulch of inner and side rows of cotton. The results of the 2010 experiment showed that configuration W154 (a narrow and deep soil-wetting pattern) was associated with a lower soil matrix potential in the side cotton rows and did not facilitate root system growth. Moreover, the root length density exhibited a single-peak distribution, with the root system growth in the side cotton rows restrained and developing toward the wider row space in the mulch. Moreover, the inner and side cotton rows showed significant differences in potential water uptake capacity. For configurations W593 (a wide and shallow soil-wetting pattern) and W314 (the reference configuration), the soil moisture environment in the mulch facilitated water uptake by the root system, the root length densities exhibited a two-peak pattern, and the root systems in the mulch of cotton rows showed normal growth. The differences between configuration W154 and configurations W314 and W593 in root water uptake capacities of the inner rows of cotton were 0.23 cm^2 and 0.16 cm^2, respectively; and the differences in root water uptake capacities of the side rows of cotton were −0.18 cm^2 and −0.17 cm^2, respectively. Thus, the potential water uptake capacity of the side cotton rows of configuration W154 is smaller than the capacities of the W314 and W593 configurations. The results of the 2011 experiment showed a similar response to the spatial structure of the cotton root system to the drip irrigation soil-wetting pattern. On the basis of these observations, it appears that a wider and shallower soil-wetting pattern contributes to a more even distribution of soil moisture in the vicinity of cotton roots, thereby promoting root system growth and the potential water uptake capacity in the mulch of the inner and side cotton rows.

The envelopes of the root length densities derived based on the results of the 2-year experiment showed that in response to all the different soil-wetting patterns, cotton root system growing depth exhibited a pattern of rapid-slow-rapid-slow growth, with the growth rate being higher at the bud and flower stages. This is because the seedling stage of cotton is the stage of root system development, whereas, at the bud stage, the root system enters its primary stage of growth, with higher growth rates of lateral roots[29]. With the further progression of growth, the development of the aboveground parts of cotton becomes prominent and thereby competes with the root system for nutrients. The center of cotton growth thus shifts from the belowground parts to the aboveground organs, resulting in a lower rate of increase in root length density during the early flower stage. During the flowering stage, the root system enters its primary stage of water uptake, with root hairs growing rapidly and the growth of the main and lateral roots declining[30]. The results of the present study showed that different soil-wetting patterns result in differences in the rate of increase in cotton root length in the vertical direction and that the rates of increase in root length density in response to wider and shallower soil-wetting patterns are higher than those in response to the narrower and deeper soil-wetting patterns. Thus, a wider and shallower soil-wetting pattern facilitates the uptake of soil water and nutrients by the cotton root system, thereby enhancing resource use efficiency in deeper soil layers.

Throughout the 2-year experiment, it was also found that a narrower and deeper soil-wetting pattern promotes the horizontal distribution of cotton root systems, which exhibits a two-peak pattern during the early stages of growth (seedling and bud stages) and a single-peak pattern during the latter stages of growth (flowering and boll-opening stages), whereas for a wider and shallower soil-wetting pattern, the horizontal distribution of the cotton root system exhibits a two-peak pattern throughout the entire growth period. This is consistent with the findings of a recent study by Li et al.[26]. These patterns can essentially be explained in terms of the following mechanism. The overall soil water suction in the mulch is smaller during the seedling and bud stages, owing to the effect of thawed snow in spring, and under these circumstances, the inner and side cotton rows under the different soil-wetting patterns exhibit a two-peak pattern. As the cotton grows during the reproductive stage, the soil-wetting patterns in the mulch are mainly determined by the drip irrigation[31], with the horizontal diffusion of moisture increasing with an increase in emitter discharge rate[32]. Although under these circumstances the root systems of the inner and side cotton rows in a wider and shallower soil-wetting pattern experience adequate water uptake and show an even growth, a narrower and deeper soil-wetting pattern is associated with a smaller soil-wetting pattern and a larger soil matrix suction in the side cotton rows, thereby restraining cotton root system distribution and structure. This in turn affects the growth of new or lateral roots and is manifested in a single-peak distribution of root length density (with decreased root length density in the side cotton rows and peak root density in the inner cotton rows only).

In order to simulate the temporal variation in root water uptake capacity in the mulch of the inner and side cotton rows under different soil-wetting patterns, the root length densities in the vertical direction were integrated (Figures 8 and 9). The experimental results showed that, for W633 (a wide and shallow soil-wetting pattern), the root system distribution of the cotton rows mirrors the soil-wetting pattern, with a non-significant difference between the potential water uptake capacities of the inner and side cotton rows. In contrast, for W169 (a narrow and deep soil-wetting pattern), the area of root system distribution was larger than the soil-wetting pattern and the root systems of the side cotton rows experienced soil moisture deficiency and inadequate water uptake, and the potential water uptake capacity in the mulch of the side cotton rows was markedly smaller than that of the inner cotton rows and markedly smaller than that of the side cotton rows of configuration W633, by an average of 0.24 cm^2 (simplified).

Mulched drip irrigation is generally designed based on systems of non-mulched drip irrigation[33], which is unreasonable both theoretically and practically, given that the edge of the mulch is buried into the soil, and thereby reduces penetration of soil moisture into the mulch to a certain degree and affects the growth of crops planted near the edge of the mulch. When the soil volume wetted by drip irrigation is smaller than the area of root system distribution, the yield of the crop plants grown near the margin of the soil-wetting patterns is lower than that of plants that grow within the soil-wetting patterns[14-16]. Moreover, when the soil-wetting pattern is larger than the area of root system distribution, soil moisture will be lost[34]. Hence, when designing drip irrigation systems, it is necessary to take into consideration the relationship between soil-wetting patterns and crop root systems[3,25]. For mulched drip irrigation of cotton, the design should consider the correspondence between soil-wetting patterns in the mulch and the root systems in rows of cotton, and in this regard, increasing emitter discharge rates in order to increase soil-wetting patterns and reduce the number of drip irrigation lines employed is a major factor that should be considered during the technical design of drip irrigation.

5 Conclusions

In this study, the models of cotton cluster root length density envelopes under mulched drip irrigation were derived based on topological theory and used these to characterize responses of the spatial structure of cotton cluster root systems to different drip irrigation soil-wetting patterns and to examine the temporal variations in potential root water uptake capacities. The results of a 2-year field experiment revealed that the root systems of cotton rows under narrower and deeper soil-wetting patterns (W154 and W169) of mulched drip irrigation showed a single-peak distribution, whereas those under wider and shallower soil-wetting patterns (W593 and W633) showed a two-peak distribution. Furthermore, rows of cotton grown near the margin of mulch distribution were found to experience lower soil moisture stress, whereas root systems in the row spaces experience normal growth. Moreover, with an increase in root length density in the vertical direction, the potential water uptake capacity of the root systems in row spaces becomes more even. These preliminary findings highlight the desirability of wider and shallower soil-wetting patterns for mulched drip irrigation.

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