ABSTRACT

A field experiment was conducted to examine the influence of mulch film removal time (10 and 1 d before the first irrigation (T10 and T1, respectively) and 1 d before the second irrigation (E1) after emergence) on cotton (Gossypium hirsutum L.) root morphology and dry matter accumulation. The control group (CK) was film mulched throughout the growth stage. In 2015, the respective root length density (RLD), root surface-area density (RSD), and root volume density (RVD) in E1 were highest during the initial flowering stage (IFS, 3537 m m–3, 3.4819 m2 m–3, and 382 cm3 m–3) and blossoming and boll forming stage (BBFS, 2472 m m–3, 3.1307 m2 m–3, and 421 cm3 m–3). The maximum root dry matter accumulation was measured in CK (2647 kg ha–1).

In 2016, which had more rainfall, RLD (1699 m m–3) and RSD (2.6877 m2 m–3) in T10 and RVD in T1 (503 cm3 m–3) were the highest during IFS. RLD in E1 (2234 m m–3), RSD (3.6770 m2 m–3) and RVD (598 cm3 m–3) in CK were the highest during BBFS. The cotton root/shoot ratio (R/T) was higher in the film-removal treatments than in CK. E1 showed the highest proportion of fine roots thinner than 1.0 mm during any stage except for 2015 BBFS. The results indicate that film removal at an appropriate time can increase RLD, RSD, and RVD, but it is conducive to the accumulation of root dry matter only in years with lower rainfall.

Core Ideas

- Film removal at an appropriate time can increase cotton root length, surface area, and volume.
- Film removal is conducive to the accumulation of root dry matter in the year with less rainfall.
- Film removal treatment promotes growth of hair roots and improves the root/shoot ratio.

THE Xinjiang Uygur Autonomous Region of China, an important cotton-growing region, is a typical irrigated arid area. Film covering and drip irrigation techniques have been employed since the early 1990s. Consequently, a unique technique of drip irrigation under plastic mulch film (Hu and Li, 2003) was developed in Xinjiang through long-term practice. The features of water and fertilizer supply, that is, “low intensity with high frequency” and the effect of mulch film in increasing soil temperature and conserving soil moisture have largely improved the per unit area yield of cotton (Jian et al., 2007; Rao et al., 2016). The cotton area in Xinjiang in 2014 (242 × 104 ha) was six times that of the 1990s (Statistical Bureau of Xinjiang Uygur Autonomous Region, 1990–2014). Currently, more than 50% of Chinese cotton production is supplied by Xinjiang, and more than 85% of the cotton fields in this region are covered with plastic mulch (Bai et al., 2015). However, the continuous use of mulch film for years has led to increasingly serious pollution of mulch film residue and has significantly influenced cotton yield and soil production. Research findings suggest that mulch film residue in the cotton fields of Xinjiang has reached 18 kg ha–1 per year (Liang and Wang, 2012; Yan et al., 2008), and the average amount of film residue in the soil after 20 yr is as high as 300.65 ± 49.32 kg ha–1 (Yan et al., 2008). If mulch film is used for 68 yr consecutively (38 yr from now) without timely regulating measures, the mulch film residue will reach 1 Mg ha–1 (Dong et al., 2013). The presence of a large amount of mulch film residue in soil hinders the movement and distribution of water and N, obstructs the growth of crop roots (Li, 2016; Yang et al., 2016) and causes deterioration of soil physical-chemical properties, water maldistribution and soil nutrient decline. When the density of mulch film residue reaches 2 Mg ha–1, alkali-hydrolyzale N and rapidly available P will decrease by 55.0 and 60.3%, respectively (Dong et al., 2013).

Pollution control of mulch film residue has become an urgent issue for agricultural production in Xinjiang and even the whole arid region. Currently, there are two major approaches for this issue: (i) the use of degradable mulch film

X. Yang, Y. Niu, and F. Ma, Shihezi Univ., Beisi Road, Shihezi, Xinjiang, P.R. China 832000; X. Yang, Z. Zhang, and H. Tian, Xinjiang Academy of Agricultural and Reclamation Science, 221 Wuyi Road, Shihezi, Xinjiang, P.R. China 832000; X. Yang and Z. Zhang, Key Lab of Xinjiang Production and Construction Corps for Cereal Quality Research and Genetic Improvement, 221 Wuyi Road, Shihezi, Xinjiang, P.R. China 832000. Received 6 June 2017. Accepted 17 July 2017. *Corresponding author (mafuyu0127@qq.com).

Abbreviations: BBFS, blossoming and boll forming stage; IFS, initial flowering stage; R/T, root/shoot ratio; RLD, root length density; RSD, root surface-area density; RVD, root volume density.

doi:10.2134/agronj2017.06.0310
Available freely online through the author-supported open access option

Copyright © 2017 American Society of Agronomy
5585 Guilford Road, Madison, WI 53711 USA
This is an open access article distributed under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/)
as a substitute for common polyethylene mulch film and (ii) mulch film recycling after harvest. However, neither can serve as an effective approach since the former has a high cost, and the latter shows a low recovery rate due to the small thickness of the mulch film (about 5 μm). As a result, removing the mulch film in the early growth stage of cotton can be an effective approach for pollution control of mulch film residue.

In terms of mulch film removal from cotton fields, several studies have been conducted (Su et al., 2011a, 2011b; Li et al., 2010; Xie et al., 2012), yet the focus was mainly on cotton growth and yield traits, with little attention placed on the establishment of the cotton root system and root growth dynamics in the context of the mulch film removal treatment. Studying and clarifying the spatial configuration and growth dynamics of the root systems in different mulch film removal periods during the early growth stage are of theoretical and practical value for cotton production promotion in this cotton-growing region. This is because the establishment of the root system plays an important role in determining the vegetative growth, reproductive growth, and final yield of cotton.

This study aimed to reveal the potential mechanism of mulch film removal during different periods with respect to cotton root configuration and dry matter accumulation. Consequently, the following were investigated: (i) the effect of mulch film removal during different periods of the early cotton growth stage on the spatial configuration in the IFS and in the BBFS and (ii) the effect of mulch film removal on cotton root and shoot dry matter accumulation during the whole growth stage. Plastic film mulching has been extensively used in arid areas in China to reduce water evaporation and increase soil temperature. How does film removal influence cotton growth while it plays the important role of reducing the pollution caused by film residues? To address the above question, appropriate cultivation measures can be formulated to minimize the negative impact of the film removal on cotton production. The results of this study will provide a scientific basis and theoretical guidance for high-yield cultivation of cotton and mulch film residue control in arid and semiarid cotton growing regions.

**MATERIALS AND METHODS**

**Test Area**

The test was performed during the cotton growing season (May–September) in 2015 and 2016 in the No. 2 experimental plot (44.3108° N, 85.986° E, altitude: 460 m) of the Xinjiang Academy of Agricultural and Reclamation Science, Shihezi, Xinjiang, China. The area lies in a typical arid climatic region with an annual average temperature of 7.5 to 8.2°C, sunshine duration of 2318 to 2732 h, frost-free period of 147 to 191 d, annual precipitation of 180 to 270 mm, annual evaporation of 1000 to 1500 mm, and ≥10°C active accumulated temperature of 3570 to 3729°C. The average temperature between May and September, ≥10°C active accumulated temperature, precipitation during the whole growth stage, and rainfall in the first quarter before sowing time in 2015 and 2016 were 22.86 and 22.58°C, 3014 and 3165°C, 94 and 120.2 mm, and 21.4 and 53.8 mm, respectively (meteorological data were collected from the Shihezi Weather Bureau).

The soil is mainly a Calciorthic (Soil Taxonomy, Chinese Soil Taxonomy), and the basic physical and chemical properties (the measurement methods refer to the Chinese industry standard) of the topsoil (0–30 cm) are as follows: organic content: 17.1 g kg⁻¹ (LY/T 1237-1999), total salt content: 1.17 g kg⁻¹ (LY/T 1251-1999), total N content: 1.12 g kg⁻¹ (LY/T 1228-2015), total P content: 0.96 g kg⁻¹ (LY/T 1232-2015), total K content: 1.84% (NY/T 87-1988), hydrolyzable N content: 86.73 mg kg⁻¹ (LY/T 1228-2015), effective P content: 13.83 mg kg⁻¹ (LY/T 1232-2015) and available K content: 319.33 mg kg⁻¹ (NY/T 889-2004).

**Test Design**

The test material was a variety of *Gossypium hirsutum* L., that is, Xinluzao 42. A random block experimental design was employed. The three mulch film removal treatments were implemented across whole plots, that is, removal of the mulch film 10 d before the first irrigation event after emergence (hereinafter referred to as T10; specifically, mulch film was removed 19 and 24 d after emergence in 2015 and 2016, respectively), removal of the mulch film 1 d before the first irrigation event after emergence (hereinafter referred to as T1; specifically, 29 and 34 d after emergence in 2015 and 2016, respectively), and removal of the mulch film 1 d before the second irrigation event after emergence (hereinafter referred to as E1; specifically, 39 and 44 d after emergence in 2015 and 2016, respectively). The control group (CK) was film mulched during the whole cotton growth stage. These four treatments were arranged randomly in the experimental area. Each treatment was replicated three times and thus, there were 12 subplots with an area of 92 m² (width: 4.6 m, length: 20 m). The mulch film was removed manually.

Six rows of cotton with a wide-narrow pattern, that is, 45 + 20 cm, were cultivated with one strip of 205-cm-wide mulch film, which was used to cover each 2.1-m-wide furrow. The row spacing of the intersection between two strips of film was 60 cm (Fig. 1). Plant spacing and planting density were 10 cm and 26 × 10⁴ plants ha⁻¹, respectively. There were 12 rows (2390 plants) of cotton in each subplot. The variety was sown under low soil moisture and emergence occurred under drip irrigation. Drip irrigation was applied to all subplots every

---

Fig. 1. Plant spacing and irrigation system used in the experiment.
10 d on the 30th and 35th day after emergence in 2015 and 2016, respectively. The subplots were irrigated seven times during the growth stage after emergence, with a total irrigation amount of 320 mm. Urea (303.6 kg ha⁻¹) and special fertilizer (390 kg ha⁻¹; N:P₂O₅:K₂O = 6%:30%:30%) for drip irrigation of cotton were applied with drip irrigation.

Variety Xinluzao 42 was sown on 24 Apr. 2015 and 5 May 2016; 15 mm of emergence water was added on 28 Apr. 2015 and 6 May 2016.

The cotton germinated on 6 May 2015 and was harvested on 10 Sept. 2015. The growth period was 127 d in 2015. In 2016, the cotton germinated on 14 May and was harvested on 26 September. The growth period was 136 d.

Sample Collection and Determination

The root system of Xinluzao 42 was collected in IFS and BBFS of 2015 and 2016 at a sample spacing of 60 by 60 by 50 cm³ in the narrow row close to the edge of the mulch film along the x, y, and z axis using the monolith method (Kim et al., 2007) (Fig. 2). The space was divided into 180 cubic soil bodies with a size of 10 by 10 by 10 cm³. The roots contained in each soil body were picked, cleaned, and then analyzed using a root analysis system (WinRHIZO PRO LA2400, Regent Instruments, Quebec, QC, Canada) to calculate the geometric morphological parameters such as root length, root surface area, root volume, and average diameter. Root scanning was performed at a resolution of 300 dpi. The sampled roots were heated in a drying oven at 105°C for 30 min to deactivate enzymes; then, they were dried at 70°C and weighed.

One subplot was considered in each treatment group with no repetition. As the spacing between the cotton plants was only 10 cm, there were 12 plants within the sampling space of each treatment group. A soil body within 60 cm along the x axis, 50 cm along the z axis and 10 cm along the y axis could be considered as a slice; therefore, the sampling space of each treatment group was divided into six slices with each containing two plants along the y axis. Thus, six slices constituted six repetitions.

Nine plants, along with the roots in the 0- to 30-cm soil layer, were sampled in each subplot every 14 d from the 35th day after emergence. Sampling was conducted on plants with similar growth vigor. These plants were marked for subsequent resampling.

The sampled plants were heated in a drying oven at 105°C for 30 min to deactivate enzymes and were then dried to a constant weight at 80°C for 8 to 10 h. They were weighted to calculate the root and shoot dry matter accumulation and to determine the R/T. There were three replicates for each treatment group.

Number of plants harvested and boll number on a single plant were investigated in each subplot before the harvest, then 20 bolls for different positions of cotton were collected for weight. Every plot of cotton is harvested to calculate the yield. The fiber quality characters were measured by HVI900 (Uster, Knoxville, TN).

Data Analysis

Microsoft Excel 2010, SigmaPlot 12.5 and DPS16.05 (Tang and Zhang, 2012) were employed for data processing, plotting, and variance analysis. Multiple comparisons were conducted using the LSD (0.05) method. Dry matter accumulation was simulated using DPS16.05 (Tang and Zhang, 2012) and the Marquardt method.

RESULTS

Influence of Mulch Film Removal on Root Length Density of Cotton

Spatial distribution (Fig. 3) suggested that RLD in the CK group was evenly distributed in various soil layers, while in the film removal treatment groups, RLD was concentrated in two areas around the main roots.

In terms of the horizontal distribution (Fig. 4), RLDs in the film removal groups during the IFS in 2015 were higher than in CK; the difference reached statistical significance at most locations along the x axis (Fig. 2) direction. The T10 group had higher RLD than the CK group during the IFS in 2016, and the difference was significant at 40 to 60 cm along the x axis (Fig. 2) direction (the intersection direction of two strips of film). With respect to the IFS and BBFS, RLDs in both T1 and

Fig. 2. Methods of root collection used in this work.
Fig. 3. Three-dimensional distribution of cotton root length density (RLD) in different groups (10 and 1 d before the first irrigation event (T10, T1) and 1 d before the second irrigation event (E1) after emergence) during the initial flowering stage (IFS) and blossoming and boll forming stage (BBFS) in 2015 and 2016. The control group (CK) was film mulched throughout the growth stage.

Fig. 4. Horizontal and vertical distribution of cotton root length density (RLD) in different groups (10 and 1 d before the first irrigation event (T10, T1) and 1 d before the second irrigation event (E1) after emergence) during the initial flowering stage (IFS) and blossoming and boll forming stage (BBFS) in 2015 and 2016. The control group (CK) was film mulched throughout the growth stage. Error bars represent the standard error (n = 6). Different letters indicate significant differences (P < 0.05) among treatments at the same point on the x or y axis.
T10 were significantly lower than those in E1 and CK in 2015; RLDs in the two other film removal treatment groups were also lower than in CK. In 2016, only T10 had a lower RLD than E1 and CK along the x axis direction.

The vertical distributions of RLD in different treatments at different growth stages showed a similar trend to the horizontal distributions in both years (Fig. 4). In 2015, however, RLD was mainly distributed at a depth deeper than 30 cm whereas it was within the 0- to 30-cm soil layer in 2016. This inter-annual difference suggested that RLD during the IFS and BBFS in 2015 was lower than that during the IFS in both vertical and horizontal directions, and that RLD during the BBFS was higher than that during the IFS in 2016.

The RLD in E1 was highest in IFS of 2015 (3537 m m⁻³) and BBFS in 2015 (2472 m m⁻³) and 2016 (2234 m m⁻³). In addition, except in 2016 IFS, RLD in T10 was the highest (1699 m m⁻³).

**Influence of Mulch Film Removal on Root Surface-Area Density of Cotton**

Figures 5 and 6 indicate that the distributions of RSD in the four groups were basically consistent with each other within the same year. Compared to 2015, RSDs in different groups were more concentrated in the 0- to 10-cm soil layer in 2016.

During the IFS in 2015, either the horizontal or vertical distribution of RSD was higher in the mulch film removal treatment groups, that is, T10, T1, and E1 compared with CK. The differences reached the mostly significant and even extremely significant levels. During the IFS and BBFS, except that the T10 group had the highest RSD at a depth of 50 cm, RSD in E1 was higher than that in the other three groups in both horizontal and vertical directions. The difference was not significant at 0 to 40 cm in the x axis direction (direction of the wide row) but was significant at 40 to 60 cm in the x axis direction (direction of the center of the two strips of film). The trend of the horizontal and vertical distributions of RSD in 2016 was basically similar to that in 2015; however, the difference between various treatments in 2016 was not as significant as in 2015.

The RSD in E1 was highest during the 2015 IFS (3.4819 m² m⁻³) and BBFS (3.1307 m² m⁻³). However, in 2016, RSD in T10 (2.6877 m² m⁻³) was highest during the IFS, and that in CK (3.6770 m² m⁻³) was highest during the BBFS.

**Influence of Mulch Film Removal on Root Volume Density of Cotton**

Based on the distribution trend (Fig. 7), RVDs in different treatments and different years were mainly distributed in two areas near the main roots. Root volume densities in E1 and T10 were distributed deep in the soil in 2015; RVDs in the other groups were distributed in the topsoil layer. Root volume densities in different treatment groups were evenly distributed in the horizontal direction (Fig. 8). In 2015, RVD in T10 was concentrated in the 20- to 40-cm soil layer during the IFS and BBFS, accounting for 55.4 and 67.3%, respectively, of the total amount of RVD in all soil layers. The RVD in E1 was distributed in the 20- to 40-cm soil layer during the IFS, accounting for 54.3% of the total RVD in all soil layers, and in the 10- to 30-cm soil layer during the BBFS, accounting for 57.1% of the total RVD in all soil layers.
Fig. 6. Horizontal and vertical distribution of cotton root surface-area density (RSD) in different groups (10 and 1 d before the first irrigation event (T10, T1) and 1 d before the second irrigation (E1) event after emergence) during the initial flowering stage (IFS) and blossoming and boll forming stage (BBFS) in 2015 and 2016. The control group (CK) was film mulched throughout the growth stage. Error bars represent the standard error (n = 6). Different letters indicate significant differences (P < 0.05) among treatments at the same point on the x or y axis.

Fig. 7. Three-dimensional distribution of cotton root volume density (RVD) in different groups (10 and 1 d before the first irrigation event (T10, T1) and 1 d before the second irrigation event (E1) after emergence) during the initial flowering stage (IFS) and blossoming and boll forming stage (BBFS) in 2015 and 2016. The control group (CK) was film mulched throughout the growth stage.
In 2016, the RVDs in different treatment groups were concentrated in the 0- to 10-cm soil layer during both growth stages. In the IFS, RVD in the 0- to 10-cm soil layer accounted for 55.9, 59.5, 57.3, and 26.9% of the total amount in the soil layer in CK, T1, E1, and T10, respectively. With respect to the BBFS, the values were 52.3, 43.8, 36.8, and 47.5%, respectively, indicating that film removal at an early stage promoted deep root growth, resulting in an even distribution in the various soil layers.

The RVD in E1 was highest during the 2015 IFS (382 cm$^3$ m$^{-3}$) and BBFS (421 cm$^3$ m$^{-3}$). The RVD in T1 (503 cm$^3$ m$^{-3}$) was highest during the 2016 IFS, and that in CK (598 cm$^3$ m$^{-3}$) was highest during the 2016 BBFS.

**Influence of Mulch Film Removal on the Proportion of the Diameter Distribution of Cotton Roots**

During the IFS of 2015 and 2016, the E1 group exhibited the highest proportion of the length of fine roots (thinner than 1.0 mm) that contributed to the total root length (97.6 and 94.7%, respectively). During the 2015 BBFS, the proportion in CK was slightly higher than in the film removal treatment groups. The proportions in CK, T1, E1, and T10 were 95.6, 94.9, 95.0, and 94.3%, respectively. During the 2016 BBFS, however, the proportions were lower in CK compared with the film removal treatment groups, accounting for 94.7, 95.2, 96.3, and 95.2%, respectively, for CK, T1, E1, and T10. The proportion of the total length of main roots coarser than 1.0 mm was the highest in CK during the IFS and the lowest during the BBFS of 2015; opposite results were observed in 2016 (Fig. 9).

**Influence of Mulch Film Removal on the Root/Shoot Ratio of Cotton**

The R/T value exhibited a downward trend since the 49th day after emergence, before which (35–49 d after emergence) Xinluzao 42 showed downward trends in the CK group in 2015 and the E1 group in 2016, and the R/T values of the other treatment groups started to increase. The R/T value of Xinluzao 42 in each of the film removal treatment groups was higher than that in CK in both years (Fig. 10).

**Influence of Mulch Film Removal on Dry Matter Accumulation of Cotton Roots and Shoots**

Variation of roots and shoots dry matter accumulation in the treatment groups (Fig. 11) basically appeared as an “S” shape. Dry matter accumulation of roots and shoots increased with cotton growth, but accumulation rates varied during the different growth stages.

The dry matter accumulation of cotton roots and shoots subjected to different treatments could be fitted using a logistic equation, that is, $Y = \frac{K}{1 + EXP (a + bt)}$, where $a$, $b$, and $K$ are undetermined coefficients (Table 1). The time when the dry matter accumulation rate reached a maximum, the maximum accumulation rate, the dry matter weight at the maximum accumulation rate, starting time of the linear accumulation stage, and end time of the linear accumulation stage, were denoted as $T_{max}$, $R_{max}$, $W_{m}$, $t_1$, and $t_2$, respectively. Dry matter accumulation from $t_1$ to $t_2$ was denoted as $\Delta W_{t_2-t_1}$. These parameters were calculated using the method developed by Ming (2006).
From Table 1, the $K$ value (estimated value of the maximum root dry matter accumulation) in CK in 2015 was nearly twice the amount in T10. In 2016, apart from T10 where the $K$ value of cotton roots was slightly lower than that of CK, the remaining film removal treatments, that is, T10, T1, and E1, had higher $K$ values of roots than CK. The inter-annual difference suggested that the $K$ value of roots for a particular treatment in 2016 was lower than that in 2015, especially in CK where the $K$ value of roots in 2016 was less than half of the 2015 value.

The difference between treatments indicated that $T_{max}$ and $t_1$ of roots occurred later in CK than in the film removal treatments in 2015, but the time of the linear accumulation of roots lasted longer. The linear accumulation time of roots in T1 and T10 was 20 d shorter than that in CK. The $\Delta W_{t2-t1}$ value of roots was higher in CK compared with the film removal treatments. In 2016, there was plenty of soil moisture, which was totally different from the situation in 2015, that is, $T_{max}$ and $t_1$ of roots in CK occurred later than in T1 and T10, which had a shorter $\Delta t$.

The inter-annual difference suggested that the $T_{max}$ of roots in the various treatment groups in 2016 occurred much earlier than that in 2015. For example, $T_{max}$ of roots in CK occurred 40 d earlier; $t_1$ of roots in CK occurred 16 d earlier in 2015 than in 2016; and there was little difference between $t_1$ of roots in 2015 and 2016. $\Delta t$ of roots measured in CK was shorter than 0.5 indicates the total length of roots with a diameter of 0–0.5 mm. The same as below).
that in each of the film removal treatments in 2016; $\Delta t$ of roots of various treatments in 2016 was less than half of that in 2015.

The maximum dry matter accumulation of shoots ($K$ in the logistic equation) was highest in CK and was almost twice the amount in the film-removal treatment groups (i.e., T10, T1, and E1) in 2015. In 2016, however, the largest $K$ value of shoots was in T1, with little difference among groups. In 2015, $T_{\text{max}}$ and $t_1$ of shoots in CK were later than in the film-removal treatment groups (i.e., T10, T1, and E1) and the rectilinear accumulation time in CK was longer, whereas opposite results were observed in 2016.

**Influence of Film-removal Time on Cotton Yield and Quality**

Cotton yield in CK was the highest in 2015, whereas it was the highest in T1 in 2016. With guaranteed irrigation, moderate aridity was beneficial for yield. Film removal at different times made little difference to quality (Table 2).

## DISCUSSION

**Cotton Root Morphological Differences in Different Periods in Response to Mulch Film Removal**

Crops are able to adapt to different soil stresses by changing their root morphologies, which, together with the spatial structures, affect crop absorption and utilization of soil water and nutrients (Palta et al., 2011; Vandoorne et al., 2012; Bodner et al., 2015). Consequently, root morphologies affect the functions of the aboveground components (Suralta et al., 2010). The use of fertilizers, crop rotation, cover crops and intercropping, and especially irrigation and drainage, can exert an influence on root functions (Palta and Yang, 2014). Morphological characteristics of roots, such as volume, surface area, and length, are significantly related to the soil moisture content (Li et al., 2011; Xue et al., 2014; Zhao et al., 2010). Several studies suggested that appropriate aridity at an early growth stage could stimulate wheat roots to grow in deep soil layers and increase root volume (Zhang et al., 2015). A study conducted by Buttar et al. (2009) showed that the first irrigation event (42 d after sowing), conducted 14 d later than normal irrigation (at 28 d after sowing) could significantly improve the biomass of cotton roots and root distribution in deep soil layers (180 cm).

Due to the fact that soil moisture is deficient after film removal (Zhang et al., 2016), the results of this study suggest that RLDs (Fig. 4) and RSDs (Fig. 6) in the film removal treatment groups were significantly higher than those in CK during the IFS of 2015. Higher precipitation in 2016 partly compensated for the moisture loss caused by film removal, so only the early film removal treatment (T10) was under light drought stress, and T10 was also the only treatment where RLD (Fig. 4) was higher than that of CK. In terms of root size (Fig. 9), the late film removal time in E1 not only satisfied the cotton’s demands for soil temperature and moisture during the early growth stage but also provided a suitable environment with

### Table 1. Parameters for logistic equation of root and shoot dry matter accumulation in various treatment groups (T10 and 1 d before the first irrigation event (T10, T1) and 1 d before the second irrigation event (E1) after emergence). The control group (CK) was film mulched throughout the growth stage.

<table>
<thead>
<tr>
<th>Roots/Shoots</th>
<th>Treatment</th>
<th>$K_1$</th>
<th>$a_1$</th>
<th>$b_1$</th>
<th>$R_{\text{max}}$</th>
<th>$t_{\text{1}}$</th>
<th>$t_{\text{2}}$</th>
<th>$\Delta t$</th>
<th>$W_{\text{max}}$</th>
<th>$\Delta W_{\text{12-11}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Roots in 2015</strong></td>
<td>CK</td>
<td>2,647.384</td>
<td>3.2369</td>
<td>-0.0334</td>
<td>0.9835**</td>
<td>97</td>
<td>57</td>
<td>136</td>
<td>79</td>
<td>22.11</td>
</tr>
<tr>
<td></td>
<td>T1</td>
<td>1,551.345</td>
<td>3.1997</td>
<td>-0.0444</td>
<td>0.9640**</td>
<td>72</td>
<td>42</td>
<td>102</td>
<td>59</td>
<td>17.22</td>
</tr>
<tr>
<td></td>
<td>E1</td>
<td>1,959.973</td>
<td>2.8992</td>
<td>-0.0333</td>
<td>0.9212**</td>
<td>87</td>
<td>48</td>
<td>127</td>
<td>79</td>
<td>16.32</td>
</tr>
<tr>
<td></td>
<td>T10</td>
<td>1,388.534</td>
<td>3.4068</td>
<td>-0.0485</td>
<td>0.9884**</td>
<td>70</td>
<td>43</td>
<td>97</td>
<td>54</td>
<td>16.84</td>
</tr>
<tr>
<td><strong>Roots in 2016</strong></td>
<td>CK</td>
<td>1,250.213</td>
<td>4.6344</td>
<td>-0.0813</td>
<td>0.9880**</td>
<td>57</td>
<td>41</td>
<td>73</td>
<td>32</td>
<td>25.41</td>
</tr>
<tr>
<td></td>
<td>T1</td>
<td>1,386.145</td>
<td>4.8151</td>
<td>-0.0781</td>
<td>0.9851**</td>
<td>62</td>
<td>45</td>
<td>79</td>
<td>34</td>
<td>27.06</td>
</tr>
<tr>
<td></td>
<td>E1</td>
<td>1,405.064</td>
<td>4.3823</td>
<td>-0.0695</td>
<td>0.9481*</td>
<td>63</td>
<td>44</td>
<td>82</td>
<td>38</td>
<td>24.41</td>
</tr>
<tr>
<td></td>
<td>T10</td>
<td>11,38.951</td>
<td>5.6592</td>
<td>-0.0959</td>
<td>0.8985*</td>
<td>59</td>
<td>45</td>
<td>73</td>
<td>32</td>
<td>27.31</td>
</tr>
<tr>
<td><strong>Shoots in 2015</strong></td>
<td>CK</td>
<td>25,062.35</td>
<td>4.7177</td>
<td>-0.0464</td>
<td>0.9796**</td>
<td>102</td>
<td>73</td>
<td>130</td>
<td>57</td>
<td>290.55</td>
</tr>
<tr>
<td></td>
<td>T1</td>
<td>8,242.745</td>
<td>3.8441</td>
<td>-0.0519</td>
<td>0.9577**</td>
<td>74</td>
<td>49</td>
<td>99</td>
<td>50</td>
<td>106.98</td>
</tr>
<tr>
<td></td>
<td>E1</td>
<td>11,478.38</td>
<td>3.7909</td>
<td>-0.0437</td>
<td>0.9954**</td>
<td>87</td>
<td>57</td>
<td>117</td>
<td>60</td>
<td>125.36</td>
</tr>
<tr>
<td></td>
<td>T10</td>
<td>11,654.38</td>
<td>4.303</td>
<td>-0.0488</td>
<td>0.9885*</td>
<td>88</td>
<td>61</td>
<td>115</td>
<td>54</td>
<td>142.24</td>
</tr>
<tr>
<td><strong>Shoots in 2016</strong></td>
<td>CK</td>
<td>15,233.52</td>
<td>4.8979</td>
<td>-0.0732</td>
<td>0.9866**</td>
<td>67</td>
<td>49</td>
<td>85</td>
<td>36</td>
<td>278.77</td>
</tr>
<tr>
<td></td>
<td>T1</td>
<td>18,790.05</td>
<td>4.4678</td>
<td>-0.0554</td>
<td>0.9953**</td>
<td>81</td>
<td>57</td>
<td>104</td>
<td>47</td>
<td>260.24</td>
</tr>
<tr>
<td></td>
<td>E1</td>
<td>15,730.95</td>
<td>4.9952</td>
<td>-0.0686</td>
<td>0.9889**</td>
<td>73</td>
<td>54</td>
<td>92</td>
<td>38</td>
<td>269.79</td>
</tr>
<tr>
<td></td>
<td>T10</td>
<td>11,573.5</td>
<td>5.2355</td>
<td>-0.0786</td>
<td>0.9933**</td>
<td>67</td>
<td>50</td>
<td>83</td>
<td>33</td>
<td>227.42</td>
</tr>
</tbody>
</table>

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
† $T_{\text{max}}$, the time when the root or shoot dry matter accumulation rate reached a maximum.
‡ $t_1$, starting time of linear accumulation.
§ $t_2$, end time of linear accumulation.
¶ $\Delta t$, days from $t_1$ to $t_2$.
†† $R_{\text{max}}$, the maximum accumulation rate.
†‡ $W_{\text{max}}$, dry matter weight at the time when the root or shoot dry matter accumulation rate reached a maximum.
§§ $\Delta W_{\text{12-11}}$, dry matter accumulation from $t_1$ to $t_2$. 

2594  Agronomy Journal  •  Volume 109, Issue 6  •  2017
Table 2. Cotton yield and quality characters in various treatment groups (10 and 1 before the first irrigation event (T10), T1 and 1 before the second irrigation event (El) after emergence) at the maturity stage. The control group (CK) was film mulched throughout the growth stage.

<table>
<thead>
<tr>
<th>Year</th>
<th>Treatment</th>
<th>No. of plants harvested</th>
<th>Single plant yield</th>
<th>Estimated yield</th>
<th>Ball number on a single plant</th>
<th>Total length of root</th>
<th>Total root length</th>
<th>RLD</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>CK</td>
<td>19.71 ± 1.07a</td>
<td>0.35 ± 0.02</td>
<td>5.34 ± 0.15a</td>
<td>5.17 ± 0.17</td>
<td>2788 ± 125</td>
<td>278 ± 125</td>
<td>2.10 ± 0.10a</td>
</tr>
<tr>
<td>2016</td>
<td>CK</td>
<td>19.67 ± 1.05a</td>
<td>0.34 ± 0.02</td>
<td>5.24 ± 0.15a</td>
<td>5.00 ± 0.17</td>
<td>2778 ± 125</td>
<td>277 ± 125</td>
<td>2.00 ± 0.10a</td>
</tr>
<tr>
<td>2015</td>
<td>E1</td>
<td>19.71 ± 1.07a</td>
<td>0.35 ± 0.02</td>
<td>5.34 ± 0.15a</td>
<td>5.17 ± 0.17</td>
<td>2788 ± 125</td>
<td>278 ± 125</td>
<td>2.10 ± 0.10a</td>
</tr>
<tr>
<td>2016</td>
<td>E1</td>
<td>19.67 ± 1.05a</td>
<td>0.34 ± 0.02</td>
<td>5.24 ± 0.15a</td>
<td>5.00 ± 0.17</td>
<td>2778 ± 125</td>
<td>277 ± 125</td>
<td>2.00 ± 0.10a</td>
</tr>
<tr>
<td>2015</td>
<td>T1</td>
<td>19.71 ± 1.07a</td>
<td>0.35 ± 0.02</td>
<td>5.34 ± 0.15a</td>
<td>5.17 ± 0.17</td>
<td>2788 ± 125</td>
<td>278 ± 125</td>
<td>2.10 ± 0.10a</td>
</tr>
<tr>
<td>2016</td>
<td>T1</td>
<td>19.67 ± 1.05a</td>
<td>0.34 ± 0.02</td>
<td>5.24 ± 0.15a</td>
<td>5.00 ± 0.17</td>
<td>2778 ± 125</td>
<td>277 ± 125</td>
<td>2.00 ± 0.10a</td>
</tr>
<tr>
<td>2015</td>
<td>T10</td>
<td>19.71 ± 1.07a</td>
<td>0.35 ± 0.02</td>
<td>5.34 ± 0.15a</td>
<td>5.17 ± 0.17</td>
<td>2788 ± 125</td>
<td>278 ± 125</td>
<td>2.10 ± 0.10a</td>
</tr>
<tr>
<td>2016</td>
<td>T10</td>
<td>19.67 ± 1.05a</td>
<td>0.34 ± 0.02</td>
<td>5.24 ± 0.15a</td>
<td>5.00 ± 0.17</td>
<td>2778 ± 125</td>
<td>277 ± 125</td>
<td>2.00 ± 0.10a</td>
</tr>
</tbody>
</table>

**Note:** Within columns, means followed by different letters are significantly different among treatments in the same year according to the LSD (0.05).

---

**Cotton Root Dry Matter Accumulation with Mulch Film Removal in Different Periods**

Adiku et al (1996) reported that root dry matter accumulation and RLD in any soil layer could be simulated using a logistic equation, and the maximum accumulation would not exceed the maximum estimated value of the equation. Li et al. (1999) found that root biomass accumulation of high-yielding cotton in northern Xinjiang followed an S-shaped curve, and the linear growth stage started from late June (full-bud stage) to late July (full-bloom stage). Research findings of this study accord with the conclusions drawn above, that is, dry matter accumulation in cotton roots exhibited an S-shaped curve in each treatment (Fig. 11), which could be fitted using a logistic equation (Table 1); the linear growth stage started from the 40 to 50th day after emergence, which was also the period from the full-bud stage to the IFS.
Under appropriate soil aridity, stem and leaf growth is restricted, and photosynthetic products are preferentially allocated to roots to promote root growth (Zhu et al., 2002; Meng et al., 2016; Rhizopoulou and Davies, 1993; Skinner et al., 1998). The research findings in the current study (Table 1) suggest that higher precipitation in 2016 compensated for the moisture loss caused by film removal. Apart from T10 where cotton was subjected to severe drought stress and had slightly lower maximum root dry matter accumulation compared with CK, the remaining treatments were all under light drought stress, and the maximum dry matter accumulation in roots was higher than that in CK.

Excessive drought stress negatively affects root growth. According to Li et al. (1999), drought stress during the growth stage can result in fewer roots, accelerate the aging of the aboveground components, and decrease root biomass production and raw cotton yield. Both total root length and dry matter accumulation of soybean roots were found to decline in arid treatments (Grzesiak et al., 1997). Under the soil condition with low precipitation in 2015, the film mulching treatment played a role in conserving soil moisture, whereas soil with the film removal treatment was under excessive drought stress. As a result, maximum dry matter accumulation in the roots of CK was significantly higher than that in any of the film removal treatments (Table 1).

Root growth can also be restricted in the case of high soil moisture and poor soil permeability. As indicated by the research conducted by Monteith et al. (1994), the influence of seasonal precipitation variation on root growth in different years was significant when soil properties remained the same. In a study conducted by Hu et al. (2009), soil moisture was maintained at a high level with drip irrigation under mulch film, which had a negative effect on cotton root growth and yield. According to Luo et al. (2013b), excessive soil moisture can increase RLD and reduce the biomass of roots and aboveground parts, which leads to yield reduction. The current study also revealed that maximum root dry matter accumulation within a treatment was lower in 2015 than in 2016, especially in CK, where maximum dry matter accumulation was reduced by more than half. There was little difference between the starting times of the linear growth stage in the 2 yr, but the time during which dry matter exhibited a linear increase in the various treatments in 2016 was nearly half of that measured in 2015, with less dry matter accumulation during the whole linear growth stage (Table 1).

Xinjiang is a region of desert-oasis agriculture with water and temperature being the most important climatic factors affecting cotton yield. Plastic film mulching has been extensively used in this region to reduce water evaporation and increase soil temperature. Previous studies on water and temperature under film removal in cotton fields (Su et al., 2011a, 2011b; Li et al., 2010; Xie et al., 2012; Zhang et al., 2016) were not comprehensive since they focused on a short time span of film removal. Studying the distribution characteristics of soil temperature and moisture in cotton fields at different film-removal times to find out the optimal film-removal time is important for understanding cotton growth. This is the focus of our next research work.

CONCLUSION

Appropriate aridity may promote root growth, and over-moist or arid soil is disadvantageous for root growth. The results of this study suggest that film removal treatment concentrates roots in the soil layers of two areas around the main root, promotes the growth of fine roots during the early growth stage, and improves the R/T ratio after the IFS. The treatment where the mulch film was removed 1 d before the second irrigation event after emergence (E1) was found to promote RLD. In the year with less rainfall, E1 resulted in a root system with a larger surface area and volume, and this treatment resulted in the root system absorbing soil moisture. Film removal under drought conditions can promote root elongation in deep soil layers, but excessive soil drought stress caused by film removal is not conducive to root dry matter accumulation, and the earlier the removal film, the more obvious this effect. The results obtained in years with more rainfall were exactly the opposite: earlier film removal promoted RSD and RVD only during the IFS. After this time, soil water stress becomes less pronounced, and the film removal treatment reduced RSD and RVD instead. However, because film removal at the optimal time (E1, T1) created an appropriate stress, such treatments are conducive to the accumulation of dry matter in roots. Early film removal (T10) was unfavorable for dry matter accumulation in roots. Inter-annual variations suggest that years with more precipitation are unfavorable for dry matter accumulation of roots in all treatments. Based on these results, in actual agricultural production, we can remove the mulch film 1 d before the second irrigation event after emergence. At this time, the role of the film in increasing soil temperature and reducing water evaporation is largely complete, and film removal can create a more favorable root growth environment and promote the healthy growth of cotton.

ACKNOWLEDGMENTS

This study was funded by the special fund for scientific research in non-profit industries (agriculture) (201503120). We extend our gratitude to Mr. Jin Wang for providing meteorological data.

REFERENCES


