Effect of Soil Temperature on Cotton Growth Under Drip-Applied Phosphate Fertilizer: Postprint

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Abstract

This study investigated the response of cotton growth to soil temperature under phosphorus fertilizer drip application, aiming to explore the role and mechanism of soil temperature regulation of cotton root growth in improving phosphorus fertilizer use efficiency. A pot experiment was conducted with three soil temperature gradients: low temperature (LT: 11–18 °C), medium temperature (MT: 22–26 °C), and high temperature (HT: 30–34 °C); this was a single-factor experiment with temperature controlled by a water bath. The effects of different soil temperatures on cotton growth traits, biomass, root distribution, soil available phosphorus distribution, and cotton phosphorus use efficiency were analyzed. The results showed that with increasing soil temperature, cotton plant height, stem diameter, leaf number, and biomass all exhibited a parabolic trend, reaching maximum values at medium temperature (22–26 °C); in the 0–5 cm soil layer, cotton root length increased with soil temperature, being 5.2%–126.9% and 4.9%–62.3% higher under high temperature treatment compared with low and medium temperature treatments, respectively; below the 5 cm soil layer, cotton root length decreased with increasing temperature, with the medium temperature treatment having the longest root length, which was 81.68%–98.43% and 170.17%–218.35% higher than low and high temperature treatments, respectively; soil available phosphorus content in each treatment showed that the higher the temperature, the lower the soil available phosphorus content, with medium and high temperature treatments being 13.7% and 20.5% lower than the low temperature treatment, respectively; the medium temperature treatment had the highest cotton phosphorus uptake and phosphorus use efficiency, followed by low temperature, and high temperature was the lowest, wherein cotton phosphorus uptake under medium temperature was 49.69% and 89.36% higher than low and high temperature treatments, respectively, and phosphorus use efficiency was double that of high temperature treatment and 50% higher than low temperature treatment. Taken together, the suitable soil temperature

range for cotton growth and improving phosphorus use efficiency is 22–26 °C.

Full Text

Effects of Soil Temperature on Cotton Growth Under Phosphate Fertilizer Drip Application Conditions

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Abstract

This study examined the response of cotton growth to soil temperature under phosphate fertilizer drip application conditions, aiming to explore the role and mechanism of soil temperature regulation of cotton root growth in improving phosphate fertilizer utilization efficiency. A pot experiment was conducted with three soil temperature gradients: low temperature (11–18°C), medium temperature (22–26°C), and high temperature (30–34°C) using a single-factor design with water bath temperature control. The effects of different soil temperatures on cotton growth traits, biomass, root distribution, soil available phosphorus distribution, and phosphorus utilization efficiency were analyzed. Results showed that with increasing soil temperature, cotton plant height, stem diameter, leaf number, and biomass all exhibited parabolic trends, peaking at medium temperature (22–26°C). Root length in the 0–5 cm soil layer increased with soil temperature, being 5.2%-126.9% and 4.9%-62.3% higher under high temperature treatment compared to low and medium temperature treatments, respectively. Below the 5 cm soil layer, cotton root length decreased with increasing temperature, with medium temperature treatment showing the longest root length, 81.68%-98.43% and 170.17%-218.35% longer than low and high temperature treatments, respectively. Soil available phosphorus content was lower at higher temperatures, with medium and high temperature treatments reducing it by 13.7% and 20.5% compared to low temperature treatment, respectively. Phosphorus absorption and utilization efficiency were highest under medium temperature treatment, followed by low temperature, and lowest under high temperature. Specifically, phosphorus absorption under medium temperature was 49.69% and 89.36% higher than low and high temperature treatments, respectively, while phosphorus utilization efficiency was twice as high as the high temperature treatment and 50% higher than the low temperature treatment. Considering the comprehensive effects of soil temperature on cotton growth, root length, soil available phosphorus distribution, phosphorus absorption, and utilization efficiency, the optimal soil temperature range for cotton growth and improved phosphorus utilization efficiency is 22–26°C.

Keywords: Soil temperature; cotton; drip phosphate fertilizer; phosphate fertilizer utilization efficiency

Introduction

Xinjiang is China' s largest cotton production base, with cotton production accounting for more than 90% of the national total. Currently, over 90% of cotton fields in Xinjiang use mulched drip irrigation water-fertilizer integration technology. This technology can supply water and fertilizer (especially nitrogen) according to cotton demand in a timely and appropriate manner, greatly improving cotton water and nitrogen use efficiency. However, compared with traditional basal phosphorus application, drip phosphorus application only increased cotton phosphorus fertilizer utilization efficiency by 2%–5%, without changing the status quo of low phosphorus fertilizer utilization efficiency. This means that even in water-fertilizer integration production systems where artificial intervention in water-fertilizer supply and crop demand coupling is easily achieved, improving crop phosphorus fertilizer utilization efficiency in the current season remains a very complex and difficult scientific and technical challenge.

Phosphorus fertilizer has very limited vertical movement distance after entering soil with drip irrigation. A series of laboratory simulation studies using ^{32}P isotope tracer technology found that the movement distance of drip-applied phosphorus fertilizer in soil is generally limited. The spatial mismatch between cotton root system and phosphorus distribution under drip phosphorus application conditions is the fundamental reason for the low utilization efficiency of drip phosphorus fertilizer, and soil temperature variation plays a very important role in this process.

The 0–5 cm soil layer is a region with drastic temperature changes that strongly affects plant lateral root growth and phosphorus absorption. Fixed-point observations in cotton fields show that under plastic film mulching conditions from seedling to squaring stage, the surface temperature can reach very high values, with daily temperature variation range of 13–34°C. The optimal soil temperature for plant root growth is around 25°C, and exceeding this threshold inhibits growth. The 0–5 cm soil layer temperature is far higher than the critical value for root growth, and this period coincides with the critical period for cotton root system establishment (rapid root length increase period). Therefore, exploring the effects of soil temperature on cotton growth and phosphorus fertilizer utilization efficiency under drip phosphorus application conditions is crucial for improving phosphorus use efficiency in Xinjiang cotton production.

Materials and Methods

1.1 Materials

This study used a pot experiment method. The test soil was gray desert soil with basic physicochemical properties: pH 7.76, available phosphorus 378 mg ·

kg^{-1}, and available potassium 83.7 $mg \cdot kg^{-1}$. The soil was air-dried and sieved for later use. The cotton variety used was Jimian 11. Temperature monitoring was conducted using right-angle soil thermometers. The test pots used soft plastic nursery pots without bottom holes. The drip irrigation device used 250 mL medical infusion bottles with controllable flow rate.

1.2 Experimental Design

The experiment was conducted in a net room of the Halophyte Garden in Karamay, Xinjiang (45°26 26 N, 85°00 39 E) in May. The experiment had one factor of soil temperature with three gradients: low temperature (LT: 11–18°C), medium temperature (MT: 22–26°C), and high temperature (HT: 30–34°C). Each treatment had 9 replicates. Soil temperature was controlled by water bath heating combined with ice addition and monitored using soil thermometers (Figure 1). Each pot was filled with 1.2 kg of air-dried soil. Nitrogen fertilizer as urea (CH_4N_2O) was applied as basal fertilizer at 0.6 g per pot and mixed evenly with the air-dried soil before being placed in the pots. The initial watering amount was 600 mL. Cotton was sown directly in the center of the pot. When seedlings grew to 2–3 true leaves, each pot was thinned to one plant. The test pots were moved to water baths, and water temperature was adjusted to each treatment's set temperature to begin formal treatment. The drip irrigation device was installed with the emitter located at the center of each pot. Phosphate fertilizer in the form of ammonium dihydrogen phosphate ($NH_4H_2PO_4$) was applied through drip irrigation at 0.6 g per pot. The drip irrigation water amount was controlled by weight method, with water applied every 3 days according to experimental conditions to maintain soil water content at 70% of field capacity. The treatment lasted for 30 days.

1.3 Sample Collection and Analysis

Soil samples were collected using the stratified cutting method at 5 cm intervals (0–5, 5–10, 10–15, 15–20, 20–25, 25–30 cm). Cotton roots in each soil layer were picked out with tweezers, washed with distilled water, and scanned using a Phantom 9980XL scanner to measure root length. Soil samples from each layer were also collected, air-dried, ground, and passed through a 0.15 mm sieve. Soil available phosphorus content was determined using the molybdenum-antimony anti-colorimetric method with $NaHCO_3$. The above-ground parts of cotton were divided into stems and leaves after measuring plant height, stem diameter, and leaf count. Fresh weight was measured for each part, then they were placed at 105°C for 30 minutes, and dry weight was measured. The samples were crushed and digested using H_2SO_4-H_2O_2 for 30 minutes, and phosphorus content was determined using the vanadium-molybdenum yellow colorimetric method.

1.4 Data Processing

Spatial distribution maps of soil phosphorus were drawn using Surfer 21 software. All statistical analyses were performed using SPSS 29.0 (IBM Corp., Armonk, NY, USA). Single-factor ANOVA and least significant difference (LSD) multiple comparison methods were used for data analysis. Microsoft Excel was used for data organization and preliminary calculations.

Results and Analysis

2.1 Effects of Soil Temperature on Cotton Growth Traits

As shown in Figure 2, cotton grew best under medium temperature treatment. Compared with high and low temperature treatments, plant height (Figure 2a) was 17.06% and 49.77% higher, stem diameter (Figure 2b) was 73.85% and 29.86% higher, leaf number (Figure 2c) was 28.62% and 72.22% higher, and total root length (Figure 2d) was 3.61% and 16.98% higher, respectively. These results indicate that medium temperature (22–26°C) was optimal for cotton vegetative growth.

2.2 Effects of Soil Temperature on Cotton Biomass and Allocation

Medium temperature treatment produced the maximum cotton biomass, followed by low temperature, with high temperature producing the minimum (Figure 3). Root biomass allocation increased continuously with surface temperature. Stem biomass allocation showed minimal differences between low and medium temperature treatments, with high temperature treatment showing the lowest allocation. Leaf biomass allocation was highest under low temperature treatment, with no significant difference between low and high temperature treatments, and medium temperature treatment showing the lowest allocation.

2.3 Effects of Soil Temperature on Cotton Root Length Distribution

The effects of soil temperature on vertical distribution of cotton root length are shown in Figure 4. Compared with low temperature treatment, high temperature treatment showed a trend of decreasing root length with soil depth, while medium temperature treatment showed gradually increasing root length with depth. In the 0–5 cm soil layer, high temperature treatment had the greatest root length, reaching 530.5 cm, which was 5.2%-126.9% and 4.9%-62.3% higher than low and medium temperature treatments, respectively. Below the 5 cm soil layer, medium temperature treatment had the longest root length, 81.68%–98.43% and 170.17%-218.35% longer than low and high temperature treatments, respectively. High temperature treatment resulted in more roots distributed in shallow soil, while medium and low temperature treatments showed characteristics of increasing root length with soil depth.

2.4 Effects of Soil Temperature on Soil Available Phosphorus Distribution

Overall, soil available phosphorus content decreased with soil depth. As shown in Figure 5, high soil available phosphorus content was generally located near the surface drip emitter. Soil available phosphorus content across treatments showed a trend of decreasing with increasing temperature. In the 0–5 cm soil layer, medium and high temperature treatments reduced available phosphorus by 13.7% and 20.5% compared to low temperature treatment, respectively, showing obvious depletion.

2.5 Correlation Between Soil Available Phosphorus Content and Cotton Root Length at Different Temperatures

Correlation analysis between soil available phosphorus content and cotton root length at different temperatures (Figure 6) showed a significant negative correlation under all three temperature treatments. The negative correlation was stronger under low and medium temperature treatments, while it was weaker under high temperature treatment. This indicates that higher soil available phosphorus content was not conducive to cotton root length increase.

2.6 Effects of Soil Temperature on Cotton Phosphorus Utilization Efficiency

Analysis of the effects of different soil temperatures on cotton phosphorus absorption and phosphorus fertilizer utilization efficiency (Table 1) showed that both were highest under medium temperature treatment, followed by low temperature, and lowest under high temperature. Phosphorus absorption was 49.69% and 89.36% higher under medium temperature compared to low and high temperature treatments, respectively. Phosphorus utilization efficiency also showed significant differences, with medium temperature treatment being the highest, twice as high as high temperature treatment and 50% higher than low temperature treatment. All organs showed similar patterns.

Discussion

3.1 Effects of Soil Temperature on Cotton Growth

Plant growth and development require water, nutrients, air, and heat obtained from soil. Cotton plant height, stem diameter, leaf number, and biomass are important indicators reflecting cotton growth and development. Biomass allocation is a plant’ s response to resource distribution patterns, resulting from allocation among different organs through photosynthesis and respiration. This allocation among plant organs is regulated by external environmental changes and related to plant growth characteristics.

Previous research has found that as soil temperature increases, cotton plant height, stem diameter, leaf number, and biomass all increase to varying degrees. Low soil temperature leads to thin stems, short plants, reduced leaf number and biomass, and decreased plant yield. Within a certain range, increasing soil temperature can promote cotton growth and development. However, if temperature is too high or remains high for extended periods, cotton seed survival rate, germination rate, seedling plant height, stem diameter, leaf number, root length, flowering and boll setting during the boll period, lint yield, seed cotton yield, and fiber quality are all affected, easily leading to yield reduction or even plant death. High temperature disrupts photosynthesis and other physiological activities in most crops, directly affecting yield. This study found that all cotton growth traits showed trends of first increasing then decreasing with soil temperature increase, with medium temperature treatment showing the best growth performance, consistent with findings from related scholars.

3.2 Effects of Soil Temperature on Cotton Root Length Distribution

Temperature is an important factor affecting root growth. Roots require a suitable temperature range to maintain normal growth rates and function, and their optimal temperature is often lower than that of above-ground parts. As the medium for plant-soil "communication," root quantity and distribution in soil directly determine crop productivity. Different light and temperature environments change cotton root diameter, root surface area, root biomass, and root length density distribution in soil. If soil temperature is too high, plants reduce carbohydrate transfer from above-ground parts to roots, limiting root development and reducing root-to-shoot ratio. High temperature also changes root architecture. Root architecture determines the soil volume that roots can contact and is the main factor controlling plant nutrient absorption efficiency.

Studies on wheat, sweet potato, sorghum, and maize have shown that under high temperature stress, crop primary roots become shorter, lateral root growth and number decrease, root growth angle decreases, and the number of secondary and tertiary roots with larger diameters increases. The explanation is that high temperature reduces root cell division rate. Soil temperature changes significantly affect root growth and development, and high temperature in the soil surface layer limits crop root colonization and survival. This study found that in the 0–5 cm soil layer, high temperature treatment produced the maximum root length of 530.5 cm, 5.2%–126.9% and 4.9%–62.3% higher than low and medium temperature treatments, respectively. Below the 5 cm soil layer, medium temperature treatment had the longest root length, 81.68%–98.43% and 170.17%–218.35% longer than low and high temperature treatments, respectively. High temperature roots were more distributed in shallow soil, likely because as soil temperature increases, plants reduce carbohydrate transfer from above-ground parts to roots, limiting root development, reducing root-to-shoot ratio, and decreasing below-ground dry weight. From these results, cotton root growth shows stronger tolerance to high soil temperature compared with other crops. Additionally, appropriately increasing low temperature is beneficial for cotton root colonization in the soil surface layer, which is advantageous for improving drip phosphorus fertilizer utilization efficiency. This also indicates that the soil temperature gradient set in this study could be further increased, and related research needs to be further conducted.

3.3 Effects of Soil Temperature on Soil Available Phosphorus Distribution and Cotton Phosphorus Fertilizer Utilization

Soil available phosphorus content is an important indicator of soil phosphorus supply capacity. Due to poor phosphorus mobility, drip application of phosphorus fertilizer at the surface leads to high accumulation in surface soil. Roots are plant organs in direct contact with soil, and the amount of phosphorus fertilizer absorbed by plants is closely related to root spatial distribution. Studies have found that having greater root surface area (lateral roots, root hairs) in surface soil is an ideal root characteristic for efficient phosphorus absorption. A series of experiments have proven that relatively shallow root systems are beneficial for efficient phosphorus acquisition. This study found that in the 0-5 cm soil layer across different temperature treatments, root length increased with temperature while soil available phosphorus content decreased with temperature, showing obvious depletion. Therefore, increased spatial matching between roots and phosphorus contributes to phosphorus absorption, corresponding to conclusions from the aforementioned scholars.

Both phosphorus absorption amount and phosphorus fertilizer utilization efficiency can serve as indicators for determining phosphorus fertilizer yield increase and efficiency improvement. Suitable soil temperature can enhance crop respiration and strengthen phosphorus absorption capacity. It can also improve various enzymatic reactions in crops, increasing respiration and thereby enhancing root phosphorus absorption and utilization efficiency. This study found that medium temperature treatment produced the highest cotton phosphorus absorption and utilization efficiency, consistent with conclusions from Duan Gangqiang et al. In this study, due to pot size limitations, cotton plant growth, root size, and spatial distribution differed from field conditions, but cotton growth basically reflected its response to soil temperature changes. Overall, controlling soil temperature at 22-26°C is most beneficial for cotton phosphorus absorption and utilization efficiency improvement. In actual production practice, soil temperature can be increased through double-layer mulching, organic fertilizer application, and windbreak establishment, or decreased through irrigation water temperature control and straw mulching measures, thereby regulating cotton root proliferation in specific zones to improve drip phosphorus fertilizer utilization efficiency. Therefore, these research results have certain reference value for achieving efficient utilization of drip-applied phosphorus fertilizer through soil temperature regulation. Future research should further conduct full growth period verification tests under field conditions and propose operable soil temperature control technologies based on the special production patterns of Xinjiang cotton fields.

Conclusion

With increasing soil temperature, cotton plant height, stem diameter, leaf number, and biomass all showed trends of first increasing then decreasing. Medium temperature treatment (22-26°C) was most favorable for cotton growth and development, and under these conditions, cotton phosphorus absorption and utilization efficiency were also highest (0.12 $kg \cdot kg^{-1}$). The underlying mechanism is that suitable soil temperature promotes proliferation of cotton roots in the 0–5 cm soil layer, and the corresponding depletion of available phosphorus in this layer provides supporting evidence. In conclusion, maintaining soil temperature at 22–26°C is beneficial for cotton growth and drip phosphate fertilizer utilization efficiency improvement.

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Note: Figure translations are in progress. See original paper for figures.