Effects of Irrigation Threshold and Drip Tape Burial Depth on Greenhouse Tomato Growth Postprint

Authors: Gu Jun, Niu Wenquan, Lü Wang, Yuan Li, Liang Bohui, Guo Lili

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Abstract

To elucidate the mutual feedback mechanism between tomato root growth and water distribution, a subsurface drip irrigation experiment was conducted in a solar greenhouse, employing four drip line burial depths (0 cm, 10 cm, 20 cm, and 30 cm) and three irrigation lower limits (maintaining soil water content at 50%, 60%, and 75% of field capacity) to investigate the effects of different irrigation lower limits and drip line burial depths on tomato root growth and dry matter partitioning. The results demonstrated that under mild and moderate water deficit conditions (irrigation lower limits of 75% and 60% field capacity), drip line burial depth exerted a significant influence on tomato water consumption, with burial depths of 10–20 cm enhancing water consumption. Increased drip line burial depth decreased root distribution in the 0–20 cm soil layer while promoting root growth in the 20–60 cm soil layer; drip line burial depth significantly affected root growth in the 0–10 cm, 20–30 cm, and 30–40 cm soil layers, but showed no significant effect on root growth in the 50–60 cm soil layer. Irrigation lower limit significantly impacted the root length and root surface area of both fine roots (d<1 mm) and coarse roots (d>1 mm), while drip line burial depth significantly affected fine root length and surface area; mild water deficit combined with a 20 cm drip line burial depth favored the growth of fine root length and surface area, reducing the proportion of coarse roots. The findings of this study indicate that mild water deficit and a drip line burial depth of 20 cm were more favorable for whole-plant dry matter accumulation, an irrigation lower limit of 75% field capacity could increase the root dry matter allocation proportion, whereas a 20 cm drip line burial depth promoted dry matter translocation to stems and leaves while reducing the root dry matter allocation proportion.

Effects of Irrigation Threshold and Lateral Depth on Tomato Growth in Greenhouse

GU Jun[1], NIU Wenquan[1,2] , LYU Wang[2], LI Yuan[1], LIANG Bohui[2], GUO Lili[2]

[1]Institute of Soil and Water Conservation, Northwest A&F University, Yangling 712100, China

[2]College of Water Resources and Architectural Engineering, Northwest A&F University, Yangling 712100, China

Abstract

Soil water is critical for crop growth, yield, and water use efficiency. To investigate the mutual responsive mechanism between root growth and different irrigation methods (e.g., deficit and lateral irrigation) on soil water distribution, root distribution, and dry matter distribution in tomato, a subsurface drip irrigation experiment was conducted in a sunlit greenhouse in Dazhai Village, Dazhai Town, Yangling City, Shaanxi Province. The study was designed as a two-factor experiment—lateral depth (D) and irrigation threshold (I). The lateral depth was divided into four levels (0 cm, 10 cm, 20 cm, and 30 cm below the surface of ridges) and the irrigation threshold set at 50%, 60%, and 75% of field capacity. Each treatment was repeated three times. The results showed that lateral depth had a significant effect on water consumption of tomato under mild water deficit (75% of field capacity) and moderate-mild water deficit (60% of field capacity) conditions, while lateral depth of 10-20 cm was much better for root water uptake than other treatments. Increase in lateral depth reduced the distribution of roots in the 0-20 cm soil layer, but promoted the growth of roots in the 20-60 cm soil layer. Lateral depth had a significant effect on root growth in the 0-10 cm, 20-30 cm, and 30-40 cm soil layers, but had no significant effect on root growth in the 50-60 cm soil layer. Root length and root surface area of fine roots (with diameter less than 1 mm) and coarse roots (diameter greater than 1 mm) of tomato were significantly affected by irrigation threshold. However, lateral depth only had a significant effect on root length and root surface area of fine roots. Then mild water deficit and lateral depth of 20 cm favored root length and surface area growth of fine roots, but reduced the growth of coarse roots. Mild water deficit and lateral depth of 20 cm better favored total dry matter accumulation, while the 75% of field capacity treatment increased root dry matter allocation. Then lateral depth of 20 cm promoted dry matter accumulation of stems and leaves, but reduced the distribution ratio of root dry matter. For the observed responses, information on how root distribution and dry matter allocation in tomato adapted to different irrigation methods provided a useful guide for field production practices and possible indicator mechanisms for high quality/yield.

Keywords: Subsurface drip irrigation; Lateral depth; Irrigation threshold; Root distribution; Dry matter distribution; Tomato

Introduction

Roots serve the functions of absorbing soil water and nutrients while providing fixation and support for plants, making them the most active absorption organs in crops. A crop' s ability to absorb water and nutrients, as well as its yield formation, is closely related to root growth, while soil moisture can affect root morphology, distribution, and root-to-shoot ratio. Previous studies have shown that a mutual feedback relationship exists between root distribution and soil moisture. High soil moisture can inhibit root growth, reduce root vigor, and cause premature root senescence, whereas water deficit can promote downward root growth to some extent but reduces primary and secondary root numbers, failing to meet plant water requirements. Water supply depends not only on quantity but also on its distribution in the soil profile. Water concentrated in the surface soil layer results in shallow root distribution, which is unfavorable for absorbing water and nutrients from deep soil layers. Conversely, excessive deep soil moisture, while promoting downward root growth due to hydrotropism, increases root dry matter consumption and is not conducive to yield formation. Therefore, research on soil moisture distribution and content in the field is important for crop growth and yield formation.

Subsurface drip irrigation is a precision irrigation method that delivers water directly to the crop root zone through buried laterals. This irrigation method can effectively reduce ineffective surface evaporation and improve plant water use efficiency, representing a new highly efficient water-saving irrigation technology. Lateral depth (water supply depth) is one of the important factors affecting soil water movement and distribution under subsurface drip irrigation. Appropriate lateral depth can create a suitable water, fertilizer, gas, and heat environment in the root zone, significantly affecting plant root morphology and distribution, rationally allocating dry matter, achieving optimal root-to-shoot ratio, and improving plant water use efficiency. Liu et al. found that lateral depth significantly affected the depth at which maximum root length density occurred in tomato (*Lycopersicon esculentum* Miller), and the proportion of deep roots increased with lateral depth, but tomato dry matter mass and nitrogen uptake decreased with increasing lateral depth. Patel et al. showed that under sandy loam conditions, full irrigation with a 10 cm lateral depth was the optimal irrigation method to obtain maximum benefit ratio. Machado et al. demonstrated that for tomato, lateral depth had no significant effect on root length density under certain irrigation conditions, but roots tended to cluster at the lateral location. In-depth research on the mutual feedback mechanism between soil moisture changes and crop root growth and development under different lateral depths and various water irrigation conditions is helpful for the precise design and water management of subsurface drip irrigation systems.

Current research on lateral depth effects on tomato has focused on yield and water efficiency, mostly addressing single mechanisms, with relatively insufficient research on tomato root distribution and dry matter allocation. This study set up three different irrigation thresholds and lateral depths to explore the effects of these two factors on water distribution, consumption, vertical root distribution, and dry matter allocation, aiming to clarify the mutual feedback mechanism between root distribution and water distribution and provide a strong theoretical basis for water management of tomato in solar greenhouses.

1.1 Experimental Site and Materials

The experiment was conducted from October 8, 2015, to April 19, 2016, in a solar greenhouse in Dazhai Township, Yangling City, Shaanxi Province. The experimental site is located at 108°02 E, 34°02 N, with an elevation of 506 m, an average annual temperature of approximately 16.1°C, annual sunshine hours of 2,164.8 h, and a frost-free period of 210 days, belonging to a warm temperate semi-humid continental monsoon climate. The greenhouse was 108 m long and 8 m wide, covered with semi-drip-proof polyethylene film. The experimental soil was Yangling soil with a bulk density of 1.39 g • cm ^{3}, mass water content of 23.63%, and porosity of 45.83%. Sand particles (0.02–2 mm) accounted for 25.4%, silt (0.002–0.02 mm) for 44.1%, and clay (0.002 mm) for 30.5%.

The tomato variety was ‘Haidi’ . Seedlings were transplanted on October 2, and each plot was irrigated with 30 mm after transplanting to ensure seedling survival. Each experimental plot was 5.5 m long and 1 m wide, with a 50 cm operating row between adjacent plots to prevent water infiltration between plots. Each plot contained 28 tomato seedlings planted in double rows with a spacing of 0.4 m between plants and 0.5 m between rows. Film mulching was applied after transplanting. One drip irrigation tape was laid in the middle of each plot, 25 cm from the tomato plants, with emitter spacing of 0.3 m and emitter flow rate of 2.8 L • h ^{1}. A 1 m long moisture monitoring tube was installed 5 cm from the lateral in the middle of each plot, and soil moisture was measured using a Field TDR 200 detector. All other agronomic techniques and fertilization management measures were consistent across treatments throughout the growth period.

1.2 Experimental Design

The experiment consisted of three irrigation thresholds: 50% of field capacity (severe water deficit, I), 60% of field capacity (moderate-mild water deficit, I), and 75% of field capacity (mild water deficit, I). The upper irrigation limit was uniformly set at 90% of field capacity. Lateral depth (D) was set at four levels: 0 cm (D), 10 cm (D), 20 cm (D), and 30 cm (D). A comprehensive experimental design was adopted, with 12 treatments and three replications, totaling 36 experimental plots. The planned wetting layer depth for each plot during the entire growth period was 40 cm. When soil water content reached the set value, the plot was irrigated, and irrigation volume was recorded by a water meter. Since it was difficult to precisely control the irrigation threshold during actual operation, each treatment was set with a ±2% range value (as a percentage of field capacity). The irrigation volume calculation formula was:

$$M = s \cdot r \cdot p \cdot h \cdot \theta_f \cdot (q_1 - q_2)/\eta$$

where M is irrigation volume (m^3); s is planned wetting layer area, taken as 5.5 m^2; r is soil bulk density, taken as 1.39 g·cm ^{3}; p is wetting ratio, taken as 100%; h is wetting layer depth, taken as 0.4 cm; __f is field capacity (volumetric water content), %; q and q are upper irrigation limit and lower soil limit (expressed as percentage of relative field capacity), %; and is water use efficiency, taken as 0.95 for subsurface drip irrigation.

The irrigation quota per application and total irrigation volume for each plot during the growth period are shown in Table 1 .

Table 1 Irrigation water quota and total irrigation water in growth period of tomato under different irrigation thresholds and lateral depths

Note: I , I , I mean irrigation thresholds of 50%, 60%, 75% of field capacity, respectively. D , D , D , D mean lateral depths of 0 cm, 10 cm, 20 cm, 30 cm, respectively.

1.3.1 Soil Moisture Measurement

Soil moisture was measured using a Field TDR 200 detector, with data collected every 10 cm to a maximum depth of 90 cm. Measurements were taken every 5 days throughout the growth period, once before transplanting and once after harvest, with two additional intensive measurements taken before irrigation in each plot.

1.3.2 Tomato Water Consumption

Based on experimental site conditions (no groundwater or precipitation recharge), tomato water consumption was calculated using the formula:

$$W = I + W_{t-1} - W_t$$

where W is tomato water consumption (mm); I is irrigation volume (mm); and *W_{t-1}* and *W_t* are soil water storage in the 0–60 cm layer at the beginning and end of the measurement period, respectively (mm).

1.3.3 Root Index Measurement

At the end of the maturity stage, three tomato plants were randomly selected from each plot. After removing the aboveground parts, a 6 cm diameter root auger was used to collect root samples close to the main root every 10 cm to a depth of 60 cm. The collected samples were soaked in water to loosen them, then rinsed with slow water flow and passed through a 0.5 mm sieve to obtain root samples. Root samples were scanned using an EPSON Perfection V700 scanner, and the scanned images were analyzed using WinRHIZO Pro software to obtain root length data. Root length density in each soil layer = total root length in each soil layer / volume of soil auger sample.

1.3.4 Dry Weight Ratio of Tomato Plant Organs

At maturity, three tomato plants with consistent growth were randomly selected from each plot. After sampling, roots, stems, leaves, and fruits were immediately separated. Samples were placed in an oven at 105°C for 15 minutes to deactivate enzymes, then dried at 70°C to constant weight. After cooling, each organ’ s dry weight was measured using a 0.01 g precision balance, and the dry weight ratio of each plant organ was calculated.

1.4 Data Processing

Experimental data were organized using Microsoft Excel software. Significance tests and interaction analysis of variance were performed using Duncan’ s new multiple range method in SPSS 22.0 statistical software, and figures were created using Origin 9.0 software.

2.1 Effects of Different Irrigation Thresholds and Lateral Depths on Soil Moisture Changes

Figure 1 [Figure 1: see original paper] shows soil moisture distribution 24 hours after irrigation and before the next irrigation within one irrigation cycle at the maturity stage. Due to different irrigation depths, surface drip irrigation and subsurface drip irrigation resulted in substantial differences in water distribution in the soil profile. As shown in Figure 1, overall soil moisture content at different depths initially increased and then decreased with increasing lateral depth. The maximum soil moisture content appeared in the 0-10 cm, 10-20 cm, 20-30 cm, and 30-40 cm soil layers for the 0 cm, 10 cm, 20 cm, and 30 cm burial depths, respectively, indicating that increased lateral depth caused the position of maximum soil moisture content to shift downward. Before the next irrigation, soil moisture changes below 60 cm were small across all treatments, ranging from 0.52% to 1.72%. The average soil moisture content in the 0-60 cm layer for I and I treatments was 18.03% and 20.43%, respectively, which was 12.94% and 23.19% lower than that of the I treatment. Analysis of variance showed significant differences among irrigation treatments ($P < 0.05$). Under the same irrigation treatment, soil moisture content varied significantly among lateral depths at 0 cm, 20 cm, 30 cm, and 40 cm depths, with ranges of 0.86%-4.94%, 0.62%-5.29%, 0.94%-5.75%, and 0.12%-4.75%, respectively, while differences at 10 cm, 50 cm, and 60 cm depths were all below 3.50%. These results indicate that different water deficit levels were the main factor affecting average moisture content, while lateral depth had greater influence on moisture content in the surface and 20-40 cm soil layers and less influence on the 50-60 cm layer.

During one irrigation cycle, tomato water consumption in the 0-60 cm layer increased significantly with irrigation threshold (Table 2). Water consumption for I and I treatments was 2.02 and 2.72 times that of the I treatment. For I and I treatments, tomato water consumption in the 0-60 cm layer initially increased and then decreased with increasing lateral depth. For I , water consumption at 10 cm and 20 cm depths differed significantly from that at 0 cm and 30 cm depths. For I , water consumption at 20 cm depth increased by 13.55%, 6.20%, and 3.24% compared with 0 cm, 10 cm, and 30 cm depths, respectively, and reached significant difference with the 0 cm depth treatment. Under I treatment, lateral depth had no significant effect on tomato water consumption in the 0-60 cm layer, but water consumption at 10 cm and 20 cm depths increased by 12.94% and 12.30%, respectively, compared with the 30 cm depth. These results demonstrate that tomato water consumption was mainly affected by irrigation threshold, and that 10-20 cm lateral depth improved tomato water consumption under mild and moderate-mild water deficit conditions.

2.2 Distribution of Tomato Root Length Density in Soil Profile Under Different Irrigation Thresholds and Lateral Depths

Figure 2 [Figure 2: see original paper] shows the effect of lateral depth on root length density under different irrigation thresholds. Overall, tomato root length density decreased with soil depth, with tomato roots concentrated mainly in the 0-30 cm soil layer. The proportion of root length density in the 0-30 cm depth range accounted for 72.35%-90.23% of total root length density across different irrigation treatments. For all irrigation treatments, root length density in the 0-20 cm layer decreased with increasing lateral depth. Compared with 0 cm depth, the average root length density proportion decreased by 14.81% and 18.09% for 20 cm and 30 cm depths, respectively, and by 7.26% for the 10 cm depth treatment. In the 20-60 cm soil depth range, the proportion of tomato root length density increased with lateral depth. Compared with the 30 cm depth, average root length density decreased significantly for 0 cm and 10 cm depths, with reductions of 35.21% and 21.22%, respectively, while the 20 cm depth only decreased by 6.42%. These results indicate that increased lateral depth reduced surface root distribution and promoted downward root growth, with roots concentrating at the lateral depth position.

Different lateral depths caused differences in root distribution in the soil profile. Under each irrigation treatment, lateral depth had a significant effect on tomato root length density in the 0-10 cm and 30-40 cm layers. Root length density in the 0-10 cm layer decreased significantly with increasing lateral depth, with significant differences between the 0 cm depth and both 20 cm and 30 cm depth treatments. In the 30-40 cm layer, tomato root length density under I and I treatments was significantly higher for 20 cm and 30 cm depths than for 0 cm and 10 cm depths, with no significant difference between 0 cm and 10 cm depths. Under I treatment, the 30 cm depth significantly increased root length density compared with other depths, while no differences were observed among 0 cm, 10 cm, and 20 cm depths. In the 10-20 cm layer, except for I treatment, 10 cm and 20 cm depths significantly increased tomato root length density compared with 0 cm and 30 cm depths, with no significant difference between 10 cm and 20 cm depths. In the 20-30 cm layer, lateral depth had a significant effect on tomato root length density under I and I treatments but not under I treatment. Under all irrigation conditions, the 20 cm lateral depth treatment showed maximum root length density, reaching significant difference with the 0 cm depth treatment in the 40-50 cm layer. Under I and I treatments, root length density at 20 cm depth was significantly higher than other depth treatments, while under I treatment, root length density at 20 cm and 30 cm depths was significantly higher than at 0 cm and 10 cm depths, with no significant difference between 0 cm and 10 cm depths. In the 50-60 cm layer, root length density at 0 cm and 30 cm depths was lower than at 10 cm and 20 cm depths, with no significant effect of lateral depth on tomato root length density. These findings indicate that the maximum root length density generally shifted downward with increasing lateral depth, and that lateral depth caused significant differences in root growth in the 0-10 cm, 20-30 cm, and 30-40 cm layers due to moisture differences, while water in the 50-60 cm layer had weaker effects on root growth.

2.3 Effects of Different Irrigation Thresholds and Lateral Depths on Root Characteristics of Different Diameters

Table 3 shows the characteristic parameters of roots of different diameters for each treatment. Root length of different diameters initially increased and then decreased with irrigation threshold. For roots with $d < 1$ mm, root length increased by 16.60% and 10.30% under I and I treatments compared with I, respectively. The I treatment significantly increased the proportion of $d < 1$ mm roots, increasing by 4.68% and 3.19% compared with I and I treatments, respectively. For roots with $d > 1$ mm, root length under I treatment increased significantly by 33.15% and 73.27% compared with I and I treatments, respectively, while also increasing the proportion of $d > 1$ mm roots, which decreased by 11.13% and 36.00% under I and I treatments, respectively. These results indicate that mild water stress promoted fine root growth and reduced coarse root proportion, while moderate-mild water stress showed the opposite effect. Root length of $d > 1$ mm initially increased and then decreased with lateral depth, while root length of $d < 1$ mm generally decreased and then increased with lateral depth. Compared with other depths, the 20 cm depth increased the proportion of $d < 1$ mm roots and decreased the proportion of $d > 1$ mm roots.

For $d < 1$ mm roots, root surface area increased significantly with irrigation threshold, and root surface area at 20 cm depth increased significantly compared with other treatments. For $d > 1$ mm roots, root surface area reached maximum under I treatment, and root surface area at 10-20 cm depth was lower than at 0 cm and 30 cm depths for treatments other than I . Compared with I and I treatments, I treatment increased the proportion of root surface area for $d < 1$

mm roots and decreased the proportion for d > 1 mm roots, while I showed the maximum proportion of root surface area for d > 1 mm roots. Compared with 0 cm, 10 cm, and 30 cm depths, the 20 cm depth increased the proportion of root surface area for d < 1 mm roots by 10.65%, 4.89%, and 12.51%, respectively, and decreased the proportion for d > 1 mm roots by 21.91%, 10.07%, and 25.75%, respectively. These results demonstrate that 20 cm lateral depth was beneficial for fine root growth and development while reducing coarse roots.

Analysis of variance showed that irrigation threshold and lateral depth had highly significant effects on root length and root surface area of d < 1 mm roots, with irrigation threshold having a greater effect than lateral depth. Irrigation threshold also had highly significant effects on root length and root surface area of d > 1 mm roots, while lateral depth had no significant effect on root length or root surface area of d > 1 mm roots. The interaction between the two factors had highly significant effects on root length and root surface area of different diameters. These results indicate that water stress was the main factor affecting root growth, while lateral depth mainly affected fine root growth. In summary, irrigation threshold significantly affected root length and root surface area of both fine and coarse roots, while lateral depth only affected fine root growth. An irrigation threshold of 75% field capacity and 20 cm lateral depth were beneficial for fine root length and root surface area growth while reducing the proportion of coarse roots.

2.4 Effects of Different Irrigation Thresholds and Lateral Depths on Tomato Dry Matter

Table 4 shows the effects of lateral depth on tomato dry matter allocation under different water deficits at maturity. Total plant dry weight at 20 cm depth was significantly higher than other treatments, with no significant difference between 0 cm and 30 cm depths. Under the same lateral depth, total plant dry weight increased significantly with irrigation threshold. These results indicate that 20 cm lateral depth with mild water deficit irrigation (irrigation threshold of I) was beneficial for tomato dry matter accumulation.

Analysis of variance showed that irrigation threshold had highly significant effects on root, stem-leaf, and fruit dry weights. Average root dry weight under I treatment was higher than under I and I , increasing by 36.01% and 13.30%, respectively. Stem-leaf and fruit dry weights increased with irrigation threshold, with I and I treatments showing significantly higher stem-leaf and fruit dry weights than I treatment. No significant difference in stem-leaf weight was observed between I and I treatments, while fruit dry weight under I was significantly lower than under I treatment at 0 cm and 20 cm depths.

Lateral depth had no significant effect on root and fruit dry weights but had a highly significant effect on stem-leaf dry weight. Under I treatment, dry weight of each organ initially increased and then decreased with lateral depth, with 20 cm depth showing the lowest root dry weight proportion and a relatively high stem-leaf dry weight proportion of total dry matter. Under I treatment, 20 cm depth showed higher stem-leaf and fruit dry weights and stem-leaf dry weight proportion of total dry matter than other treatments, while fruit dry weight proportion of total dry matter was the lowest but with small differences from other treatments. The 30 cm depth showed the maximum root dry weight proportion, increasing by 16.01%, 5.84%, and 7.55% compared with 0 cm, 10 cm, and 20 cm depths, respectively. Under I treatment, 10 cm depth showed the highest root and fruit dry weight proportions of total dry matter. Compared with 10 cm and 30 cm depth treatments, 0 cm and 20 cm depths showed lower root and leaf dry weight proportions of total dry matter but higher stem-leaf dry weight proportions. The interaction between irrigation threshold and lateral depth had significant effects on total plant dry weight, stem-leaf dry weight, and fruit dry weight, but no significant effect on root dry weight or root-to-shoot ratio.

Root-to-shoot ratio is an important indicator reflecting the coordination between root and aboveground growth. Under each water treatment, I showed a significantly higher root-to-shoot ratio than I treatment. Under I treatment, the average root-to-shoot ratio across lateral depths showed no significant difference from I and I treatments. Lateral depth had no significant effect on tomato root-to-shoot ratio, with 20 cm lateral depth treatment showing lower root-to-shoot ratio than other lateral depth treatments. Under I and I treatments, 10 cm and 30 cm lateral depths showed higher root-to-shoot ratios than other depths. In summary, mild water deficit was beneficial for dry matter translocation to roots, while 20 cm lateral depth could reduce dry matter translocation to roots and promote dry matter accumulation in stems and leaves.

This study investigated the effects of different irrigation methods on soil moisture, root growth, and dry matter allocation through greenhouse drip irrigation experiments, providing important guidance for water management of greenhouse tomatoes. Since this experiment was conducted in a greenhouse, further research is needed under more complex field conditions.

Key Findings

1) Increased lateral depth caused the position of maximum soil moisture content to shift downward, with greater influence on moisture content in the surface and 20-40 cm soil layers and less influence on the 50-60 cm layer. Under mild and moderate-mild water deficit, lateral depth had a significant effect on tomato water consumption, with 10-20 cm lateral depth improving tomato water consumption.

2) Increased lateral depth reduced root distribution in the 0-20 cm soil layer and promoted root growth in the 20-60 cm soil layer, with roots concentrating at the lateral depth position. Lateral depth significantly affected root growth in the 0-10 cm, 20-30 cm, and 30-40 cm layers but had no

significant effect on root growth in the 50–60 cm layer.

3) Irrigation threshold significantly affected root length and root surface area of both fine and coarse roots, while lateral depth significantly affected only fine root growth. An irrigation threshold of 75% field capacity and 20 cm lateral depth were beneficial for fine root length and root surface area growth while reducing the proportion of coarse roots.
4) An irrigation threshold of 75% field capacity and lateral depth of 20 cm were more conducive to total plant dry matter accumulation. An irrigation threshold of 75% field capacity could increase root dry matter allocation proportion, while 20 cm lateral depth could promote dry matter translocation to leaves and reduce root dry matter allocation proportion.

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