Analysis of Soil Moisture Dynamics under Direct-Insertion Root Irrigation in Shapotou District (Postprint)

Authors: Ma Zhenyong, Du Hulin, Liu Rongguo, Yan Zizhu, Liu Ligang, Liu Chao, Niu Jinshuai

Date: 2017-11-07T00:00:00+00:00

Abstract

To improve water use efficiency during afforestation and formulate an optimal irrigation regime in the Shapotou region, a water-saving experiment using direct-insertion root irrigation was conducted in a two-year-old sand-fixing Haloxy lonammodendron forest in the Shapotou Nature Reserve of Zhongwei, Ningxia, to analyze and simulate soil water infiltration and recession patterns during direct-insertion root irrigation. The results showed that: 1) During direct-insertion root irrigation, the variation of soil water content with irrigation time followed a Logistic curve; after irrigation cessation, the soil water recession pattern conformed to a power function model. 2) Under the experimental conditions, the maximum infiltration rates of soil water in different soil layers were in the order of 60 cm > 40 cm > 80 cm > 100 cm > 20 cm; the time required to reach the maximum infiltration rate was shortest in the 40 cm soil layer, averaging 1.22 h, and longest in the 100 cm soil layer, averaging 4.57 h; the average maximum infiltration rate in the 1 m deep soil layer was 1.65% · h^{1}, and the average time to reach maximum infiltration rate was 2.16 h. 3) Based on simulation results, it is recommended that the irrigation cycle for direct-insertion root irrigation in Haloxy lonammodendron forests in the Shapotou region be approximately 4 d, with a single irrigation duration of 6–10 h. 4) Two hours after irrigation cessation, the recession rate of soil water content in each soil layer increased with soil depth; 48 h after irrigation cessation, the soil water recession rate in each layer was essentially zero; throughout the entire growth period of Haloxy lonammodendron, the soil water recession rate in the 1 m deep soil layer was highest during the fruiting period at 2.20% · h^{1} and lowest during the dormant period at 1.31% · h^{1}. 5) Direct-insertion root irrigation had the minimal influence on soil water in the 20 cm soil layer and the maximal influence on soil water in the 60 cm soil layer; during irrigation, soil water isolines were radially distributed from the 60 cm soil layer isoline as the center toward the surface and deeper soil layers; after irrigation, the average soil water content in each layer showed significant differences ($P<0.05$) between the 20 cm and 60 cm soil layers and the other layers. The study demonstrates that the soil water infiltration pattern during direct-insertion root irrigation follows a Logistic curve, the recession pattern follows a power function curve, direct-insertion root irrigation has the minimal impact on soil water in the 20 cm soil layer and the maximal impact on soil water in the 60 cm soil layer, the irrigation cycle for direct-insertion root irrigation in Haloxy lonammodendron forests in the Shapotou region is approximately 4 d, and the single irrigation duration should be 6-10 h.

Full Text

Preamble

Chinese Journal of Eco-Agriculture, Jan. 2017, 25(1): 104-117
ChinaXiv Cooperative Journal
DOI: 10.13930/j.cnki.cjea.160596

Variation in Soil Water in Shapotou Area under Straight-Tube Root Irrigation*

MA Zhenyong[1],[2], DU Hulin[1], LIU Rongguo[3], YAN Zizhu , LIU Ligang[3], LIU Chao[3], NIU Jinshuai[3]

[1] Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China
[2] University of Chinese Academy of Sciences, Beijing 100049, China
[3] Ningxia Shapotou National Nature Reserve Administration, Zhongwei 755000, China
Gansu Desert Control Research Institute, Lanzhou 730070, China

Abstract: To improve water use efficiency during afforestation and develop optimal irrigation scheduling in the Shapotou region, a straight-tube root irrigation experiment was conducted on biennial sand-fixation *Haloxylon ammodendron* forests in the Shapotou Nature Reserve of Zhongwei, Ningxia. The study analyzed and modeled soil water infiltration and depletion patterns during straight-tube root irrigation. Results showed that: (1) During irrigation, soil water content variation over time followed a Logistic curve, while post-irrigation depletion followed a power function model. (2) Under experimental conditions, the maximum infiltration rates across soil layers ranked as 60 cm > 40 cm > 80 cm > 100 cm > 20 cm. The 40 cm layer required the shortest time to reach maximum infiltration rate (average 1.22 h), while the 100 cm layer required the longest (average 4.57 h). The average maximum infiltration rate for the 1 m soil profile was $1.65\% \cdot h^{1}$, reached at an average time of 2.16 h. (3) Based on modeling results, the recommended straight-tube root irrigation cycle for *H. ammodendron* forests in Shapotou is approximately 4 days, with single irrigation durations of 6-10 h. (4) Two hours after irrigation cessation, soil water depletion rates increased with soil depth. After 48 h, depletion rates in all layers approached zero. During the entire growth period, the maximum depletion rate in the 1 m soil layer occurred during the grain-filling stage (2.20% · h ^{1}) and the minimum during the aestivation stage (1.31% · h ^{1}). (5) Straight-tube root irrigation had minimal impact on the 20 cm soil layer and maximal impact on the 60 cm layer. During irrigation, soil water content isolines radiated outward from the 60 cm depth line toward both surface and deeper layers. Post-irrigation average soil water contents in the 20 cm and 60 cm layers differed significantly from other layers ($P < 0.05$). The study demonstrates that soil water infiltration under straight-tube root irrigation follows Logistic curves, depletion follows power function curves, with minimal influence on the 20 cm layer and maximal influence on the 60 cm layer. The recommended irrigation cycle is approximately 4 days with 6–10 h per irrigation.

Keywords: Artificial sand-fixation forest; Straight-tube root irrigation; Soil water; Infiltration; Depletion; Irrigation cycle

Introduction

In extremely arid desert regions, water is the key abiotic limiting factor constraining ecological patterns and processes. Improving crop water use efficiency represents a crucial approach to addressing agricultural water scarcity. Water-saving irrigation technologies offer the most direct method for enhancing water utilization efficiency. Straight-tube root irrigation, developed from traditional drip irrigation systems, employs straight-tube seepage emitters and water-conducting micro-tubes to deliver irrigation water directly to plant root zones, achieving minimal or even zero evaporative loss. Soil water movement, distribution, and storage exhibit distinct spatiotemporal dynamics influenced by soil properties, surface water, groundwater, and other factors. Investigating soil water variation patterns under straight-tube root irrigation enables the development of rational irrigation regimes that maximize water conservation.

As a subsurface irrigation technology, straight-tube root irrigation innovatively delivers water directly to specific depths within plant root distribution layers, achieving cross-layer irrigation that reduces soil water evaporation and improves irrigation efficiency. However, limitations exist: the outlet functions as a point source, and under combined gravitational and capillary forces, the soil wetting body forms an irregular ellipsoidal distribution, creating spatially heterogeneous soil water content. This technology requires surface distribution pipes with subsurface micro-tubes, making it unsuitable for dense annual crops like wheat but appropriate for sparse perennial crops such as jujube and fruit trees. Compared with other subsurface drip irrigation technologies, straight-tube root irrigation offers advantages in cost savings and field installation simplicity.

Current research on straight-tube root irrigation primarily focuses on water-saving potential, irrigation scheduling, and soil water trend analysis. Du et al. demonstrated over 30% water savings compared to surface drip irrigation in protective forests along the Tarim Desert Highway. Bao et al. found soil evaporation losses under surface drip irrigation were double those under straight-tube root irrigation for jujube forests in the lower Tarim River. Ma et al. reported stable soil water distribution in 40–60 cm layers during irrigation cycles, with depletion concentrating in the 20 cm layer early in the cycle and shifting to 80 cm later. Du et al. documented a daily soil water depletion rate of 0.69% and an average irrigation cycle of 22 days for jujube forests in the lower Tarim River. However, analysis and modeling of soil water variation patterns during straight-tube root irrigation remain unaddressed, while surface drip irrigation research on soil water-salt movement, water-fertilizer coupling effects, and numerical simulation of soil water transport is well-established.

The Shapotou region experiences scarce rainfall, intense evaporation, and deep groundwater tables. Agricultural production and artificial sand-fixation forests rely heavily on groundwater irrigation, with severe over-extraction—some wells reaching 380 m depth. Current irrigation methods predominantly involve surface drip and flood irrigation, where intense evaporation and leakage result in low water use efficiency. Located on the southeastern edge of the Tengger Desert within the artificial sand-fixation vegetation protection zone along the Baotou-Lanzhou Railway, Shapotou' s primary tasks are cultivating sand-fixing plants and windbreak establishment to ensure railway safety and maintain ecological balance. To improve water use efficiency during afforestation, straight-tube root irrigation experiments were conducted on biennial sand-fixation *H. ammodendron* forests from April to November 2015. By examining soil water variations across different growth stages, this study preliminarily analyzed and modeled soil water infiltration and depletion patterns to provide theoretical foundations for efficient water-saving irrigation technologies and optimal irrigation scheduling for windbreak forest establishment and ecological maintenance.

1.1 Study Area Overview

The experiment was conducted from April to November 2015 at the Ningxia Zhongwei Environmental Protection Ecological Demonstration Base. The site lies on the southeastern edge of the Tengger Desert, west of Shapotou District in Zhongwei City (37°52 N, 105°07 E), adjacent to the Yingyan Highway. The 433.33 hm^2 area has an average elevation of 1,400 m, situated in a transitional zone between the Alxa Plateau desert and desert steppe, representing a typical desert ecosystem nature reserve in China. The region has a mean annual temperature of 9.8 °C (maximum 38.2 °C, minimum -25 °C) with large diurnal temperature variations. Annual precipitation averages 185.6 mm, concentrated in July–September, while annual evaporation reaches 2,500–3,000 mm. Mean relative humidity is 39.1% (minimum 10%). The average annual wind speed is 2.7 m · s ^{1}, with maximum gusts of 19.3 m · s ^{1}; sand-driving winds (>5 m · s ^{1}) occur approximately 196 days annually (based on 1956–2013 data from Shapotou Meteorological Station). The soil matrix consists of loose, infertile mobile aeolian sandy soil, primarily silt (0.01–0.05 mm) and fine sand (0.05–0.25 mm).

Stable water content in the sand layer is only 2–3%, field capacity is 14.8%, and surface soil bulk density is 1.47 g•cm ^{3}. The groundwater table lies at 80 m depth, inaccessible to plants. Natural vegetation includes *Hedysarum scoparium*, *Agriophyllum squarrosum*, and *Artemisia ordosica*.

The experimental site comprised biennial artificially cultivated *H. ammodendron* forests established on leveled mobile dunes fixed with straw checkerboards. The *H. ammodendron* survival rate was 95%, with vigorous growth and average height of 0.5 m. The experimental area covered 2.67 hm^{2} with row and plant spacing of 2 m each.

1.2 Experimental Design

The straight-tube root irrigation system (Patent No. 201120255632.4, invented by Du Hulin) was manufactured by Changzhou Bolite Plastic Industry Co., Ltd. The emitters had a flow rate of 4 L•h ^{1}. The water-conducting microtubes had an outer diameter of 13.0 mm, inner diameter of 5.5 mm, and length of 40 cm, with seepage micropores (1–1.2 mm diameter) uniformly distributed at the 30–40 cm end section. After irrigation, no water remained in the pipes. A schematic diagram is shown in [Figure 1: see original paper].

Soil water content was measured using a PC-2S soil temperature and moisture monitoring system (Liaoning Jinzhou Sunshine Meteorological Technology Co., Ltd.) with TDR (time-domain reflectometry) sensors. A 1 m soil profile was excavated 10 cm from the root irrigation emitter. Five soil moisture sensors were horizontally inserted at 20 cm intervals starting from 20 cm below the surface on the same vertical profile for continuous in-situ monitoring of volumetric water content dynamics. TDR probes were 8.5 cm long, measuring volumetric water content with 0.1% resolution, 0–100% measurement range, and ±2% accuracy.

Emitter spacing matched plant spacing (2 m), and lateral pipe spacing matched row spacing (2 m). To minimize experimental error, three adjacent vigorous *H. ammodendron* plants were selected, with three replicates established on corresponding growth profiles adjacent to emitters. Waterproof plastic sheets (1.5 m deep × 2 m wide) were vertically installed between emitters to prevent interference. TDR recorders continuously collected soil volumetric water content data from three profiles at 1 h intervals to analyze variation patterns during irrigation and depletion.

The experiment was established on April 7, 2015. Irrigation cycles and durations followed local drip irrigation experience. *H. ammodendron* experiences growth peaks in spring and autumn with summer dormancy in July–August. Irrigation events were scheduled as: budding stage on April 15 (17 h) and May 13 (10 h), flowering stage on June 22 (24 h), aestivation stage on August 7 (23 h), grain-filling stage on September 5 (13 h), and seed maturity stage on October 20 (9 h). The budding stage included two irrigation events; other growth stages had one each. Six root irrigation trials without rainfall were selected across the entire growth period, during which *H. ammodendron* grew vigorously. Descriptive statistics (mean, range, standard deviation, coefficient of variation) were calculated for soil water variation during irrigation. Significance analysis was performed on means, and isoline maps of 1 m soil water content were generated to investigate spatiotemporal variability and dynamic distribution patterns.

1.3 Data Processing

All soil water contents reported are volumetric water contents, calculated using arithmetic means. Tables, scatter plots, and line charts were prepared using Microsoft Excel 2007. Soil water isoline maps were generated using Surfer 13.0. Statistical analysis was performed using SPSS 19.0. Other graphics were processed using AutoCAD 2013 and Photoshop CS6.

2.1 Analysis of Soil Water Infiltration Patterns in Different Growth Stages under Straight-Tube Root Irrigation

Soil water variation across layers during six irrigation trials showed that soil water content increase followed three stages: slow initial increase, linear increase during 1-5 h of irrigation, and stabilization at maximum values. After 1 h of irrigation, average soil water content from surface to deep layers was 1.38%, 2.15%, 2.47%, 1.55%, and 0.9%, respectively. After 5 h, values were 2.63%, 7.77%, 12.27%, 9.4%, and 6.68%, respectively. Soil water content (y) variation with irrigation time (x) followed a Logistic equation:

$$y = \frac{K}{1 + A \cdot e^{-Bx}} \tag{1}$$

where y is soil volumetric water content (%), x is irrigation time (h), and K, A, B are curve parameters. Using flowering and grain-filling stages (when *H. ammodendron* growth is most vigorous) as examples, Eq. (1) was fitted to soil water content (y) versus irrigation time (x) for different layers. Initial values for parameter K were determined using the four-point method, while A and B were determined using least squares principles. Fitting results for different layers are shown in ; all models were highly significant. Based on these equations, soil water content at any irrigation time can be calculated for each layer.

The average emitter flow rate across six trials was 3.63 L·h ¹. Due to the experimental site' s sandy soil properties with high hydraulic conductivity, soil water content in all layers except 20 cm increased rapidly within 1-4 h (lasting approximately 2 h). After 4-6 h, each layer reached maximum water content: 8.05% at 40 cm, 12.5% at 60 cm, 9.58% at 80 cm, and 7.47% at 100 cm. Continued irrigation maintained relatively stable water contents. Therefore, with an emitter flow rate of 4 L·h ¹, the minimum single irrigation duration should be 6 h, when soil water content essentially reaches maximum values. Since emitter outlets are distributed at 30-40 cm depth, irrigation water first reaches this depth. Water then moves upward to surface layers (0-30 cm) primarily through capillary forces and root water uptake. The 0–100 cm soil profile consists entirely of sandy soil with weak capillary action, combined with intense surface evaporation, resulting in slow water content increase in the 0–20 cm layer, which reached maximum values only after 8–9 h (average 3.68%). The average maximum water content in the 20 cm layer was 3.79–8.28% lower than other layers.

2.1.2 Changes in Soil Water Infiltration Rate Differentiating Eq. (1) yields the soil water infiltration rate equation:

$$y' = \frac{K \cdot A \cdot B \cdot e^{-Bx}}{(1 + A \cdot e^{-Bx})^2} \tag{2}$$

Substituting parameters (K, A, B) produces equations for infiltration rate versus time. Using flowering and grain-filling stages as examples, infiltration rate curves for different layers were plotted (FIGURE:3). The 20 cm layer showed minimal variation, reaching maximum rates of 0.36% · h ^{1} at 2.37 h (flowering) and 0.49% · h ^{1} at 3.44 h (grain-filling). By 10 h, rates declined to 0.09% · h ^{1} (flowering) and 0.12% · h ^{1} (grain-filling), approaching zero by irrigation end. Other layers showed sharp parabolic changes, with the 60 cm layer exhibiting the highest maximum rates: 9.84% · h ^{1} at 1.34 h (flowering) and 12.55% · h ^{1} at 2.41 h (grain-filling). Across six trials, average infiltration rates in the 1 m profile varied significantly during 0–10 h, with all layers reaching maxima during 1–6 h, then gradually decreasing to <0.01% · h ^{1} after 10 h. This indicates minimal soil water increase after 10 h; considering the sandy soil properties, irrigation beyond 10 h results in nearly 100% water loss. Therefore, 10 h is recommended as the maximum irrigation duration.

Differentiating Eq. (2) yields Eq. (3), which determines maximum infiltration rates. When $y'' = 0$, the corresponding time $x = (\ln A)/B$ represents the occurrence time of maximum infiltration rate, and the corresponding y-value is the maximum rate.

$$y'' = \frac{K \cdot A \cdot B^2 \cdot e^{-Bx} \cdot (A \cdot e^{-Bx} - 1)}{(1 + A \cdot e^{-Bx})^3} \tag{3}$$

Calculations for flowering and grain-filling stages, plus six trials across the entire growth period, showed that time to reach maximum infiltration rate ranked as: 40 cm < 60 cm < 20 cm < 80 cm < 100 cm. The 40 cm layer required the shortest time (0.82 h in flowering, 1.64 h in grain-filling), while the 100 cm layer required the longest (3.49 h and 5.65 h, respectively). Maximum infiltration rates ranked as: 60 cm > 40 cm > 80 cm > 100 cm > 20 cm, with the 60 cm layer highest (9.84% · h ^{1} flowering, 12.55% · h ^{1} grain-filling) and the 20 cm layer lowest (0.36% · h ^{1} and 0.49% · h ^{1}). Across six trials, the 1 m soil profile reached maximum infiltration rate at an average time of 2.16 h, with an average maximum rate of 1.65% · h ^{1}.

2.2 Soil Water Depletion Patterns after Straight-Tube Root Irrigation

Based on TDR data, soil water depletion within 48 h after irrigation cessation was analyzed for individual layers and the 1 m profile average (FIGURE:4). Except for the 20 cm layer, all layers showed rapid depletion during 0–12 h, then slowed. After 48 h, water contents in all layers declined below 5%. Depletion trends followed an obvious "L-shaped" distribution, well-described by power function models.

The general power function expression is:

$$y = C \cdot x^{b} \tag{4}$$

where y is soil water content after irrigation cessation (%), x is time (h), and C, b are parameters.

2.2.1 Analysis of Soil Water Depletion Patterns in Different Layers

Using flowering and grain-filling stages as examples, power function models were fitted to soil water content (y) versus time (x) within 48 h after irrigation cessation. F-test validation confirmed all models were highly significant (R^2 > 0.96). Six trials across growth stages showed the 1 m profile average also followed power function distributions (R^2 > 0.98) (TABLE:4). These models enable calculation of soil water content at any post-irrigation time and depletion amounts between time intervals.

Calculations using TABLE:3 equations showed that after 48 h, water contents in the 20 cm and 40 cm layers were below 1%, while 60 cm, 80 cm, and 100 cm layers contained 1.53%, 1.71%, and 2.34% (flowering) and 1.32%, 1.7%, and 1.24% (grain-filling), respectively. Using TABLE:4 equations, average water content in the 1 m profile after 84 h was below 1% for all six trials (0.58%, 0.54%, 0.92%, 0.96%, 0.74%, and 0.62%), approaching the wilting coefficient for xerophytic plants. Therefore, excluding rainfall and dew formation, an irrigation cycle of 4 days is recommended.

2.2.2 Changes in Soil Water Depletion Rate Differentiating Eq. (4) yields the soil water depletion rate equation (absolute value considered for practical significance):

$$|y'| = |C \cdot b \cdot x^{b-1}| \tag{5}$$

Single irrigation events during flowering and grain-filling stages showed depletion rates decreasing over time (FIGURE:5). Two hours after irrigation cessation, depletion rates ranked as: 100 cm > 80 cm > 60 cm > 40 cm > 20 cm, with the 100 cm layer highest (3.17% • h ^{1}) and the 20 cm layer lowest (0.33% • h ^{1}). After 24 h, all layers had rates <0.06% • h ^{1}. After 48 h, rates approached zero. Across six trials, the maximum average depletion rate for the 1 m profile occurred during the grain-filling stage ($2.20\% \cdot \mathrm{h}^{1}$) and the minimum during aestivation ($1.31\% \cdot \mathrm{h}^{1}$). The average rate dropped sharply after 10 h (from $1.84\% \cdot \mathrm{h}^{1}$ to $0.17\% \cdot \mathrm{h}^{1}$, >90% reduction) and fell below $0.1\% \cdot \mathrm{h}^{1}$ after 24 h.

2.3 Vertical Variation Analysis of Soil Water in Different Growth Stages under Straight-Tube Root Irrigation

Descriptive statistics for six irrigation trials across growth stages were analyzed using one-way ANOVA (TABLE:5). Coefficients of variation ranked as: 100 cm > 80 cm > 60 cm > 20 cm > 40 cm, with the 100 cm layer highest (59.45%) and the 40 cm layer lowest (31.04%). Soil water variation ranges during irrigation ranked as: 60 cm > 80 cm > 100 cm > 40 cm > 20 cm. Post-irrigation mean water contents differed significantly between the 20 cm and 60 cm layers versus other layers ($P < 0.05$), while the 40 cm and 80 cm layers showed no significant difference.

Isoline distribution maps (FIGURE:6) revealed densest isolines near the 60 cm layer and sparsest near the 20 cm layer, forming a patch centered at 60 cm that radiated toward surface and deeper layers. This indicates highest spatial heterogeneity at 60 cm and lowest at 20 cm.

Discussion

Soil water variation and transport represent active research topics in surface drip, subsurface drip, and mulched drip irrigation, influenced by environmental meteorological factors, site conditions, irrigation methods, timing, and amounts. Most research focuses on surface and mulched drip irrigation, employing numerical simulation under controlled conditions, field studies on infiltration models under constant-head conditions, and parameter studies for infiltration models. Few studies address soil water infiltration patterns under field conditions. Straight-tube root irrigation is a novel technology, and investigating its soil water dynamics in sandy soils is significant. Sandy soils exhibit weak capillary action, intense surface evaporation, and high permeability. The 1 m profile in Shapotou consists entirely of typical aeolian sandy soil with extremely low background water content. Post-irrigation water rapidly moves laterally while layers slowly increase; as the wetting front expands, capillary forces strengthen, accelerating water transport; continued irrigation leads to complete water loss through deep percolation due to poor water retention, following a Logistic pattern well-described by the Logistic model. Post-irrigation depletion (except in the 20 cm layer) shows rapid decline within 10 h followed by substantial reduction in depletion amount and rate, exhibiting a clear "L-shaped" distribution well-modeled by power functions, consistent with Zhang et al.' s findings for drip irrigation.

Soil water infiltration rate indicates how quickly layers reach maximum wetting under specific emitter flow rates, crucial for determining appropriate irrigation durations. Key factors include flow rate, irrigation technology, soil texture, and environmental conditions. This study shows the 40 cm layer reached maximum infiltration rate fastest and the 100 cm layer slowest, because emitter outlets at 30-40 cm deliver water first to the 40 cm layer, which then infiltrates to 100 cm. Maximum infiltration rates ranked as 60 cm > 40 cm > 80 cm > 100 cm > 20 cm. This likely occurs because, at constant flow rates, sandy soil’ s high permeability rapidly transports water to the 60 cm layer, filling the vadose zone and increasing bound water, film water, and capillary water. After interception by the 60 cm layer, gravitational potential decreases while matric potential increases, reducing downward infiltration rates. The 60 cm layer thus shows the highest rate, while intense surface evaporation and weak capillary action minimize water transport to the 20 cm layer, yielding the lowest rate there.

Soil water depletion rate quantifies water loss through transpiration, evaporation, and leakage after irrigation cessation. Reducing evaporative and leakage losses decreases depletion rates, increases soil water storage, and indirectly improves water use efficiency. After irrigation, all layers are fully wetted with gravitational potential exceeding matric potential, making the 100 cm layer’ s depletion rate highest. Without evaporation, the 20 cm layer should have the lowest rate, but intense evaporation in Shapotou increases its rate above the 40 cm layer. Thus, depletion rates rank as: 100 cm > 80 cm > 60 cm > 20 cm > 40 cm. Modeling indicates soil water content falls below 1% after 4 days, requiring re-irrigation. Studying depletion rate variations supports development of efficient irrigation cycles.

Understanding vertical variability and spatiotemporal distribution of irrigation water quantifies soil water variation across layers and times. Spatial heterogeneity was highest at 60 cm and lowest at 20 cm. Significant differences in mean water content occurred between the 20 cm and 60 cm layers versus others, with minimal irrigation impact at 20 cm and maximal impact at 60 cm. Straight-tube root irrigation offers low cost and simple field installation. This study preliminarily reveals soil water variation patterns for *H. ammodendron* forests in Shapotou’ s sandy soils at 4 L • h ^{1} emitter flow, establishing preliminary irrigation scheduling to support technology promotion and improvement, and providing references for future research on solute transport under straight-tube root irrigation. However, actual water-saving efficiency and evaporation patterns require further investigation.

Conclusion

This study demonstrates that soil water content variation during straight-tube root irrigation follows Logistic curves, while post-irrigation depletion follows power function models. The 40 cm layer reached maximum infiltration rate fastest (average 1.22 h) and the 100 cm layer slowest (average 4.57 h). Across six trials, the 1 m profile reached maximum infiltration rate at an average time of 2.16 h, with an average maximum rate of 1.65% • h ^{1}. Modeling results recommend an irrigation cycle of approximately 4 days with single irrigation durations of 6-10 h for *H. ammodendron* forests in Shapotou. Infiltration rates were highest in the 60 cm layer and lowest in the 20 cm layer, while depletion rates were highest in the 100 cm layer and lowest in the 20 cm layer.

During straight-tube root irrigation, the 20 cm layer showed minimal changes in infiltration, distribution, and depletion, while the 60 cm layer exhibited changes most consistent with model predictions. Straight-tube root irrigation had minimal impact on the 20 cm layer and maximal impact on the 60 cm layer. Soil water isolines radiated outward from the 60 cm layer toward surface and deeper layers during irrigation.

References

[1] Kidron G J. Analysis of dew precipitation in three habitats within a small arid drainage basin, Negev Highlands, Israel[J]. *Atmospheric Research*, 2000, 55(3/4): 257-270.

[2] Zhang X Y. Regulating mechanisms for improving farmland water use efficiency[J]. *Chinese Journal of Eco-Agriculture*, 2013, 21(1): 80-87.

[3] Bao Z W, Du H L, Jin X J. Water-saving potential in Aeolian sand soil under straight tube and surface drip irrigation in Taklimakan Desert in Northwest China[J]. *Science in Cold and Arid Regions*, 2011, 3(3): 243-251.

[4] Du H L, Wang T, Xiao H L, et al. Root irrigation experiments used in the protective forest belt along the Tarim desert highway[J]. *Journal of Desert Research*, 2010, 30(3): 522-527.

[5] Shao L W, Sun H Y, Chen S Y, et al. Review of root hydraulic lift in root-soil systems[J]. *Chinese Journal of Eco-Agriculture*, 2011, 19(5): 1080-1085.

[6] Bao Z W, Du H L, Shi X B, et al. A comparison between the rhizospheric irrigation and the drip irrigation by monitoring the soil evaporation with micro-lysimeters[J]. *Journal of Desert Research*, 2013, 33(1): 160-166.

[7] Ma W Y, Du H L, Shi X B. Water demand and irrigation scheduling of root-zone irrigation for Jujube tree in the downstream area of Tarim River[J]. *Acta Agriculturae Boreali-occidentalis Sinica*, 2014, 23(11): 92-99.

[8] Du H L, Ma W Y, Feng Q, et al. Soil moisture variation after irrigation in *Zizipubs jujube* field in the lower reaches of Tarim River[J]. *Journal of Desert Research*, 2014, 34(3): 773-779.

[9] Chen B H, Cao J D, Wang L J, et al. Research on distribution and movement rules of soil water under different drip irrigation conditions[J]. *Water Saving Irrigation*, 2010(7): 6-9.

[10] Zhang Z G, Li H, Li J, et al. Effects of irrigation amount on soil water infiltration and redistribution under drip irrigation[J]. *Research of Agricultural Modernization*, 2016, 37(1): 174-181.

[11] Chen X S. Laboratory experimental study on soil-water movement of surface drip irrigation and subsurface drip irrigation[D]. Changchun: Jilin Agricultural University, 2011: 13-39.

[12] Liu M X, Yang J S, Li X M, et al. Distribution and dynamics of soil water and salt under different drip irrigation regimes in northwest China[J]. *Irrigation Science*, 2013, 31(4): 675-688.

[13] Zhang J Z, Wang Z H, Hudan • TUMAREI. Influence of straw mulching on soil water/salt movement and cotton root distribution under drip irrigation[J]. *Chinese Journal of Eco-Agriculture*, 2013, 21(12): 1467-1476.

[14] Min W, Hou Z A, Ma L J, et al. Effects of water salinity and N application rate on water- and N-use efficiency of cotton under drip irrigation[J]. *Journal of Arid Land*, 2014, 6(4): 409-423.

[15] Huang Y H, Wang K, Yang J H. Distribution of soil water and available nitrogen in purple soil under drip fertilization[J]. *Journal of Soil and Water Conservation*, 2014, 28(5): 87-94.

[16] Wang H, Wang X D. Distribution of soil water and available phosphorus under drip fertigation[J]. *Journal of Northwest A&F University: Natural Science Edition*, 2007, 35(5): 227-232.

[17] Yin F H, Liu H L, Xie Z M, et al. Movement of N, P and K of cotton drip irrigation special fertilizer in soil and the fertilizer use efficiency[J]. *Geographical Research*, 2010, 29(2): 291-300.

[18] Wang J, Ye Z, Chu G X. Coupling effects of water and phosphate fertilizer supply on soil P availability and use efficiency[J]. *Chinese Journal of Eco-Agriculture*, 2015, 23(11): 1377-1383.

[19] Chen J, Zhang Z, Yunger J A, et al. Distribution and application of urea with precision fertilization device of drip irrigation in cotton fields[J]. *Transactions of the Chinese Society for Agricultural Machinery*, 2014, 45(12): 62-68.

[20] Phogat V, Mahadevan M, Skewes M, et al. Modelling soil water and salt dynamics under pulsed and continuous surface drip irrigation of almond and implications of system design[J]. *Irrigation Science*, 2012, 30(4): 315-333.

[21] Zhou Q Y, Kang S Z, Zhang L, et al. Comparison of APRI and Hydrus-2D models to simulate soil water dynamics in a vineyard under alternate partial root zone drip irrigation[J]. *Plant and Soil*, 2007, 291(1/2): 211-223.

[22] Li H. Experiments and numerical simulations of soil-water movement in subsurface drip irrigation[D]. Wuhan: Wuhan University, 2005: 24-68.

[23] Chi B L, Huang X F, Zhang D M, et al. Numerical simulation and validation of soil water movement under subsurface drip irrigation with point-source emitter[J]. *Transactions of the Chinese Society of Agricultural Engineering*, 2005, 21(3): 56-59.

[24] Zhang Z S, He M Z, Tan H J, et al. Evaporation from soils covered with biological crusts in revegetated desert —A case study in Shapotou Desert Research and Experiment Station[J]. *Acta Pedologica Sinica*, 2007, 44(3): 404-410.

[25] Li X R, Ma F Y, Xiao H L, et al. Long-term effects of revegetation on soil water content of sand dunes in arid region of Northern China[J]. *Journal of Arid Environments*, 2004, 57(1): 1-16.

[26] Wang Z R, Wang W Y, Wang Q J, et al. Experimental study on soil water movement from a point source[J]. *Journal of Hydraulic Engineering*, 2000(6): 39-44.

[27] Zhu D L, Wang Z N, Wang D X, et al. The principles of water distribution and design parameters of drip irrigation in different soils[J]. *Acta Universitatis Agriculturalis Boreali-Occidentalis*, 2000, 28(2): 45-49.

[28] Zhang Z G, Li H, Li J, et al. Effects of different dripper discharges on soil water infiltration/redistribution under drip irrigation[J]. *Agricultural Research in the Arid Areas*, 2016, 34(2): 225-231.

[29] Zheng Y P. The simulation research on the soil water infiltration process under the drip irrigation[D]. Yangling: Northwest A&F University, 2008.

[30] Zhao W J, Li X P, Fan Y W, et al. Study on soil water infiltration of gravel-mulched field in northwestern arid area[J]. *Chinese Journal of Soil Science*, 2016, 47(1): 150-155.

[31] Cai H J, Xu J T, Wang J, et al. Yearly variation of soil infiltration parameters irrigated field based on WinSRFR4.1[J]. *Transactions of the Chinese Society of Agricultural Engineering*, 2016, 32(2): 92-98.

[32] Dong X H, Liu X J, Peng T, et al. Hydrus-1D modeling water flow transport in a layered soil profile[J]. *Journal of Anhui Agricultural Sciences*, 2016, 44(4): 29-31.

[33] Ma H Y, Wang X, Zhang Z Y, et al. Numerical simulation of water-salt distribution under brackish water film hole furrow irrigation based on HYDRUS-3D model[J]. *Transactions of the Chinese Society for Agricultural Machinery*, 2015, 46(2): 117-124.

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