Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2018.22325

118 (2018) 1–11
June

Effects of different drip irrigation patterns on water distribution in potted Yunnan red loam and yellow-sand soil and pepper growth

Yijie Zhang[a], Zhenjie Yang[a], Haolin Yang[a], Shiyu Song[a], Wenqi Xu[a], Lingqiong Kong[b], Yang Yu[a,*]

[a]*College of Mechanical and Electrical Engineering, Yunnan Agricultural University, Kunming 650201, China, email: nygc126@126.com (Y. Yu)*
[b]*College of Water Conservancy, Yunnan Agricultural University, Kunming 650201, China*

Received 7 November 2017; Accepted 4 February 2018

ABSTRACT

It is important to study the law of water distribution in potted soil and the appropriate irrigation methods for improving the level of water-saving irrigation in greenhouse cultivation. In this study, pepper was taken as the experimental crop. Two kinds of drip irrigation models (root zone infiltrating irrigation and surface drip irrigation) and two kinds of irrigation emitter arrangements (a 3 × 120° distribution and a 2 × 180° distribution) were used to plot out the distribution pattern of soil water in a potted planting environment for two kinds of soils (Yunnan red loam and yellow-sand soil). Then, the growth indices of peppers were compared. The results showed that drip irrigation models and soil types had a significant interactive effect on soil water distribution ($P < 0.01$); in Yunnan red loam, the matric potential played a major role in the transport of irrigation water, while in yellow-sand soil, gravitational potential played a major role. Under root zone infiltrating irrigation, the high-water-content distribution area of the two types of soil is more continuous and balanced than that of surface drip irrigation, and the balance of water distribution of the yellow-sand soil is better than that of the red loam. In Yunnan red loam, the growth indices of peppers (plant height, stem diameter, fruit fresh weight, fruit dry weight, and similarly hereinafter) increased by 12.9%, 14.3%, 46.1%, and 36.8%, respectively; in yellow-sand soil, the growth indices under root zone infiltrating irrigation were 31.7%, 25.9%, 26.9%, and 35.3%, which were lower than those of surface drip irrigation. The experiment shows that in a greenhouse potting environment, Yunnan red loam with root zone infiltrating irrigation offers more water-saving potential. The results provide a theoretical basis and data support for the rational selection of drip irrigation models for facility agriculture in Yunnan.

Keywords: Irrigation methods; Root zone infiltration irrigation; Surface drip irrigation; Water distribution; Yunnan red loam; Yellow-sand soil

1. Introduction

Of the many irrigation methods, drip irrigation is currently the most effective water-saving irrigation method in arid areas. The arrangements of drip irrigation emitters can be divided into surface drip irrigation and underground drip irrigation. Among them, the root zone infiltrating irrigation is a new, efficient, and water-saving subsurface drip irrigation method that uses emitters to deliver small flows of water, nourishment, and pesticides in pipelines into the soil near the root of crops in a uniform and precise manner to facilitate root uptake. The method conserves water and fertilizer, and increases yield [1,2]. Compared with surface drip irrigation technologies, root infiltration irrigation can reduce surface evaporation and overcomes many disadvantages of the former, including surface runoff loss [3–6].

At present, there are many studies on the distribution of soil moisture in different drip irrigation models [7–12], but most of them are designed for a field planting environment.

* Corresponding author.

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Compared with field planting, the distribution of soil moisture in potted plants in solar greenhouses is more influenced by the flowerpot boundary. Consequently, special research is needed. Gan et al. [13] carried out a contrast test on potted kidney bean growth where drip irrigation and sprinkling irrigation were used in loam, and the study showed that the growth index of the kidney beans under drip irrigation was significantly higher than that under sprinkler irrigation; Shi et al. [14] contrasted potted maize where drip irrigation, micro-infiltrating irrigation, and sprinkling irrigation were used in saline soil, and the results showed that under micro-infiltrating irrigation, the water content of the root layer of the maize was the highest, the water content was the most stable, and the water-use efficiency was the highest. Zhang et al. [15,16] carried out a contrast test on the potted pepper where small-flow micro-pressure drip irrigation was used in clay loam, and the results showed that the use of a small irrigation quota and high-frequency irrigation had a significant effect on the inhibition of surface evaporation; Wang et al. [17–19] carried out a soil water consumption test on potted cotton under different drip irrigation models in medium loam soil, and the results showed that the variable quantity of soil moisture in subsurface drip irrigation was lower than that in surface drip irrigation.

Indeed, many scholars have done considerable research on soil moisture distribution and its effect on crop growth under the drip irrigation model. To the best of our knowledge, however, there are no reports on the study of the moisture distribution law of special soil types in Yunnan, especially red loam, and its effect on crop growth under different drip irrigation models. Yu et al. [20] first explored the effects of different irrigation emitter types on the distribution of soil moisture in potting soil under the conditions of solar greenhouses. On the basis of this study, the influence of different drip irrigation models on the distribution of soil moisture and crop growth in Yunnan greenhouses was studied in order to provide theoretical guidance and technical support for the water-saving irrigation of greenhouse-potted crops in Yunnan.

2. Materials and methods

2.1. Experimental materials

The pepper used in this study was the Hanyu Super-large Cayenne Pepper, an early-maturing variety with wide applicability (purchased from Shanghai Minghui Landscaping Co., Ltd., Shanghai, China). Pig manure after putrefaction and fermentation, collected from livestock farms nearby, was used as the base fertilizer. The irrigation emitters used were flow adjustable irrigation emitters manufactured by Guangzhou Shunlv Sprinkling Equipment Co., Ltd., Guangzhou, China. Each emitter is disk-shaped and has eight evenly distributed narrow slots. Irrigation water flows horizontally out of the drip holes (1 mm × 1.5 mm in size) at a flow rate of 1 L/h in the 3 × 120° mode and 1.5 L/h in the 2 × 180° mode. Two kinds of soil (Yunnan red loam and Yunnan yellow-sand soil) were used in this study. The Yunnan red loam was taken from the Back Hill test base of Yunnan Agricultural University (102°45′5″E, 25°8′7″N), and the Yunnan yellow-sand soil was taken from the test sand field of Yunnan Agricultural University. After natural air drying, the two types of soil were screened with a 2 mm screen. Table 1 shows the basic properties of the soils.

2.2. Experimental design

The experiments were carried out in the Back Hill tri-arch film greenhouse of Yunnan Agricultural University on July 20, 2015. Two irrigation methods (root infiltration irrigation and surface drip irrigation, denoted IG and IM, respectively) and two emitter modes (3 × 120° and 2 × 180°, denoted DT and DS, respectively) were applied in the potted cayenne pepper experiments in two kinds of soil in Yunnan (Yunnan red loam and Yunnan yellow-sand soil, denoted SR and SY, respectively). The eight treatments were repeated three times, respectively, resulting in a total of 24 groups of experiments being conducted.

The testing system primarily comprised a water source, water pipelines, Y-60 pressure gauges (manufactured by the First Plant of Xi'an Automation Instrument Factory, Xi'an, China), DN20 flow meters (manufactured by Ningbo Water Meter Factory, Ningbo, China), irrigation emitters, pots, TDR SK-100 soil moisture meters (manufactured by Shanghai JK Precision Instrument, Shanghai, China), a 330 constant temperature oven (manufactured by Shanghai Yetuo Instruments and Meters Co., Ltd., Shanghai, China), an electronic scale (manufactured by Dongwan Nancheng Changxie Electronic Products Factory, Dongwan, China), a vernier caliper (manufactured by Wuxi Kaibaoding Tools Co., Ltd., Wuxi, China), and other devices (see Fig. 1).

2.3. Experimental methods

2.3.1. Installation of experimental devices

In accordance with the design scheme, the prepared soil sample (unit weight: 1.23 g/cm^3) was uniformly poured into the test pots (upper diameter: 35 cm, lower diameter: 22 cm, height: 30 cm). The emitter for root infiltration irrigation was inserted vertically into the pot through the center of the surface of the soil (to a depth of –7.5 cm; the coordinate was established with the center of the soil surface as the origin, right side positive and below being negative). Subsequently, following 2 weeks of acclimatization, pepper seedlings were

Table 1
Physical properties of Yunnan red loam and Yunnan yellow-sand soil

Soil types	Buck density (g cm^{-3})	Field capacity (%)	Soil particle compositions (%)		
			Clay (<0.002 mm)	Silt (≥0.002–0.02 mm)	Sand (≥0.02–2 mm)
Red loam	1.23	22.30	39.47	35.32	25.21
Yellow sand	1.23	0.36	4.66	25.13	70.21

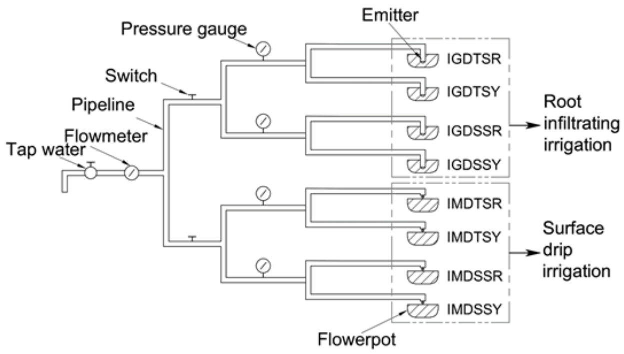

Fig. 1. Sketch of the test system used in the experiments.

transplanted to the test pots, with the depth of each root placed at the same level as the depth of the emitter. The emitter for surface drip irrigation was placed 2 cm upwards of the center of the surface of the soil in the pot. Before the experiments, the initial mass fraction of soil water was 13.5% in all the treatments. During the experiments, water pressure was 0.05 MPa in all the treatments.

2.3.2. Measurement of soil water content

From July 20, 2015 to September 16, 2015, the measurement cycle of soil moisture content (i.e., the irrigation interval) was 4 d, and two sets of measurements (denoted MC1 and MC2) were respectively performed in a cycle 5 min and 24 h after irrigation. Soil moisture content was measured using the TDR SK-100 soil moisture meter 30 times — specifically, 15 times for each of MC1 and MC2. A 3D coordinate system for measuring soil moisture content was established with the center of the soil surface as the origin, and z-axis, x-axis, and y-axis pointing upwards, rightwards, and forwards, respectively. Twelve measuring points (see Fig. 2(a)) were set on each of the x-axis profile and y-axis profile in the 3D coordinate system, and soil moisture content at 24 measuring points was measured in each test group. Emitters were arranged in DT and DS modes, respectively (see Figs. 2(b) and (c)).

2.3.3. Measurement of pepper growth indices

A ruler was used to measure the plant height — specifically, the vertical height from soil surface to the highest point of the plant — and a vernier caliper for the stem diameter at the stem base. From July 20, 2015 to September 16, 2015, plant height and stem diameter were measured every 4 d, and the average of three measurements was used as the sampling result. After the harvest, all the parts (stem, root system, and fruit) of the pepper were cleaned thoroughly, and the water on the surface wiped dry using paper towels. Then, an electronic scale was used to measure the fresh weight of all the parts. Finally, all the parts were placed into the constant temperature oven for 30 min at 105°C to remove water and then further dried at 75°C until the weight was sufficiently constant for measurement to be conducted.

2.4. Data analysis methods

2.4.1. Soil water distribution analysis [18]

Significance analysis through inter-subject effect tests was conducted on the soil water distribution data obtained from the root zone of the pepper using SPSS. Microsoft Excel was used to compute the averages of the soil moisture content data obtained in the treatments, after which Surfer was used to draw the soil moisture distribution diagram and derive the mass fraction of soil moisture (%). AutoCAD was used to calculate the area (cm^2) of every 1% vertical section, whose mass fraction of soil moisture was within the range of 0%–17%. The value obtained was then divided by the total area of the vertical profile of the soil in the pot to give the percentage of the area of each section to the total vertical profile area (hereafter referred to as the "soil area percentage (%)").

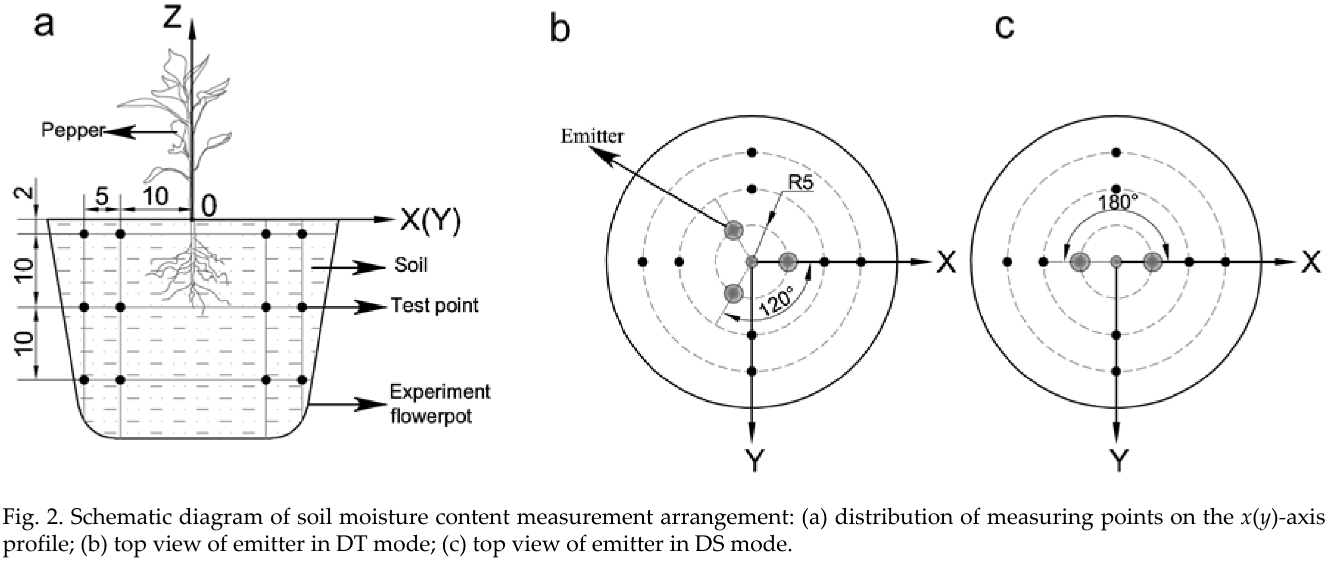

Fig. 2. Schematic diagram of soil moisture content measurement arrangement: (a) distribution of measuring points on the $x(y)$-axis profile; (b) top view of emitter in DT mode; (c) top view of emitter in DS mode.

2.4.2. Analysis of the growth conditions of the pepper

SigmaPlot and SPSS were used to carry out data processing and significance analysis in order to assess the growth conditions of the pepper in the Yunnan red loam and Yunnan yellow-sand soil under different irrigation methods.

3. Results

3.1. Significance analysis of experimental factors

Significance analysis was conducted using the irrigation method, soil type, and emitter mode as independent variables, and the soil moisture content as a dependent variable. The results obtained are displayed in Table 2.

As shown in Table 2, the irrigation method, soil type, and irrigation method had a significant effect on soil water distribution, with the respective results $P < 0.05$, $P < 0.05$, and $P < 0.01$, whereas the emitter mode had no significant effect on soil water distribution ($P > 0.05$).

3.2. Water distribution patterns in different types of soil under different irrigation methods for potted pepper

3.2.1. Effects of different irrigation methods and different soil types on soil water distribution

Diagrams of soil water distribution (MC1 and MC2) in each measurement cycle were drawn. MC2 represents the results measured 24 h after irrigation, which can clearly reflect the stable soil water distribution [20–22]. The soil water distribution diagrams of MC2 (x-axis and y-axis profiles), which illustrate the effects of different soil types on soil water distribution under different irrigation methods, are shown in Figs. 3 and 4. Table 3 explains the soil water distribution shown in the figures.

It is clear from Figs. 3 and 4 and Table 3 that the difference in high-water-content section distribution on the x-axis and y-axis profiles between DT and DS modes was primarily caused by the difference in the number of emitters and the location of drip holes. Because Yunnan red loam is relatively sticky and heavy, soil water may encounter substantial resistance in the process of downward diffusion. For this reason, the width of the vertically downward diffusion of soil water was relatively small, and this means unobvious water percolation. Thus, matric potential played an essential role in the Yunnan red loam. Because yellow-sand soil has good water permeability and poor water-holding capacity, the width of the vertically downward diffusion of soil water was relatively large, which means obvious water percolation. Thus, gravity potential played an essential role in the Yunnan yellow-sand soil. Under root infiltration irrigation, the high-water-content section in both the red loam and yellow-sand soil was distributed on both sides of the root zone of the pepper. However, the section in red loam was more concentrated and water did not readily infiltrate. Surface drip irrigation for the red loam encountered greater resistance in the process of downward diffusion than the yellow-sand soil, and water in the red loam was mainly distributed in the topsoil, while water in the yellow-sand soil had an obvious tendency of downward percolation and thus could transport to the root zone of the pepper.

3.2.2. Analysis of soil area percentage in different soils under different irrigation methods

Because the distribution patterns of soil area percentage in the DT and DS modes were basically the same, the soil area percentage of the two soils was analyzed only using the MC1 and MC2 results in the DT mode under the two irrigation methods. Table 4 shows the results.

As can be seen in Table 4, (1) the moisture mass fraction sections in the red loam and yellow-sand soil corresponding to a soil area percentage greater than 70% were continuously distributed under root infiltration irrigation. Taking MC1 results for example, the soil area percentages on the x-axis and y-axis profiles in the red loam were 71% and 72%, respectively, and the corresponding sections were distributed continuously in the ranges >4%–13% and >7%–16%, respectively; the soil area percentages on the x-axis and y-axis profiles in the yellow-sand soil were 73% and 74%, respectively, and the corresponding sections were distributed continuously in the ranges >7%–15% and >9%–17%, respectively. (2) By comparing MC1 results with MC2 results under root infiltration irrigation, it can be concluded that the moisture mass fraction sections corresponding to the MC2 soil area percentage >70% were narrower than the sections corresponding to the MC1 percentage >70%. Taking the x-axis profile for example, the section in the red loam corresponding to the MC2 soil area percentage >70% was within the range 7%–12% with a span of 12%–7% = 5%, which is significantly smaller than the span (13%–4% = 9%) corresponding to the MC1 soil area percentage >70%; the section in the yellow-sand soil corresponding to the MC2 soil area percentage >70% was within the range 10%–15% with a span of 15%–10% = 5%, which is significantly smaller than the span (15%–7% = 8%) corresponding to the MC1 soil area percentage >70%. In addition, compared with the yellow-sand soil, the moisture mass fraction section in the red loam corresponding to the soil area percentage >70%

Table 2
Significance analysis results for soil moisture

Source	Type III sum of squares	Degree of freedom	Mean square	F value	P value
Irrigation method	484.357	1	484.357	11.105	0.001
Soil type	280.549	1	280.549	6.432	0.011
Emitter distribution	3.790	1	3.790	0.087	0.768

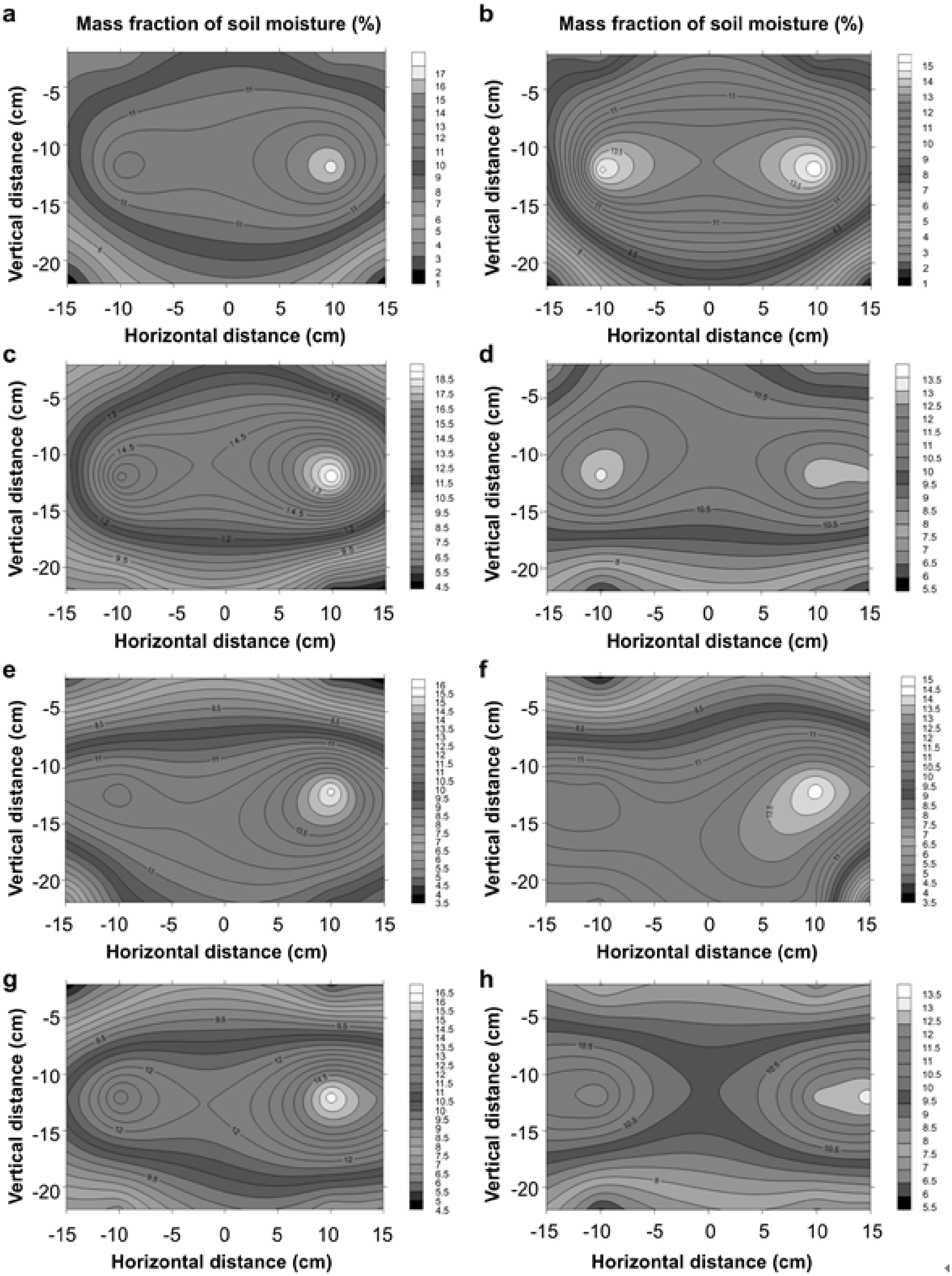

Fig. 3. Water distribution in two soils in two emitter modes under root infiltration irrigation: (a) *x*-axis profile of IGDTSR, (b) *y*-axis profiles of IGDTSR, (c) *x*-axis profile of IGDSSR, (d) *y*-axis profiles of IGDSSR, (e) *x*-axis profile of IGDTSY, (f) *y*-axis profiles of IGDTSY, (g) *x*-axis profile of IGDSSY, (h) *y*-axis profiles of IGDSSY.

Note: IGDTSR and IGDTSY respectively represent the Yunnan red loam and Yunnan yellow-sand soil under root infiltration irrigation in 3 × 120° emitter mode. IGDSSR and IGDSSY respectively represent the Yunnan red loam and Yunnan yellow-sand soil under root infiltration irrigation in 2 × 180° emitter mode. Coordinates were established with the center of the soil surface as the origin, right side positive, and downward negative (this system is also used hereafter). The value indicated by the color bar graph is the mass fraction of soil moisture (%).

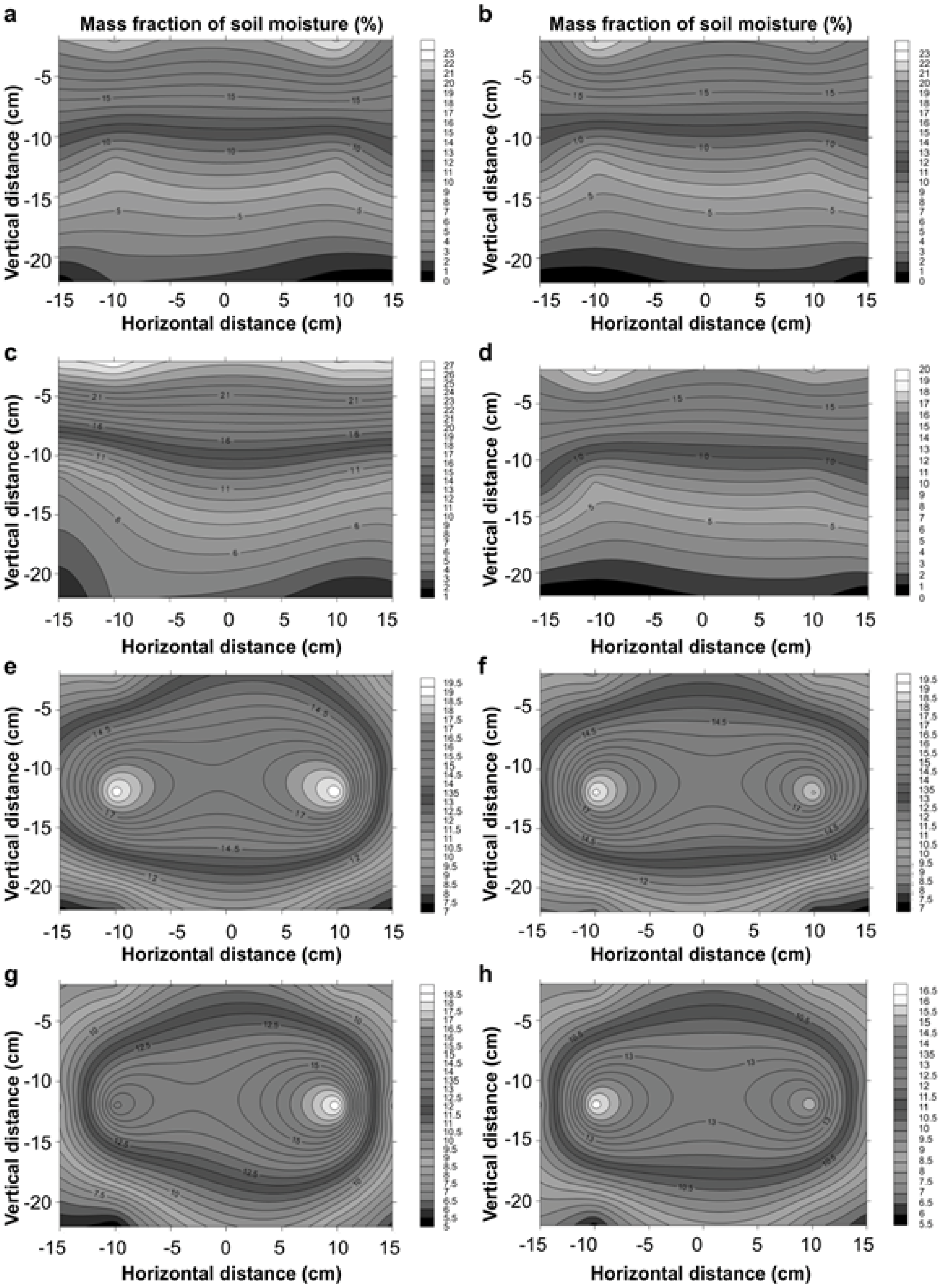

Fig. 4. Water distribution in two soils in two emitter modes under surface drip irrigation: (a) x-axis profile of IMDTSR, (b) y-axis profile of IMDTSR, (c) x-axis profile of IMDSSR, (d) y-axis profile of IMDSSR, (e) x-axis profile of IMDTSY, (f) y-axis profile of IMDTSY, (g) x-axis profile of IMDSSY, (h) y-axis profile of IMDSSY.

Note: IMDTSR and IMDTSY respectively represent the Yunnan red loam and Yunnan yellow-sand soil under surface drip irrigation in 3 × 120° emitter mode. IMDSSR and IMDSSY respectively represent the Yunnan red loam and Yunnan yellow-sand soil under surface drip irrigation in 2 × 180° emitter mode. Coordinate was established with the center of the soil surface as the origin, right side positive, and downward negative (this system is also used hereafter). The value indicated by the color bar graph is the mass fraction of soil moisture (%).

Table 3
Description of water distribution in soil for growing potted pepper

		Distribution of high-water-content section
Root infiltration irrigation	Yunnan red loam (see Figs. 3(a)–(d))	The high-water-content section was symmetrically distributed on both sides of the root zone of the pepper. In DT mode, the one-way maximum width of horizontal diffusion of the high-water-content section was approximately 8 cm, and the maximum width of vertically downward diffusion was approximately 6 cm. In DS mode, the one-way maximum width of horizontal diffusion of the high-water-content section was approximately 7 cm, and the maximum width of vertically downward diffusion was approximately 5 cm. The difference, which was insignificant, was related to different distribution modes of drip holes on the emitter.
	Yunnan yellow-sand soil (see Figs. 3(e)–(h))	The high-water-content section was asymmetrically distributed on both sides of the root zone of the pepper. In DT mode, the one-way maximum width of horizontal diffusion of the high-water-content section was approximately 11 cm, and the maximum width of vertically downward diffusion was approximately 10 cm. In DS mode, the one-way maximum width of horizontal diffusion of the high-water-content section was approximately 12 cm, and the maximum width of vertically downward diffusion was approximately 11 cm. The difference, which was insignificant, was related to different distribution modes of drip holes on the emitter.
Surface drip irrigation	Yunnan red loam (see Figs. 4(a)–(d))	The high-water-content section was mainly distributed in the topsoil. In DT mode, the one-way maximum width of horizontal diffusion of the high-water-content section was approximately 6 cm, and the maximum width of vertically downward diffusion was approximately 7 cm. In DS mode, the one-way maximum width of horizontal diffusion of the high-water-content section was approximately 5 cm, and the maximum width of vertically downward diffusion was approximately 6 cm. The difference, which was insignificant, was related to different distribution modes of drip holes on the emitter.
	Yunnan yellow-sand soil (see Figs. 4(e)–(h))	The high-water-content section moved down to both sides of the root zone of the pepper and was symmetrically distributed. In DT mode, the one-way maximum width of horizontal diffusion of the high-water-content section was approximately 6 cm, and the maximum width of vertically downward diffusion was approximately 10 cm. In DS mode, the one-way maximum width of horizontal diffusion of the high-water-content section was approximately 5 cm, and the maximum width of vertically downward diffusion was approximately 9 cm. The difference, which was insignificant, was related to different distribution modes of drip holes on the emitter.

was closer to the root zone of the pepper. (3) The moisture mass fraction sections in the two soils corresponding to soil area percentage >70% were discontinuous under surface drip irrigation, and the high-water-content section in the red loam covered a larger scope and was more discontinuous. Taking MC1 results as an example, the moisture mass fraction sections corresponding to a soil area percentage of 73% on the x-axis profile in the red loam were distributed discontinuously in the ranges >2%–12% and >20%–25%, and the sections corresponding to a soil area percentage of 71% on the y-axis profile in the red loam were distributed discontinuously in the ranges >1%–11%, >18%–19%, and >20%–22%; the moisture mass fraction sections corresponding to the soil area percentage of 72% on the x-axis profile in the yellow-sand soil were distributed discontinuously in the ranges >2%–12% and >14%–15%, and the sections corresponding to the soil area percentage of 71% on the y-axis profile in the yellow-sand soil were distributed discontinuously in the ranges >2%–5% and >8%–16%. (4) By comparing MC1 results with MC2 results under surface drip irrigation, it can be concluded that the moisture mass fraction sections corresponding to the MC2 soil area percentage >70% were narrower than the sections corresponding to the MC1 percentage >70%. Taking x-axis profile for example, the accumulated span of the sections in the red loam corresponding to the MC2 soil area percentage >70% was (12%–1%) + (19%–17%) = 13%, which is smaller than the accumulated span of (12%–2%) + (25%–20%) = 15% corresponding to the MC1 soil area percentage >70%; the span of the section in the yellow-sand soil corresponding to the MC2 soil area percentage >70% was (18%–11%) = 7%,

Table 4
Soil area percentage of Yunnan red loam and Yunnan yellow-sand soil under two irrigation methods in DT mode

Soil moisture section (%)	Root infiltration irrigation								Surface drip irrigation							
	MC1				MC2				MC1				MC2			
	Red loam		Yellow sand		Red loam		Yellow sand		Red loam		Yellow sand		Red loam		Yellow sand	
	x	*y*	*x*	*y*	*x*	*y*	*x*	*y*	*x*	*y*	*x*	*y*	*x*	*y*	*x*	*y*
0–1	0.2	0.5									0.9	1.2	1.8	2.4		
>1–2	2.0	0.8			0.5	0.4			2.3	6.6[a]	5.1	4.3	4.6[a]	7.2[a]		
>2–3	2.1	0.9			0.6	0.6			7.4[a]	12.2[a]	8.7[a]	6.4[a]	8.7[a]	8.0[a]		
>3–4	3.0	1.1		0.1	0.9	1.3			9.9[a]	9.5[a]	7.9[a]	6.0[a]	7.4[a]	7.1[a]		
>4–5	3.8[a]	1.7	1.3	0.3	1.4	1.9	1.0	0.7	8.2[a]	7.4[a]	7.4[a]	5.6[a]	6.9[a]	6.7[a]		
>5–6	7.3[a]	2.4	1.9	1.6	2.0	2.3	2.2	2.2	7.0[a]	5.7[a]	6.8[a]	5.5	6.4[a]	6.3[a]		
>6–7	9.1[a]	3.5	3.3	1.8	3.0	3.2	4.0	3.8	5.6[a]	4.8[a]	6.6[a]	5.4	6.0[a]	5.8[a]		
>7–8	9.7[a]	6.6[a]	6.1[a]	2.5	10.8[a]	12.1[a]	5.8	5.6	5.0[a]	4.3[a]	6.2[a]	5.5	5.4[a]	5.1[a]	0.7	0.8
>8–9	12.0[a]	6.8[a]	6.4[a]	3.7	14.9[a]	13.0[a]	6.1	6.0	3.9[a]	3.9[a]	5.8[a]	5.6[a]	4.6[a]	4.6[a]	2.2	2.0
>9–10	15.5[a]	7.3[a]	6.9[a]	5.8[a]	14.9[a]	14.8[a]	6.4	5.9	3.5[a]	3.7[a]	5.8[a]	6.0[a]	4.3[a]	4.3[a]	3.1	3.2
>10–11	4.9[a]	7.2[a]	7.6[a]	6.4[a]	15.8[a]	14.9[a]	7.5[a]	7.6	3.4[a]	3.1[a]	5.7[a]	6.7[a]	4.2[a]	4.3	6.4	8.2
>11–12	4.6[a]	7.3[a]	9.7[a]	7.3[a]	18.5[a]	18.8[a]	9.2[a]	8.0[a]	3.1[a]	3.0	5.8[a]	7.4[a]	4.2[a]	4.2	9.3[a]	10.0[a]
>12–13	3.9[a]	7.5[a]	14.4[a]	9.6[a]	8.7	9.1	14.0[a]	8.7[a]	2.9	2.9	5.4	8.0[a]	4.0	4.0	11.0[a]	10.9[a]
>13–14	3.6	8.1[a]	13.2[a]	11.3[a]	6.4	6.7	25.0[a]	19.0[a]	2.8	3.0	5.4	6.9[a]	3.9	4.1	12.9[a]	14.2[a]
>14–15	3.3	8.8[a]	8.6[a]	14.7[a]	2.9	1.0	21.0[a]	31.8[a]	2.8	2.9	5.4[a]	6.2[a]	4.1	4.2	13.4[a]	15.3[a]
>15–16	2.5	12.0[a]	5.3	12.6[a]			6.2	9.6[a]	2.7	2.9	5.3	6.2[a]	4.0	4.3[a]	13.6[a]	19.2[a]
>16–17	2.4	5.3	5.1	6.2[a]			2.8	2.0	2.7	2.9	4.2	5.2	4.1	4.5[a]	14.6[a]	10.4[a]
>17–18	2.1	5.2	4.0	3.8					2.8	3.0	1.4	2.0	4.3[a]	4.7[a]	7.8[a]	4.4[a]
>18–19	2.2	3.6	2.4	4.1					2.8	3.3[a]	0.3	1.3	4.5[a]	4.7[a]	2.8	1.3
>19–20	1.9	2.5	1.2	4.2					2.8	3.0			4.1	2.4	0.2	0.1
>20–21	1.8	1.5	0.8	2.5					3.0[a]	3.2[a]			2.1	0.8		
>21–22	1.2	0.5	0.5						2.9[a]	3.3[a]			0.5	0.3		
>22–23	0.8	0.1	0.2						3.0[a]	2.6						
>23–24									3.2[a]	1.2						
>24–25									3.5[a]	0.4						

[a]Indicates the soil area percentage values of sections constituting the result of soil area percentage >70%.

which is significantly smaller than the accumulated span of (12%–2%) + (15%–14%) = 11% corresponding to the MC1 soil area percentage >70%. In addition, as can be seen from the MC2 results, which represent the stable water distribution state, the sections in the red loam corresponding to the soil area percentage >70% were unevenly distributed with sections with lower and higher moisture mass fraction in the majority; by contrast, the sections in the yellow-sand soil corresponding to the soil area percentage >70% were evenly distributed and more concentrated in the middle part. (5) By comparing root infiltration irrigation with surface drip irrigation, it can be seen that the high-water-content sections under root infiltration irrigation were more concentrated in the middle, specifically, near the root zone of the pepper, and continuously and uniformly distributed with small span, whereas the high-water-content sections under surface drip irrigation had large spans and were discontinuously and unevenly distributed. Taking MC2 results for example, the spans of sections in the red loam and yellow-sand soil corresponding to the soil area percentage >70% were both 5% under root infiltration irrigation, mainly concentrated in the range >7%–16%, while the spans of sections in the red loam and yellow-sand soil corresponding to the soil area percentage >70% were (12%–1%) + (19%–17%) = 13% and 18%–11% = 7%, respectively, under surface drip irrigation, mainly concentrated in the ranges >1%–10% and >11%–18%.

3.3. Effects of soil water distribution on pepper growth indices

3.3.1. Effects of soil water distribution on pepper plant height and stem diameter

Graphs of pepper plant height and stem diameter changing over time under different soil water distribution patterns were drawn (see Fig. 5), and a comparative analysis of the three test groups (C1, C2, and C3) was conducted according to the growth conditions of the pepper. As can be seen, the figure indicates the following: (1) The pepper in group C1 (IGDTSR and IGDSSR; i.e., root infiltration irrigation + red loam) had the highest growth rate, with an average plant height and maximum stem diameter of 75.5 and 7.2 cm, respectively. This is because the high-water-content section

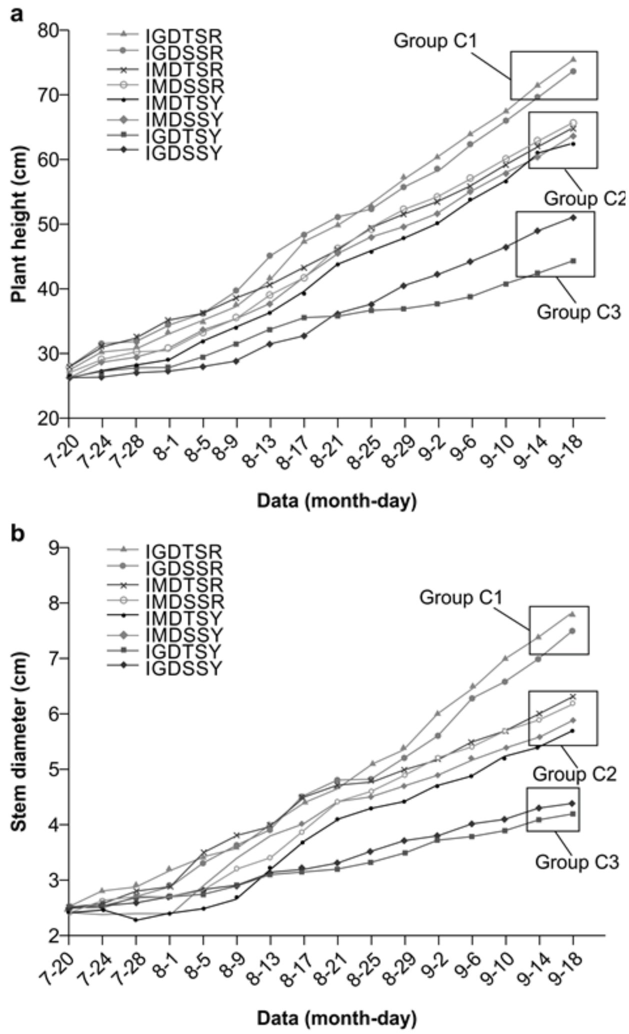

Fig. 5. Effects of soil water distribution on pepper plant height and stem diameter.

in the red loam under root infiltration irrigation was mainly distributed in the root zone and thus could provide sufficient water for pepper growth. (2) The pepper in group C2 (IMDTSR, IMDSSR, IMDTSY, and IMDSSY; i.e., surface drip irrigation) had normal growth rate, with the plant height and stem diameter growth rates of the pepper in the red loam (IMDTSR and IMDSSR) slightly higher than those of the pepper in the yellow-sand soil (IMDTSY and IMDSSY). This is because the high-water-content section in the red loam under root infiltration irrigation was mainly distributed in the topsoil (approximately 5 cm in depth), which was above the root zone of the pepper (approximately 7.5 cm in depth), and thus, the section was farther from the root zone compared with group C1, which resulted in less water to the root. In addition, owing to the effect of gravity potential, the high-water-content section in the yellow-sand soil under surface drip irrigation (IMDTSY and IMDSSY) enables rapid transport from the top soil layer to the lower soil layer (approximately 12 cm in depth). The root of pepper plants can absorb water only when soil water is at the root zone. Consequently, the pepper under these conditions absorbed less water than the pepper in the red loam under surface drip irrigation (IMDTSR and IMDSSR). (3) The pepper in group C3 (IGDTSY and IGDSSY; i.e., root infiltration irrigation + yellow-sand soil) had the lowest growth rate, with average plant height and maximum stem diameter 44.2 and 4.3 cm, respectively. This is because, under the effect of gravity potential, most of the water in the yellow-sand soil under root infiltration irrigation filtered into the deep soil layer (approximately 12 cm in depth), leaving very little water for the pepper to absorb.

3.3.2. Effects of soil water distribution on other growth indices of pepper

Fig. 6 shows bar graphs of the fresh weight and dry weight of the stem, root, and fruit after harvest under different soil–water distribution patterns. As can be seen in the figure, group C1 had the best growth indices, followed by group

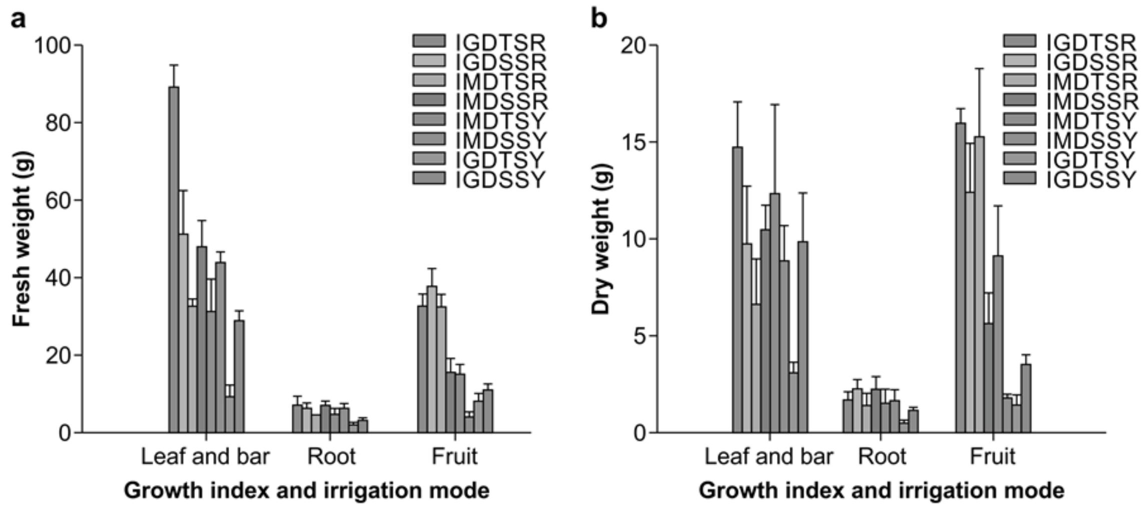

Fig. 6. Effects of soil water distribution on other growth indices of the pepper: (a) bar graphs of the fresh weight of the leaf and bar, root, and fruit; (b) bar graphs of the dry weight of the leaf and bar, root, and fruit.

C2 and group C3 (which had the worst). Taking pepper fruit for example, the average fresh weight (70 g) and dry weight (28.6 g) of the pepper in group C1 were respectively 46.1% and 36.8% higher than those (fresh weight: 47.9 g; dry weight: 20.9 g) of the pepper in IMDTSR and IMDSSR (part of group C2; surface drip irrigation + red loam), 270% and 160% higher than those (fresh weight: 18.9 g; dry weight: 11 g) of the pepper in IMDTSY and IMDSSY (part of group C2; surface drip irrigation + yellow-sand soil), and 302% and 484% higher than those (fresh weight: 17.4 g; dry weight: 4.9 g) of the pepper in group C3 (IGDTSY and IGDSSY; root infiltration irrigation + yellow-sand soil). This indicates that the growth conditions of the pepper were closely related to the water distribution in its root zone. Owing to the effect of matric potential, the high-water-content sections in the red loam were more concentrated; under root infiltration irrigation, the root of the pepper could absorb sufficient water, and the pepper grew best; under surface drip irrigation, by contrast, the high-water-content sections in the red loam were predominantly distributed in the topsoil and could provide relatively sufficient water; thus, the pepper grew moderately. Because of the effect of gravity potential, water in the yellow-sand soil infiltrated more quickly. Under surface drip irrigation, the high-water-content sections in the yellow-sand soil were discontinuously distributed and could only provide a small amount of water to the root during the process of infiltration; consequently, the growth of the pepper was affected. Under root infiltration irrigation, the root could not absorb enough water owing to the rapid filtration in the yellow-sand soil; consequently, pepper growth was most significantly affected under this condition.

4. Discussion

To the best of our knowledge, basic research is unavailable on the law of moisture distribution in Yunnan red loam under different drip irrigation patterns, especially root zone infiltrating irrigation. Yu et al. [20], in their earlier stage of research, focused on exploring the effects of different irrigation emitter types and different drip irrigation patterns on soil moisture distribution in red loam and yellow-sand soil in greenhouses without potted planting. The focus of our paper, by contrast, is on the effects on crop growth indices of the moisture distribution in potting soil with plants. In our experiment, a comparative study was made on two kinds of drip irrigation models – namely surface drip irrigation and root zone infiltrating irrigation. In general, after comparing root zone infiltrating irrigation with surface drip irrigation, the former reduced invalid surface evaporation, avoiding surface runoff loss and other shortcomings, and was consequently more conducive to crop growth. The results of our experiment also show that the growth of peppers under root zone infiltrating irrigation in potted Yunnan red loam is better than growth under surface drip irrigation. However, surface drip irrigation in yellow-sand soil is more favorable for the growth of peppers than infiltrating irrigation. This indicates that the earlier stage of research on the infiltration law for different soil textures is crucial, providing an important basis for subsequent scientific applications of irrigation techniques.

Second, compared with field planting, greenhouse-potted soil forms a controllable and small independent environment. Thus, more accurate quantitative studies of the soil moisture distribution can be made. In this study, Surfer and AutoCAD were jointly used to accurately map the moisture distribution patterns of different potted soils in different drip irrigation patterns and different irrigation emitter patterns (as shown in Figs. 4 and 5). Moreover, the percentage of soil moisture in each area was calculated (as shown in Table 4). This research method can accurately quantify the movement and redistribution of water in small potting soil environments, and it can provide detailed reference data for the scientific management of potted crop irrigation.

This test used only one pilot irrigation emitter (an irrigation emitter that could adjust the flow of the horizontal arrangement of the effluent hole) and one test crop (shallow-rooted pepper). However, the direction of the effluent hole of the irrigation emitter had a significant effect on soil moisture distribution [20], and crops with different root characteristics will likewise affect the soil moisture distribution [22,23]. Therefore, in the future, we should further develop contrast tests on the effects of various irrigation emitter types and crops with various root types on the soil moisture distribution of Yunnan greenhouse-potted soil, in order to obtain more efficient water-saving irrigation methods. Furthermore, optimization experiments will be conducted to test mixtures of Yunnan red loam and yellow-sand soil at certain mixing ratios under various irrigation methods, to determine new water-saving root filtration technologies suitable for Yunnan Province.

5. Conclusions

- The soil type and irrigation method have a significant effect on water distribution in the soil for growing potted pepper ($P < 0.05$), but the emitter mode has no significant effect on soil water distribution ($P > 0.05$).
- Matric potential plays an essential role in the transport of irrigation water in the Yunnan red loam. Owing to the effect of matric potential, water does not readily infiltrate. Under root infiltration irrigation, the high-water-content sections in the red loam are mainly distributed in the root zone of the crop, enabling the root to absorb sufficient water; thus, the pepper grew best. Under surface drip irrigation, the high-water-content sections in the red loam are mainly distributed in the topsoil where evaporation loss is great, resulting in less water being available; thus, the crop grew only moderately. Gravity potential plays an essential role in the transport of irrigation water in Yunnan yellow-sand soil. Owing to the effect of gravity potential, water readily infiltrates. As a result, under root infiltration irrigation, the high-water-content sections in the yellow-sand soil facilitated rapid transport to the deep soil layer, resulting in the crop being unable to absorb sufficient water; thus, the crop growth was the worst. Under surface drip irrigation, the high-water-content sections in the yellow-sand soil provide a small amount of water to the root in the process of infiltration, resulting in moderate crop growth.
- The sections in the two types of soil corresponding to a soil area of 70% under root infiltration irrigation were continuously distributed, while they were discontinuously distributed under surface drip irrigation. Water distribution

in the Yunnan red loam was less continuous than that in the Yunnan yellow-sand soil. Thus, it can be concluded that water distribution under root infiltration irrigation is more uniform than that under surface drip irrigation, and water distribution in the yellow-sand soil is more uniform than that in the red loam. Therefore, uniformity of water distribution in the root zone of crops can be improved effectively by adding a certain proportion of yellow-sand soil into Yunnan red loam and applying root infiltration irrigation.

- With Yunnan red loam, the growth indices of the pepper under root infiltration irrigation (plant height: 75.5 cm, stem diameter: 7.2 cm, fresh fruit weight: 70 g, and dry fruit weight: 28.6 g) were, respectively, 12.9%, 14.3%, 46.1%, and 36.8% higher than those of the pepper under surface drip irrigation (plant height: 66.9 cm, stem diameter: 6.3 cm, fresh fruit weight: 47.9 g, and dry fruit weight: 20.9 g), indicating that root infiltration irrigation should be adopted for Yunnan red loam as it has significant water conservation potential. In the Yunnan yellow-sand soil, the growth indices of the pepper under root infiltration irrigation (plant height: 44.2 cm, stem diameter: 4.3 cm, fresh fruit weight: 11.25 g, and dry fruit weight: 5.5 g) were, respectively, 31.7%, 25.9%, 26.9%, and 35.3% lower than those of the pepper under surface drip irrigation (plant height: 64.8 cm, stem diameter: 5.8 cm, fresh fruit weight: 15.4 g, and dry fruit weight: 8.5 g), indicating that root infiltration irrigation is not suitable for Yunnan yellow-sand soil, and the application of surface drip irrigation in the soil would have a relatively good irrigation effect.

Acknowledgments

This research work was supported by the Special Scientific Research Program for Public Welfare Sectors (Territorial Resources) [Grant no. 201511003–3]. The funding agency had no role in the study design, the collection, analysis, or interpretation of data, the writing of the report, or the decision to submit the article for publication.

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