Experimental Study of Water Movement in Sugarcane Field Soil with Drip Irrigation

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Abstract
This study investigated water movement in the major soil types in sugarcane fields with drip irrigation in Guangxi, China. Laboratory simulation experiment of water movement with drip irrigation was performed in soil columns at three emitter flow rates (1.38, 2.20 and 2.80 L/h). The results showed that: 1) Soil type greatly affected the shape of the wetted soil volume (WSV). With gradually increasing hydraulic conductivity, the ellipsoid shape of the WSV gradually changed from wide-shallow to narrow-deep. 2) Soil type also greatly affected water distribution in the WSV. With gradually increasing hydraulic conductivity, the size of the WSV increased progressively while the average soil water content gradually decreased. 3) Drip irrigation amount was the major determinant of the size of the WSV. Both the radial and vertical wetted distances of the soil had an exponential relationship with irrigation amount.

Keywords: SUGARCANE FIELD, EMITTER FLOW RATE, WATER MOVEMENT.

1. Introduction

Drip irrigation is an extensively used water-saving irrigation technique, which directly delivers water or a mixture of water and fertilizer through emitters to crop roots evenly and accurately. Drip irrigation only wets a local area of soil, so as to achieve the purpose of saving water, increasing production and saving labor. The patterns of water movement in drip-irrigated soil are an important basis for the design of drip irrigation systems, which has been studied extensively by researchers. By means of laboratory test, Wang et al. analyzed the relationships between emitter flow rate, irrigation duration, wetting front and water distribution under the boundary of point source infiltration with non-sufficient water supply and variable boundary conditions with surface ponding, the percentage of wetted soil was considered as an indicative parameter of drip irrigation, which is less than 1.0[1]. Li et al. studied water infiltration characteristics of latosol in Leizhou Peninsula, South China[2]. Cote et al. investigated water and solute transport in soil with subsurface drip irrigation[3]. Singh et al. simulated water movement in soil with subsurface drip irrigation from line source[4]. Bhatnagar et al. analyzed water movement in soil under a single surface trickle source[5]. Zhang et al. combined laboratory test with numerical simulation using the Hydrus software to investigate water movement in soil with drip irrigation from multiple point source[6]. Based on an experimental study, Mu et al. built the calculation formula for three-dimensional simulation of wetted soil volume (WSV) under drip irrigation and then used this formula to explore reasonable determination of irrigation depth and irrigation quota[7]. Chen et al.

experimentally studied wetting front movement and redistribution in sandy soil with drip irrigation[8], whereas Liu et al. reported on water movement in sandy loam with drip irrigation[9]. Sun et al. identified the major influence factors of soil wetting pattern and analyzed their impact with point drip irrigation[10]. Moreover, researchers have investigated soil water energy status[11], WSV characteristics[12], and numerical simulation methods under different irrigation conditions[13]. These results have provided useful references for drip irrigation design[14].

Guangxi Province is an important production base of sugarcane in China, which accounts for more than 60% of cane sugar production in this country. In Guangxi, sugarcane is mainly grown on dry slopes that are difficult to irrigate through traditional channels. The problem of seasonal drought has been prominent, seriously hampering the development of cane sugar industry. Development of efficient water-saving irrigation in sugarcane is an effective way to ease the drought threat and increase the production and efficiency in sugarcane fields in Guangxi. Drip irrigation is the irrigation mode commonly used for efficient water-saving irrigation in sugarcane. Because the development of efficient water-saving irrigation in South China is started late, few studies have been conducted on water movement in sugarcane field soil in Guangxi. This situation leads to certain randomness in selecting emitter flow rate, irrigation amount and other parameters for the design of dripper irrigation systems, negatively affecting the benefits of drip irrigation project. Therefore, the systematical study of water movement in sugarcane field soil with drip irrigation has great application value to guiding the development of sugarcane drip irrigation project in Guangxi.

According to the results of the provincial soil survey[15], four representative soil types were selected from sugarcane fields in Guangxi. Soil column experiment of water movement with drip irrigation was performed in the laboratory. The effects of soil type, emitter flow rate and irrigation amount on water movement in soil with drip irrigation were analyzed, in order to determine the parameters suitable for different soil texture.

2. Materials and Methods

2.1. Experimental Soil

The major soil types in the Guangxi sugarcane growing area include lateritic red soil and latosol. Owing to regional differences, the soil physical and chemical properties show certain differences. For comparative analysis of water movement patterns in different types of sugarcane field soil, soil samples were collected from the experimental field of pilot demonstration bases for sugarcane efficient water-saving irrigation technology in southwestern Guangxi (Longze Village, Taiping Town, Jiangzhou District and Xinli Village, Leiping Town, Daxin County), central Guangxi (Yubu Village, Jinji Town, Wuxuan County), and southern Guangxi (Wulangjiang Village, Xichang Town, Hepu County). The sampling depth was controlled within the plow layer at 10–40 cm depth and 8 tons of soil was obtained at each site. The soil samples were air-dried, crushed and passed through a 2-mm sieve before use.

During the experiment, 5-cm thick soil was loaded into the soil box each time and compacted by layer with a flat plate, as required by the experimental design. The initial soil water content (WC) and dry density were measured each time after the completion of soil loading. The soil samples were classified according to the soil classification criteria proposed by the US Department of Agriculture. The type and physical characteristics of the experimental soil are shown in Table 1.

Table 1. Physical properties of experimental soil from sugarcane field in Guangxi, China

Site	Mechanical composition/%			Type (texture)	Dry density/ $(g\cdot cm^{-3})$	Saturated WC/ $(cm^3\cdot cm^{-3})$	FWHC/ $(cm^3\cdot cm^{-3})$	Initial WC/ $(cm^3\cdot cm^{-3})$	Saturated HC/ $(cm\cdot min^{-1})$
	<0.002 mm	0.002–0.05 mm	>0.05 mm						
Jiangzhou	61.6	35.1	3.3	Clay	1.12	0.577	0.487	0.158	1.19208
Daxin	40	52.3	7.7	Silty clay	1.21	0.537	0.465	0.143	1.3325
Wuxuan	32.1	52.7	15.2	Silty clay loam	1.25	0.518	0.45	0.112	1.47625
Hepu	1.9	40.5	57.6	Loamy sand	1.53	0.381	0.33	0.065	1.83583

* WC, water content; FWHC, field water-holding capacity; HC, hydraulic conductivity.

2.2. Experimental device

The experiment was conducted at the Nanning Irrigation Experiment Station. The experimental system consisted of a water supply device, a soil box and a soil-water probe. The water supply device was a peristaltic pump with adjustable flow velocity, which could regulate the flow rate to simulate the emitter. The soil box was a rectangular plexiglass box, 100 cm long, 60 cm wide and 85 cm high. The emitter was fixed to the middle of the long side of the glass box. The emitter was kept 2 cm away from the glass wall to avoid the impact of wall. Four soil-water probe probes were buried at 15 cm away from the emitter, at 5, 15, 25 and 35 cm depths, respectively. Data were recorded by the probes every 10 min.

2.3. Experimental design

Laboratory soil column experiments of water movement with surface drip irrigation were performed in three common scenarios of dripper flow rate (1.38, 2.20 and 2.80 L/h) using the four types of experimental soil. During the experiment, the irrigation amount of each emitter was 18 L. As the experimental WSV accounted only half of the actual WSV, the emitter flow rate and irrigation amount were set according to the symmetry, 1/2 of the respective analog values. Each experiment was repeated three times and each experimental value was expressed as the mean of three measurements. To prevent evaporation, the soil surface was covered with a plastic film during the experiment..

The radius of surface ponding and the horizontal and vertical wetting front changes were recorded continuously during the experiment. After completion of drip irrigation, soil was immediately collected at 5 cm intervals by mesh-stratified sampling for measuring soil WC. Soil WC changes monitored by the soil-water meter were recorded.

2.4. Statistical analysis

Based on the experimental data, plots were made using the Surfer software. Correlation and regression analyses were conducted using Excel software.

3. Results and Discussion

3.1. Effect of soil type on shape of the WSV

Figure 1. depicts changes in the shape of the WSV for different irrigation durations in the four types of experimental soil with drip irrigation at the emitter flow rate of 1.38 L/h and total irrigation amount of 18 L. As can be seen, soil type had a significant effect on the shape of the WSV in drip-irrigated soil. The WSV of clay presented one quarter of a lying ellipse, with radial wetted distance (r) > vertical wetted distance (z) during the experiment (Figure 1.A). In contrast, the WSV of loamy sand presented one quarter of a standing ellipse, with r < z (Figure 1.D). The WSV of silty clay and that of silty clay loam were somewhere in between (Figure 1.B, 1.C), consistent with the results of Revol et al[16].

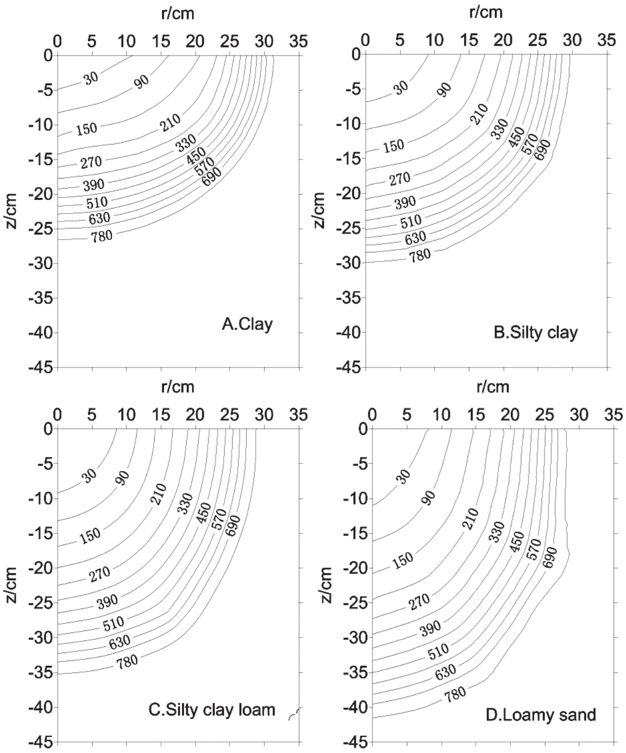

Figure 1. The shape of wetted soil volume in different types of sugarcane field soil with drip irrigation of the same amount (18 L) and emitter flow rate (1.38 L/h) (A) clay; (B) silty clay; (C) silty clay loam; (D) loamy sand (r is radial wetted distance and z is vertical wetted distance).

To facilitate the analysis, we define the r/z ratio as the percentage of wetted soil. Table 2. shows that among the four types of experimental soil, the r/z ratio of clay was relatively high, i.e., 2.50 at 30 min of irrigation and 1.17 at the end of irrigation. The r/z ratio of silty clay came second, i.e., 1.38 at 30 min of irrigation and 0.99 at the end of irrigation. The r/z ratio of silty clay loam was relatively low, i.e., 0.96 at 30 min of irrigation and 0.81 at the end of irrigation. The r/z ratio of loamy sand was the lowest, i.e., 0.73 at 30 min of irrigation and 0.67 at the end of irrigation. Clearly, the r/z ratio was directly related to soil texture and hydraulic conductivity (HC). The higher the soil stickiness, the higher the r/z ratio. In the same soil type, the r/z ratio gradually decreased with increasing irrigation duration. Changes in the r/z ratio with time were greatest in clay and smallest in loamy sand.

Drip irrigation is a complex infiltration process with dynamic boundary, in which three mobile water boundaries are formed, including surface ponding,

Table 2. Relationship between the percentage of wetted soil and irrigation duration in experimental soil

Soil type	Irrigation duration/min												
	30	90	150	210	270	330	390	450	510	570	630	690	780
Clay	2.50	2.32	1.71	1.65	1.54	1.40	1.38	1.33	1.29	1.26	1.23	1.20	1.17
Silty clay	1.38	1.33	1.24	1.20	1.13	1.08	1.04	1.02	1.01	1.01	1.00	1.00	0.99
Silty clay loam	0.96	0.92	0.90	0.89	0.86	0.85	0.83	0.83	0.82	0.82	0.82	0.82	0.81
Loamy sand	0.73	0.73	0.72	0.72	0.72	0.71	0.70	0.70	0.69	0.68	0.68	0.68	0.67

saturated zone and unsaturated zone. As driven by soil matric potential and gravitational potential, water diffuses from the saturated zone to the unsaturated zone through the interface. Soil HC substantially varies with different soil types. When soil HC is low and emitter flow is greater than diffusion (clay and silty clay), surface ponding takes place in the vicinity of the emitter and the extent of the ponding area expands progressively. The extent of the soil saturated zone, the area of the interface and the amount of the diffusion also expand. Until the emitter flow equals the diffusion, the area of surface ponding essentially stabilizes. During this process, the z value is mainly affected by infiltration due to the joint action of soil matric potential and gravitational potential, whereas the r value is mainly affected by infiltration due to the action of soil matric potential and the area of surface ponding. In soil with high stickiness and low HC, the initial surface ponding area is large and expands relatively fast. Thus, the r value grows fast, resulting in a high r/z ratio. However, the growth rate of the r value is diminished as the increasing trend in the extend of surface ponding area is slowing down. On the other hand, with the advance of the infiltration process and the stabilization of the surface ponding area, the joint action of soil matric potential and gravitational potential exert a greater effect than the single action of the former potential. Thus, the z value grows faster than the r value. In this way, the r/z ratio presents a decreasing trend over time. When the soil has high HC and the emitter flow is less than diffusion (silty clay loam and loamy sand), there is no obvious surface ponding in the vicinity of the emitter. During the irrigation process, the z value is mainly affected by infiltration due to the joint action of soil matric potential and gravitational potential, whereas the r value is mainly controlled by infiltration due to soil matric potential. Vertical infiltration occurring in the soil is faster and the r/z ratio is less than 1 with a smaller range of decreases over time.

The shape characteristics of the WSV are of great importance to the design of drip irrigation system in sugarcane. Sugarcane is a crop associated with drill sowing, shallow roots, and close planting. The cropping pattern of wide-narrow rows is presently widely used in sugarcane field with drip irrigation (wide row spacing 1.2-1.3 m; narrow row spacing 0.4-0.5 m). Previous study has shown that 62% of sugarcane roots are distributed in the 0-20 cm soil layer, with 23.4% of the roots distributed in the 20-40 cm soil layer; the optimal irrigation depth of sugarcane is at 20 cm during the initial growth stage, which changes to 25-30 cm in the vigorous growth stage [17]. During the irrigation process, the vertical wetted distance (z) is not easy to observe and it can be determined based on the r/z ratio and the radial wetted distance (r) of the respective soil type. For clay and silty clay, there is r/z >1; then r = ~25 cm is suitable for the initial growth stage and r = ~30–35 cm is suitable for the vigorous growth stage. For silty clay loam and loamy sand, there is r/z = 0.6–0.8; then r = ~16 cm is suitable for the initial growth stage and r = ~20–25 cm is suitable for the vigorous growth stage.

3.2. Effect of soil type on water distribution

Figure 2. presents soil water contours of the four types of experimental soil with drip irrigation at the emitter rate of 1.38 L/h and total irrigation amount of 18 L. Changes in the soil water contours exhibited consistent trends among the four types of soil samples. That is, in the vicinity of the emitter, soil water content was higher and changes slowly; around the WSV, soil water content changed sharply. Soil type generally had a great effect on water distribution in drip-irrigated soil. For different soil types, the shape of soil water contours was substantially similar to that of the respective WSV. The soil water contours of clay presented one quarter of a lying ellipse (Figure 2.A) while those of loamy sand presented one quarter of a standing ellipse (Figure 2.D). In the soil with high stickiness and water-holding ability, the size of the WSV was relatively small and soil water content was relatively high, with water accumulation observed in the upper soil layer; in the soil with low stickiness and water-holding ability, the size of the WSV was relatively large and soil water content was relatively low, with an evident trend of water infiltration in vertical direction. For example, if taking the WSV as a regular ellipse, the WSV of clay accounted for ~80% of that of loamy sand. The initial water content of clay was 0.158 and the water content at the visible

boundary of the WSV was 0.22; more than 40% of the WSV reached the water content of 0.54 or higher, that is, higher than the soil's field water-holding capacity (FWHC) and close to the saturated soil water content (as limited by the sampling conditions, it was difficult to precisely define the boundary of saturated soil water content); the infiltration depth of the WSV was 26.8 cm (Figure 2.A). The initial water content of loamy sand was 0.065 and soil water content at the visible boundary of the WSV was 0.10; only 20% of the WSV reached the water content of 0.34 or higher, that is, higher than the soil's FWHC and close to the saturated soil water content; the infiltration depth of the WSV was 41.2 cm (Figure 2.D).

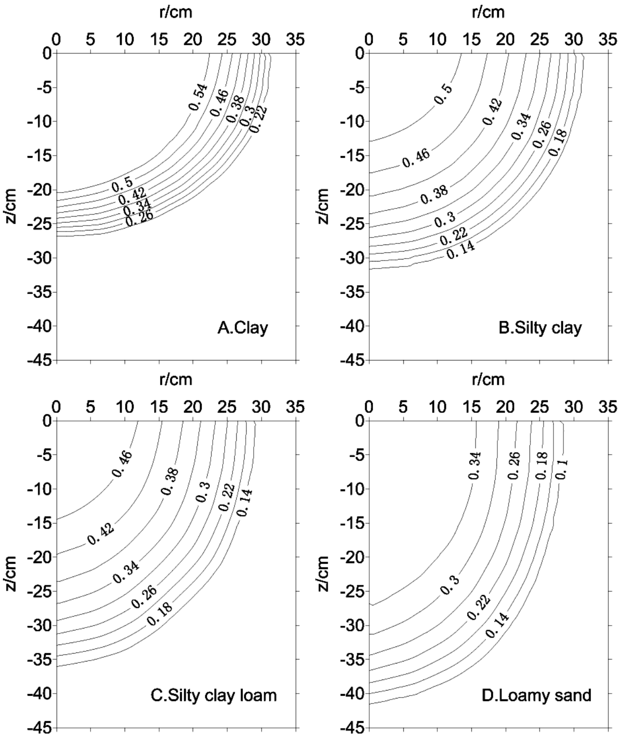

Figure 2. Contours of soil water content in different types of sugarcane field soil with drip irrigation of the same amount (18 L) and emitter flow rate (1.38 L/h) (A) clay; (B) silty clay; (C) silty clay loam; (D) loamy sand.

Water distribution patters in soil are of great guiding significance to cultivation of sugarcane as well as the operation and management of drip irrigation systems in sugarcane fields. For the soil with high stickiness and water-holding capacity, the vertical infiltration capacity of water should be improved through agronomic measures, so as to achieve the purpose of soil water conservation. In practical irrigation, it is recommended to irrigate a small amount of water several times. This strategy will keep soil water content within the appropriate range for sugarcane grown; it also avoids the formation of large saturated area due to a large irrigation amount in a single time, which could reduce soil aeration and easily lead to soil compaction. For the soil with low stickiness and water-holding capacity, the single irrigation amount should be controlled reasonably to reduce deep percolation.

3.3. Effect of emitter flow rate on water movement

Figure 3. depicts changes in the radial (r) and vertical (z) distances of soil wetting front in clay and loamy sand as a function of irrigation duration with the irrigation amount of 18 L and emitter flow rates of 1.38, 2.20 and 2.80 L/h. Emitter flow rate had a certain effect on water movement in soil. For the same irrigation duration, emitters with higher flow rates had a larger irrigation amount, which resulted in larger r and z values than those with lower flow rates. With the same irrigation amount, emitters with higher flow rates finished the irrigation in a shorter period of time, which resulted in slightly but not significantly smaller r and z values immediately after the end of irrigation than those with lower flow rate. In different soil types, the effect of emitter flow rate on water movement varied. In clay, emitter flow rate affected both the r and z values to a certain degree (Figure 3.A, 3.B); in loamy sand, emitter flow rate affected the z value more obviously, while the r value was less affected(Figure 3.C, 3.D). With drip irrigation at different emitter flow rates, both the r and z values had an exponential relationship with irrigation duration (t) as formula (1) and formula (2).

$$r = \alpha * t^{\beta} \quad (1)$$

$$z = \alpha' * t^{\beta'} \quad (2)$$

where $\alpha, \beta, \alpha', \beta'$ are constant.

This result is consistent with previous finding by Zhang et al[18]. The fitting parameters are shown in Table 3.

The above analysis indicates that the effect of using higher emitter flow rate to increase the radial wetted distance (r) or using lower emitter flow rate to increase the vertical wetted distance (z) is not obvious for several major soil types of sugarcane field in Guangxi. Presently, the emitter flow rates frequently used in Guangxi, 1.38, 2.20 and 2.80 L/h, are all suitable for application in sugarcane drip irrigation system. From the perspective of project cost saving and irrigation uniformity, we recommend using the emitter flow rate of 1.38 L/h or lower.

3.4. Effect of irrigation amount on water movement

Table 3. shows that in the same soil type, the parameters α and α' increased with emitter flow rate, while β and β' remained unchanged and could be re-

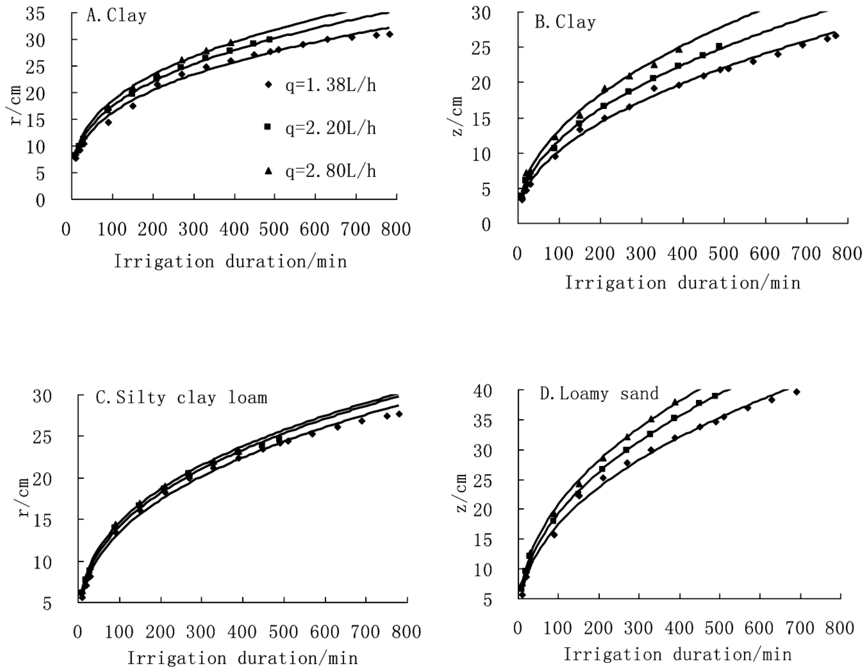

Figure 3. Exponent relationship between wetting front diffusion (radial wetted distance, r; vertical wetted distance, z) and drip irrigation duration (t) in different types of sugarcane field soil with different emitter flow rates (A) r vs. t in clay; (B) z vs. t in clay; (C) r vs. t in loamy sand; (D) z vs. t in loamy sand.

Table 3. Regression parameter for fitted curves of wetting front and irrigation duration in experimental soil with drip irrigation at different emitter flow rates

Soil type	Emitter flow rate/$L \cdot h^{-1}$	*Constant* α	*Constant* β	*Fitting coefficient* R^2	*Constant* α'	*Constant* β'	Fitting coefficient R^2
Clay	1.38	3.41	0.34	0.994	1.13	0.48	0.998
	2.20	3.57	0.34	0.999	1.34	0.47	0.997
	2.80	3.85	0.34	0.998	1.51	0.47	0.989
Loamy sand	1.38	2.39	0.37	0.997	2.27	0.44	0.993
	2.20	2.59	0.37	0.999	2.45	0.45	0.998
	2.80	2.83	0.36	0.999	2.75	0.44	0.998

garded as constants. This result indicates that under drip irrigation conditions, the diffusion of soil wetting front is related to not only irrigation duration but also emitter flow rate (q). Since the product of q and t is irrigation amount (Q) and β is regarded as a constant, the above formula can be transformed formula (3) and formula (4).

$$r = \alpha * t^{\beta} = \lambda * q^{\beta} * t^{\beta} = \mu * Q^{\beta} \qquad (3)$$

$$z = \alpha' * t^{\beta'} = \lambda' * q^{\beta'} * t^{\beta'} = \mu' * Q^{\beta'} \qquad (4)$$

where r is the radial wetted distance of soil, cm; z is the vertical wetted distance of soil, cm; q is emitter flow rate, L/h; t is irrigation duration, min; Q is irrigation amount, L; and α, α', β, β', λ, λ', μ, and μ' are constant.

As mentioned above, with the same irrigation amount, the r and z values had no large differences with different emitter flow rates. That is, irrigation amount, which embodies the two factors of emitter flow rate and irrigation duration, is the most important factor affecting wetting front diffusion in soil.

Changes in the r and z values of the wetting front in clay and loamy sand as a function of irrigation duration are illustrated in Figure 4. Clearly, the r and z values were in an exponential relationship in irrigation amount in either clay (Figure 4.A, 4.B) or loamy sand (Figure 4.C, 4.D). This result well confirms the above inference.

In summary, in the same soil type, irrigation amount is the primary factor affecting water movement in sugarcane field. If the initial soil water content coincides with the data of the experimental soil (Table 1), the suitable irrigation amount of single emitter estimated in accordance with the optimal irrigation depth of sugarcane at the vigorous growth stage (25-30 cm) is: ~15 L for clay, ~12 L for silty clay, ~10 L for silty clay loam and ~7.5 L for loamy sand. In the actual practice, if the initial water con-

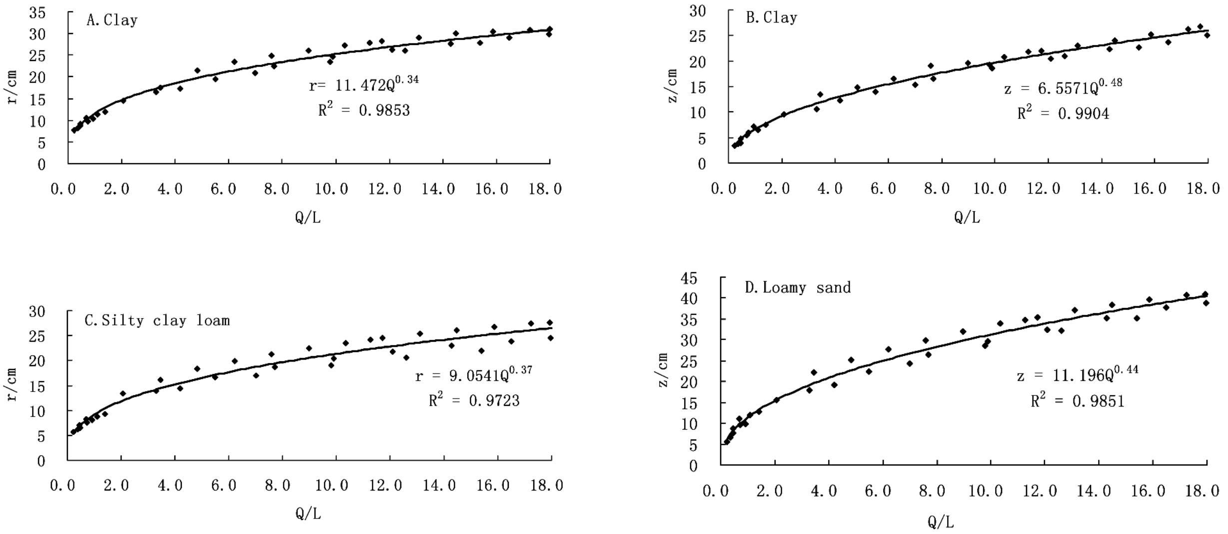

Figure 4. Exponent relationship between wetting front diffusion (radial wetted distance, r; vertical wetted distance, z) and drip irrigation amount (Q) in different types of sugarcane field soil (A) r vs. Q in clay; (B) z vs. Q in clay; (C) r vs. Q in loamy sand; (D) z vs. Q in loamy sand.

tent of the soil before irrigation is higher than that of the experimental soil (Table 1), the suitable irrigation amount of single emitter for different soil types can be adjusted according to the relationship between irrigation amount and radial wetted distance (r), the percentage of wetted soil (r/z ratio) and the optimal irrigation depth.

Conclusions

Soil type had a significant effect on the size, shape and water distribution of wetted soil volume in sugarcane fields with drip irrigation. In clay and silty clay soils with high stickiness and low hydraulic conductivity, wetted soil volume occurred in a relatively small size and presents one quarter of a lying ellipse (r/z >1), with water accumulation in the upper soil layer. For these soil types, a larger single irrigation amount is required to reach the desired irrigation depth. During practical irrigation, it is recommended irrigating a small amount of water several times, so as to facilitate water infiltration in the soil. In silty clay loam and loamy sand with low stickiness and high hydraulic conductivity, wetted soil volume occurred in a relatively large size and presented one quarter of a standing ellipse (r/z <1), with an obvious trend of water infiltration to deeper soil. During practical irrigation, the single irrigation amount should be reasonably controlled to reduce deep percolation.

Emitter flow rate had a certain effect on water movement in sugarcane field soil with drip irrigation. Within the same irrigation duration, emitters with higher flow rates had a larger irrigation amount, so that the resultant radial (r) and vertical (z) wetted distances were both larger than those with lower flow rates. This effect was not obvious with the same amount of drip irrigation. Moreover, the effect of using emitter with higher flow rate to increase the radial wetted distance of soil was not evident in several major types of sugarcane filed in Guangxi. In the same soil type, irrigation amount was the primary factor affecting water movement in sugarcane field soil with drip irrigation. In practical production, the suitable irrigation amount of single emitters for different soil styles can be determined based on the relationship between irrigation amount and radial wetted distance (r), the percentage of wetted soil (r/z), and the optimal irrigation depth.

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