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Irrigation quotas influenced the characteristics of the preferential flow in cotton fields under mulched drip irrigation in Northwest China

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Abstract: Preferential flow is associated with potential issues of poor irrigation water-fertiliser efficiency in a cultivated field. In addition, a preliminary understanding of how irrigation quotas contribute to this prevalent phenomenon is limited. Thus, one blank control group and three different irrigation quotas were set (0, 450, 550 and 650 mm) and the dye tracing image method was applied to investigate the characteristics of the preferential flow in cotton fields under mulched drip irrigation. On the basis of the results, we found significant differences in the preferential flow degree between the four groups (P = 0.02); the mean scores of the dyed area ratio D_c and variation coefficient C_v from the soil stained profile were 29.83%, 45.77%, 37.36%, 39.40% and 0.98, 1.12, 1.28, 1.17 for the total irrigation quota 0, 450, 550 and 650 mm, respectively, indicating an increasing and then decreasing tendency for the non-uniformity as well as variation in the soil water flowing as the irrigation quota being put on. At the same time, the preferential flow ratios showed a similar trend compared with D_c as well as C_v, which were 4.64%, 13.70%, 40.03%, and 23.60% for the irrigation amounts of 0, 450, 550, and 650 mm, respectively. In general, we concluded that the degree of preferential flow with an irrigation quota of 550 mm (local irrigation practice) was highest while no irrigation led to a more uniform flow in the cotton fields with film mulched. The present study goes some way towards supplementing our understanding of preferential flow in agricultural practice.

Keywords: Brilliant Blue FCF; dye tracing image; non-uniformity; soil preferential migration; variability

Preferential flow is generic terminology referring to the phenomenon when water moving through a porous medium follows favoured pathways, thereby bypassing other parts of the medium (Beven & Germann 1982; Luxmoore 1981). Although several systematic reviews of this process have been undertaken to define the rapid flow through the macropores as 'concealed surface runoff', it was not until the late 1970 s that more field and indoor experiments were carried out due to rising environmental concerns about losses of agricultural chemicals to groundwater contamination (Bruggeman 1997). There is a large volume of published studies describing the factors affecting preferential flow, such as cracks, the roots

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zone and holes in the soil made by animals, which may provide preferential channels for the water and solutes to rapidly infiltrate into deeper soil layers in cultivated fields, thus resulting in a poor irrigation water-fertiliser efficiency. (Stone & Wilson 2006; Jarvis 2007; Forsmann & Kjaergaard 2014; Alaoui 2015). A considerable amount of literature has also emphasised other influencing factors: the soil properties, rainfall intensity, agronomic measures, and alternating thawing and freezing. (Jarvis 2007; Vidon & Cuadra 2010; Cheng et al. 2020). These factors may trigger changes in the soil structure, lead to intensifying the soil spatial heterogeneity and redistribute the preferential flow paths (Niu et al. 2006). Moreover, it has also been demonstrated that preferential flow could be substantial with a high initial soil water content in a field investigation (Yao et al. 2017), where the author also reported a close association between the degree of preferential flow and the macropore network in time and space.

Preferential flow, notwithstanding its very complicated mechanism, can be quantified and measured by a variety of methods. The dye tracing image method is the main approach for its merits of direct non-uniform water distribution expression in soils without a high financial investment (Morris et al. 2008). When this method is applied, Brilliant Blue FCF, a food-grade dye, is commonly chosen during the field experiment because of its non-toxicity, easy solubility in water, and distinguishability (Forrer et al. 2010; Ahmed et al. 2015). The obtained images are used to describe how water flows and distributes in a soil through a series of the processing; then the degree of the non-uniformity and other characteristics will be determined via calculating the key data. (Flury et al. 1994; Baveye et al. 1998; Forrer et al. 2010; Ahmed et al. 2015). Obviously, this method renders the preferential flow to a no longer ambiguous concept and bases a line on much more other imaging ways.

Since irrigation is a pivotal condition that has a considerable impact on agricultural development, it is of significance to investigate the characteristics of preferential flow in arid areas – Xinjiang, for instance, at a field scale. Xinjiang has a cold arid desert climate (BWk per the Köppen climate classification) (Peel et al. 2007), and irrigation is a crucial factor for the sustainable development of the oasis agriculture in this region (Danierhan et al. 2013). Given the small precipitation capacity and large evaporation volume, drip irrigation under a mulched film has been practiced across Xinjiang since the early 1990s (Liu et al. 2014). Compared with furrow irrigation and flood irrigation, drip irrigation is considered an efficient way to distribute water more uniformly and restrain the deep percolation (Karlberg et al. 2007). The implementation of mulch blocks the soil from drying during irrigation and minimises the unproductive evaporation from the soil. Furthermore, the mulch is usually valuable in regulating the soil temperature, decreasing the soil degradation, and improving fertiliser-use efficiency and weed prevention. (Liu et al. 2014). Hence, a plastic film cover effectively enhances the crop growth and yield (Romic & Romic 2003; Wang et al. 2009).

While research has been carried out to quantify the preferential flow in farmlands, no single study exists that continues throughout the whole growing season of the crop and implements different irrigation quotas. Besides, reports about investigations into preferential flow in Xinjiang, where water resources are in shortage and mulched drip irrigation has widely been used, are pretty limited. Therefore, this paper gives an account of quantifying the non-uniform characteristics and evaluating degrees of the preferential flow in a cotton filed under mulched drip irrigation with different irrigation volumes. This work may generate fresh insights into the rational selection of irrigation schemes in drought regions.

MATERIAL AND METHODS

Experimental site. A field experiment was conducted in 2020 at the Key Laboratory of Modern Water-Saving Irrigation of the Xinjiang Production and Construction Corps (XPCC) in the Xinjiang Uygur Autonomous Region (as is shown in Figure 1). Located in the south of the Junggar Basin, the middle section of the northern face of the Tianshan Mountains, the study plot has an average altitude of 451 m, an average precipitation of 207 mm, an average evaporation of 1 660 mm, an average ground slope of 6‰ and an average annual sunshine time of 2 856 h. It has an arid desert climate, and its soil type is loamy.

Experimental set-up. In the light of the local current irrigation plan, which is 500 to 600 mm, and the cotton field water capacity, we set up three different irrigation quotas: a total irrigation quota of 650 mm (HI); a total irrigation quota of 550 mm (MI); a total irrigation quota of 450 mm (LI); 0 mm (CK) as the blank-controlled group (Table 1). With regards to the CK group, we only watered at the

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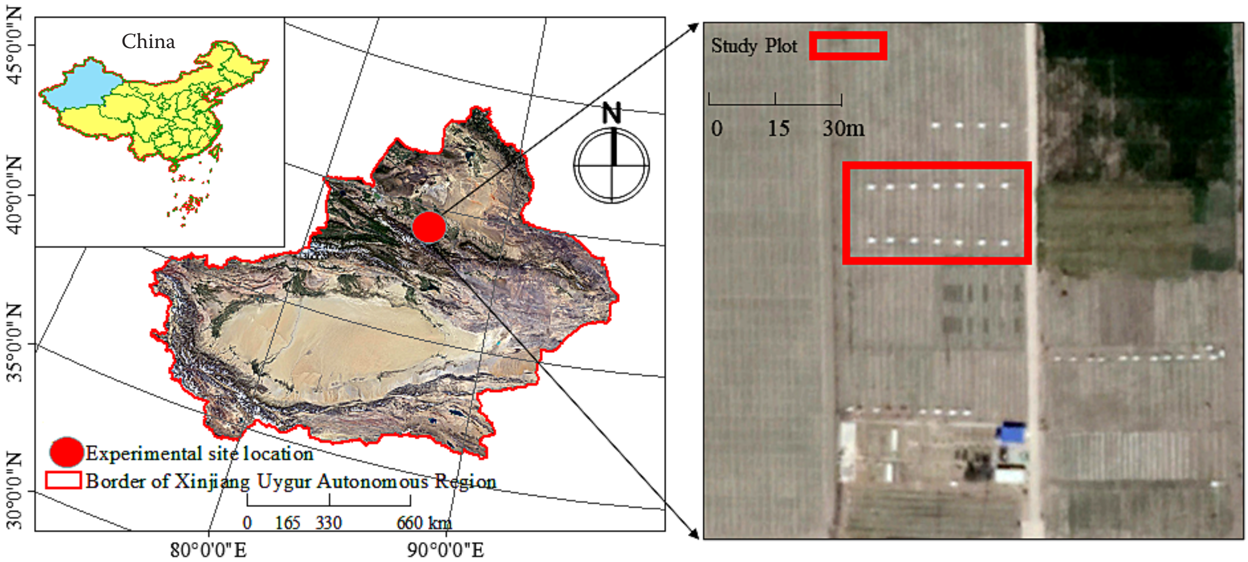

Figure 1. Maps and imagery of the study site; Xinjiang is located in northwest China; the field experiments were conducted at the Key Laboratory of Modern Water-Saving Irrigation of the Xinjiang Production and Construction Corps (44°19'N and 85°59'E) in Shihezi City, Xinjiang

seedling stage until the cotton emerged, after which watering was not involved in the other growth periods of the cotton. A cotton planting mode of one film, three tubes, six rows was utilised, as Figure 2 shows. We had three replicate plots in one irrigation treatment, and there were 12 plots. The irrigation bucket and water gauges were installed to control the irrigation amount. We artificially planted the cotton, consistent with mechanical planting. A rough bird's eye view of the experimental plan of each irrigation treatment can be seen in Figure 2. The field was cultivated (with ploughing depth of 30 to 40 cm) once a year and fallowed in the winter season.

We had planned to carry out the dye tracer experiment 24 h after the total irrigation quotas up to 650, 550, 450 mm at the boll opening stage, in which the soil structure could be steady as there is less irrigation as well as the recession of the cotton root function. A stainless square frame (0.5 × 0.5 × 0.4 m) was used (Figure 2), and the water-soluble food additive Brilliant Blue FCF ($C_{37}H_{34}N_2Na_2O_9S_3$) was used as the dye tracer. We selected the central part of three films in each experimental plot as the excavated position (Figure 2). Prior to the dye tracer experiment, we first scraped and cleared the film and cotton carefully above the soil surface, avoiding destroying the original structure of the soil as much as possible. Then the frames were embedded into the soil at a depth of 0.2 m and the surface soil layers within 2–5 cm of both sides of the frame wall were compacted to prevent the dye tracer from infiltrating the border.

Then, we manually sprayed 20 l of distilled water mixed with Brilliant Blue FCF at a concentration of 4 g/l on the surface soil surrounded by the frame with a uniform speed. Finally, a piece of film was laid on the soil surface in the inner frame after no obvious pooling water appeared 24 h after the dye tracer experiment, we removed the film and frame, created a trench (0.4 × 0.4 m) to gain the images of the vertical cross-sections by a digital camera (Nikon-D5300, Nikon Imaging Sales Co., Ltd, China). Each dyeing area was excavated longitudinally at 10 cm intervals with four sections (Figure 2), we procured 12 images in one treatment, which came to 48 images in this experiment. Since

Table 1. Irrigation schedule

No.	Irrigation quota (mm)	Irrigation time interval (days)	Irrigation start date	Irrigation end date
1	650	7	24. 04. 2020	22. 09. 2020
2	550	7	23. 04. 2020	20. 09. 2020
3	450	7	22. 04. 2020	20. 09. 2020

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the dye tracer does not have any influence on the soil structure, after taking one picture, we used ring knives to collect vertical soil samples around every excavation profile with an interval of 10 cm (at every depth, we collected three ring knives) (Figure 2). Then the soil non-capillary porosity was determined. The initial water content and post water content were also sampled and calculated. Three points were selected randomly (under the drip irrigation tube, between the tubes, between the films) to be drilled to a depth of 50 cm immediately before and after the dye tracing experiment as well for the last irrigation schedule. We used an oven to dry the soil specimens in aluminium boxes and recorded the changes in the mass before and after being dried, which can decide the gravimetric water content (g/g).

Image processing. The soil profile images suffered from geometric distortion, in-homogeneous illuminations, and colour differences (Wu et al. 2014). Firstly, we used Adobe Photoshop (Adobe Systems, 2018) to assist with the geometric correction of the images; afterwards, we continued to adjust the brightness and colour of those images. The image was then transferred to binary pictures by adjusting the grayscale and threshold value; the dyed part was replaced with black (RGB = 0), while the non-dyed part was replaced with white (RGB = 255). Image-Pro Plus 6.0 was next applied to lower the noise of the binary pictures, the changes are presented in Figure 2, while Figure 3 shows the ultimate binary images. Finally, we used a count order to calculate the relevant data.

Mathematical statistics indices

(1) Dyed area ratio (D_c): the percentage of the dyed area of a certain soil depth profile to the total area of the depth. The equation is:

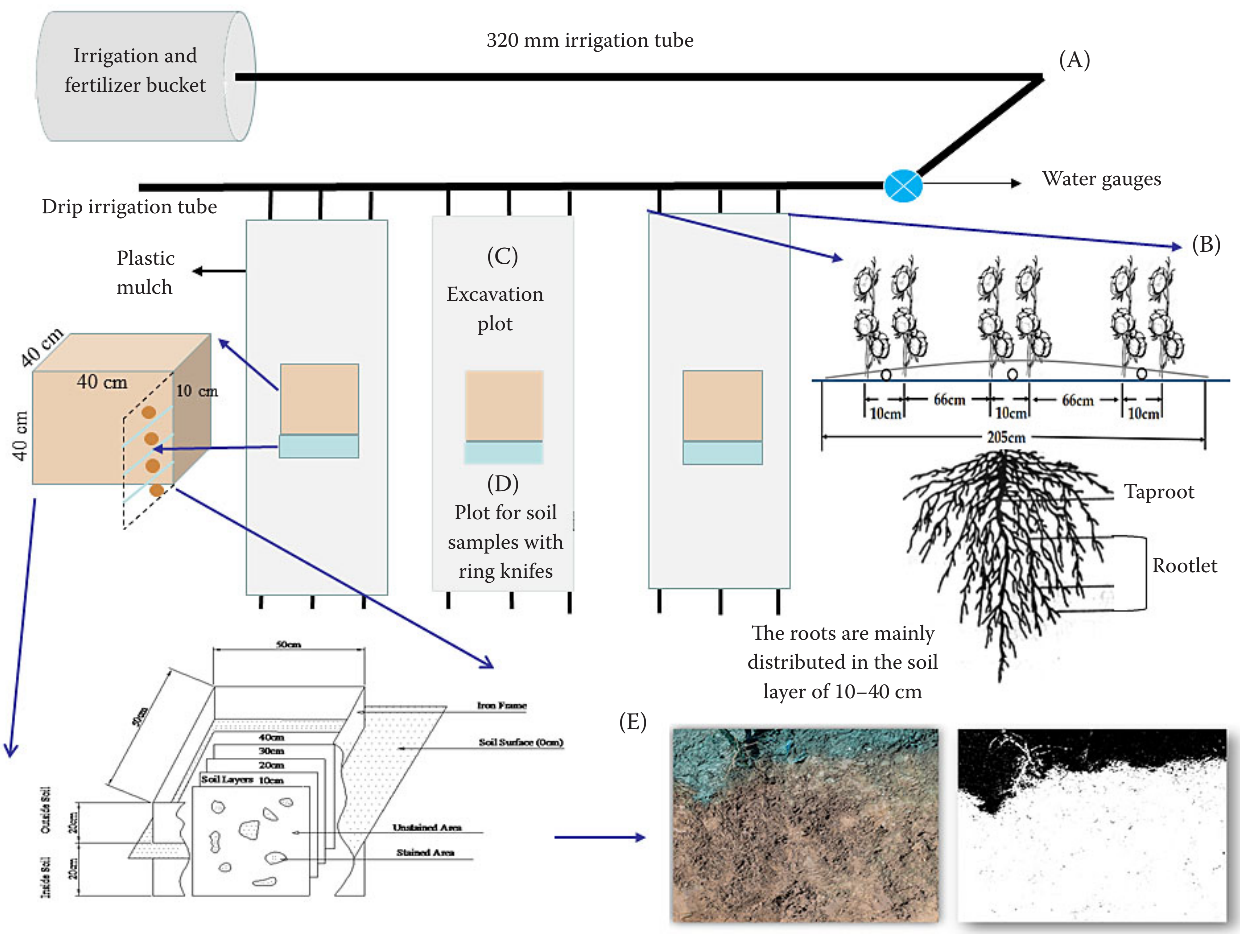

Figure 2. Experimental layouts of the cotton field with the film mulching cultivation system (A), the planting mode of cotton and its usual root depth (B), excavation plot and the way we excavated to obtain the original images (C), the sampling site with ring knives and how we collected the samples (D), and (E) a comparison of the original and binary images after the image processing

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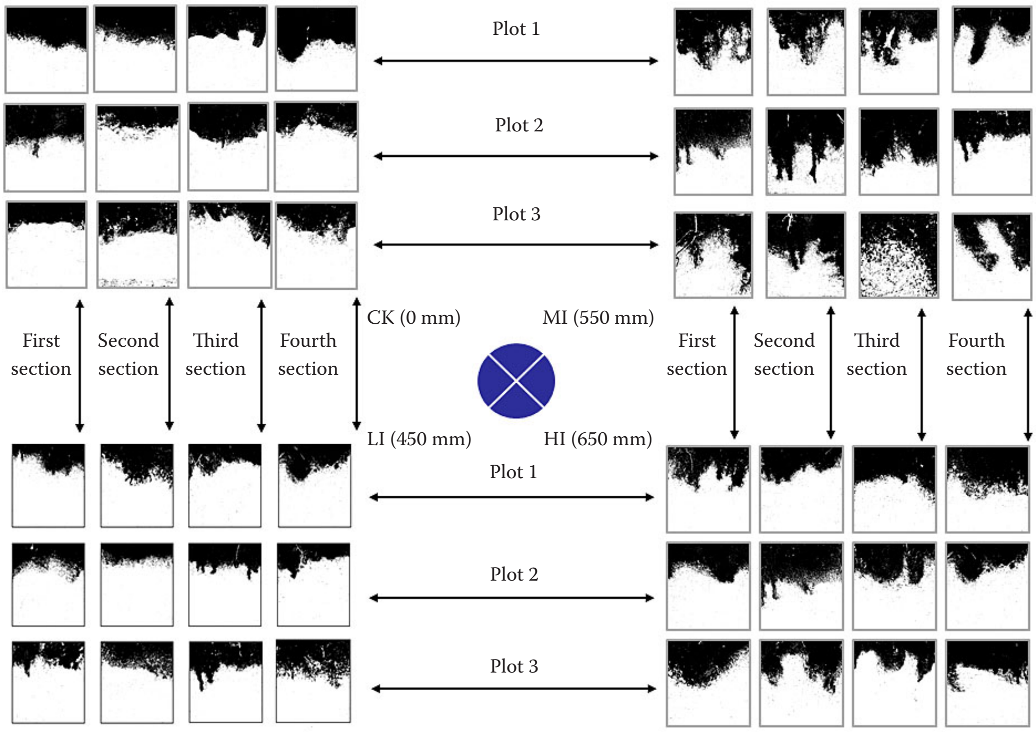

Figure 3. All the ultimate binary images from the four treatments were prepared by image processing
The Image-Pro Plus (Ver. 6.0) was applied to calculate the relative data; CK, LI, MI, HI denote the set of irrigation quotas of 0, 450, 550, and 650 mm, respectively

$$D_C = \frac{D}{D + N_d} \times 100\% \quad (1)$$

where:
D – the dyed area (cm^2);
N_d – non-dyed area (cm^2).

(2) Matrix flow depth (U_{niFr}): when the dyeing area ratio is greater than 80%, the dyeing area is used as the matrix flow area, and the maximum depth that it can reach is the matrix flow depth.

(3) Preferential flow ratio ($P_{\text{F-fr}}$): the percentage of the preferential dyeing area to the total dyeing area. The equationis:

$$P_{\text{F-fr}} = \left(1 - \frac{U_{\text{niFr}} W}{T}\right) \times 100\% \quad (2)$$

where:
U_{niFr} – the matrix depth (cm);
W – the soil profile width (cm);
T – the total area of the corrected soil profile.

(4) Coefficient of variation of the soil staining profile (C_v) indicates the degree of difference in the stained soil profile, and the equation is:

$$C_v = \frac{\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(D_{ci} - \overline{D_c}\right)^2}}{\frac{1}{n}\sum_{i=1}^{n} D_{ci}} \quad (3)$$

where:
D_{ci} – the average value of the dyed area ratio at soil layer per unit;
$\overline{D_c}$ – the average value of the dyed area ratio.

(5) Soil non-capillary porosity (P_n):

$$P_c = W \times S \quad (4)$$

where:
P_c – the soil capillary porosity;
W – the field water capacity (%);
S – the soil bulk density (g/cm^3).

$$P_n = P_1 - P_c \quad (5)$$

where:
P_1 – the total soil porosity

(6) Water content (W):

$$W = \frac{P_1 - P_2}{P_2 - P_0} \quad (6)$$

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where:

P_1 – the sum of the mass of the wet soil and the aluminium boxes (g);

P_2 – the sum of the mass of the dry soil and the aluminium boxes (g);

P_0 – the mass of the empty aluminium boxes (g).

IBM SPSS Statistics software (Ver. 19.0, IBM Corp., Chicago, IL, USA, 2010) was used to perform the statistical analysis. We then calculated the mean values and analysed the differences among the average values obtained from each treatment using the least significant differences tests at a significance level of α = 0.05. The bi-variate correlations (Pearson's coefficient was the default correlation coefficient) were carried out to determine the variation between the experimental data.

RESULTS AND DISCUSSION

Non-uniformity and variability characteristics. Prior to the dye tracing experiment, the initial water content of the four treatments presented no significant difference; there was an increasing trend in the water content with regards to the soil depths, and this trend tended to decrease when the depth reached –30 to –40 cm (Figure 4A). The post water content was higher than the initial water content except for that in the CK treatment (Figure 4B); in addition, the decreasing point in the water content with regards to the depth increased to –10 to –20 cm compared to the initial water content.

The soil non-capillary porosity means the water holding capacity of the preferential channels in the soil. The farming practices profoundly affect this index (Figure 5). The average non-capillary porosity value in the CK group was the lowest, which had a slight increase with regards to the soil depths. The MI and HI groups had more non-capillary porosity in the shallow soil layer (–10 cm to –20 cm), which decreased, but was still higher than those without irrigation. The LI group did not show much variability in the non-capillary porosity from –10 cm to –40 cm.

The total dyed area value (D_c) was 24.88%, 29.83%, 45.77%, and 37.36% for the CK, LI, and MI, HI treatments, respectively, showing an increasing trend at first but a decreasing one with a higher irrigation quota, where the MI group (550 mm) reported the highest percentage (Figure 6). The values of D_c at different depths (every 1 mm) were also determined, and apparently, the difference could be significant between some depths (Figure 7). This difference was mainly

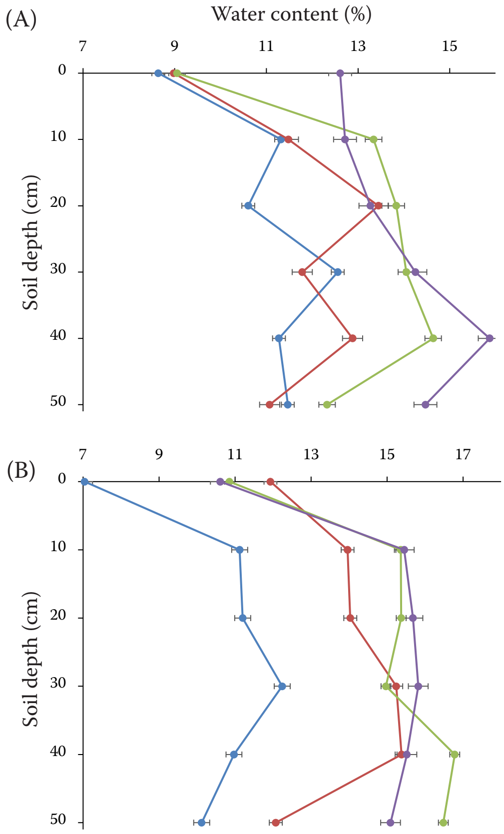

Figure 4. The initial water content was measured 24 h before the dye tracing experiment (A) and the post water content was measured 24 h after the dye tracing experiment (B)
The error bar reflects the standard error of the measured soil water content at each 10 cm soil layer depth

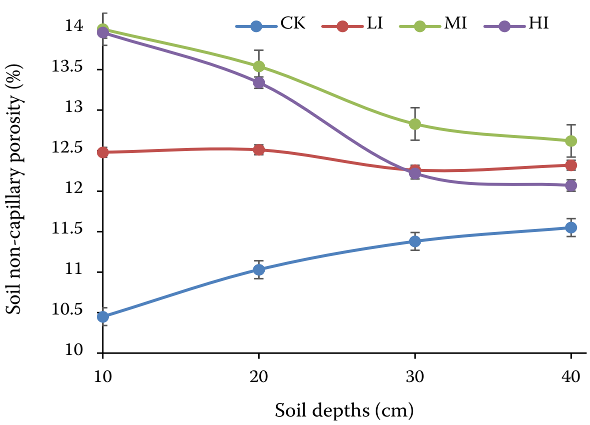

Figure 5. The soil non-capillary porosity by depths when implementing the different irrigation quotas; the soil sampling was simultaneously collected during the dye tracing experiment
The error bar represents the standard error of the measured soil non-capillary porosity at each 10 cm soil layer depth

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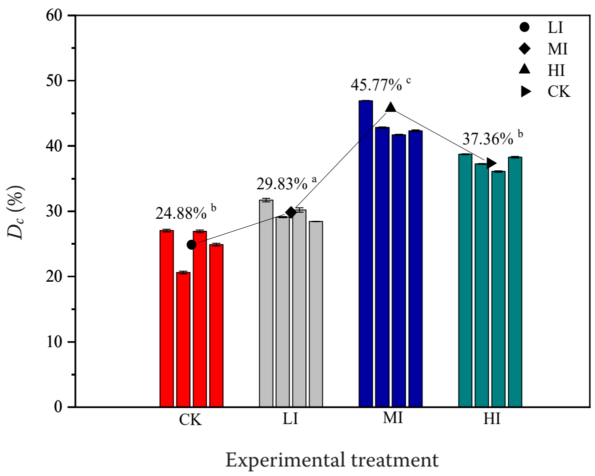

Figure 6. The average dyed area ratio (D_c) of the soil profile in four different irrigation quotas

[a, b, c]refer to the correlations between the different irrigation quotas, the error bar represents standard error; the significance level was P = 0.05; CK, LI, MI, HI denote the set of irrigation quotas of 0, 450, 550, and 650 mm, respectively

reflected in the non-monotonous drop of D_c by the soil depths, which were consistent with the results reported by Sheng (2012). In the LI treatment (450 mm), the dyed area, which was over 85%, was above –15 cm, where the uniform flow mainly occured. However, this depth became shallower (–15 to –10 cm) with a drastic variation in D_c at –20 to 0 cm in the MI treatment (550 mm), indicating a more non-uniform flow in the soil profile. In the HI treatment (650 mm), the variation in D_c between the depths was not as dramatic as in the MI treatment, but in comparison with the LI treatment, more non-uniform flow still appeared. Yet without implementing irrigation, the CK treatment (0 mm) presented a more uniform flow in the soil and fewer changes between the depths than the other three groups, whose depth of dyed area over 85% was more than –20 cm.

The movement of water in a soil can be complicated and random (Karlberg et al. 2007). When the mulched drip irrigation was applied decades ago in XPCC, the cultivation, residual film, freeze-thaw cycle, as well as the straw return could have influenced the soil structure, which may bring about the development of non-uniform flow in this area. According to Sheng (2012) and Wang & Cheng (2012), this was mainly because (1) when the infiltration amount was small, the water flow could be steady due to the fact that the water volume of the upper layer in the soil did not outstrip the water-conducting ability of the preferential channels, so that the water could infiltrate into a deeper soil layer through the channel adequately; (2) when the upper infiltration amount was up to a certain level in which it had already surpassed the water capacity of the preferential channel, lateral infiltration occurred due to the accumulation of the water retarded at the shallow layer in the soil. Hence, the irrigation amounts reshaped this infiltration. As a result, this lateral infiltration decreased the vertical infiltrated intensity, squeezed the percolation space and, thus, increased the uniformity.

The varying values of C_v are concerned with quantifying the uniformity in the stained soil profile. The higher the C_v value was, a higher heterogeneity of the soil section emerged (Jaynes et al. 2001). The average number of C_v in the MI group was 1.28, with 1.12, 1.17, and 0.98 in the LI, HI, and CK groups, respectively, suggesting that, under the irrigation quota of 550 mm, the variability of its dyeing patterns was the largest and the water flowed more uniformly without applying irrigation (Figure 8).

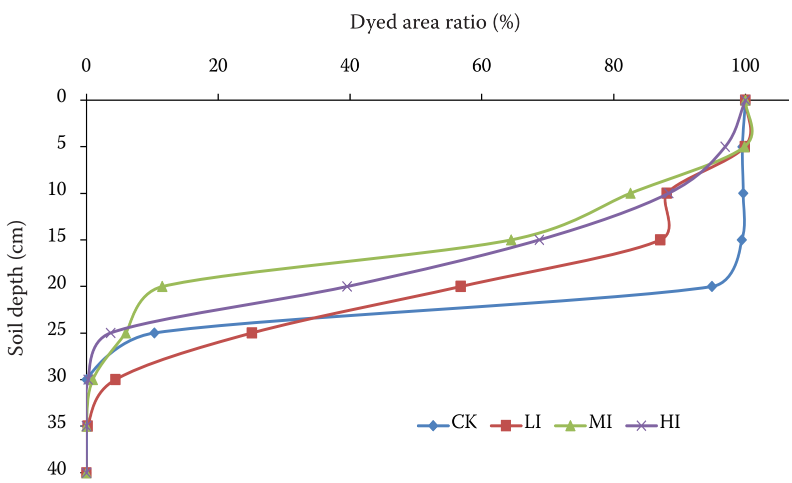

Figure 7. The average dyed area by depth (1 mm) when implementing the different irrigation quotas

CK, LI, MI, HI denote the set of irrigation quotas of 0, 450, 550, and 650 mm, respectively

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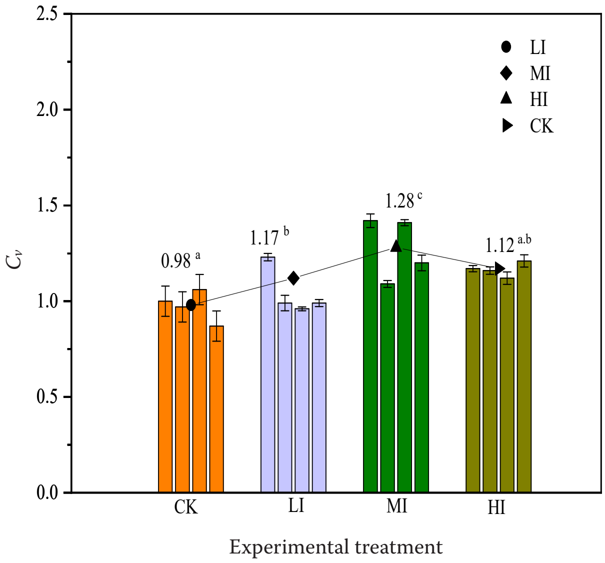

Figure 8. The coefficient of variation (C_v) indices of the four different irrigation quotas

a, b, c refer to the correlations between the different irrigation quotas, the error bar represents the standard error; the significance level was P = 0.05; CK, LI, MI, HI denote the set of irrigation quotas of 0, 450, 550, 650 mm, respectively

Overall, as the irrigation quota increased, the soil water flowing uniformity at first increased, but then decreased. In the MI treatment, the values of C_v and D_c were discovered to be higher than in the rest of the other treatments, showing more non-uniformity in the soil profile. These findings suggested that the irrigation amount impacted the non-uniform characteristics. We speculated that as the pace of the irrigation volume increased, the water flow mainly concentrated in the rapid local fast preferential flow channels. When the irrigation amount expanded, the total water amount in the tracks increased, resulting in the full development of preferential channels in this part. Nevertheless, in the HI treatment, the high infiltration amount caused a slow preferential channel and the matrix flow channel to develop well, leading to wide expansions and connections in the preferential channels, which can reduce the variability and the non-uniformity of the flowing water in the soil in some ways.

Quantitative evaluation of preferential flow. Overall, the matrix depths of all the treatments were all over 10 cm. The CK treatment had the highest matrix depth (18.79 cm), at 16.32, 11.39, and 13.05 cm in the LI, MI, and HI treatments (Figure 9), respectively, suggesting that the agricultural practice may change the infiltration depth in the matrix domain in the soil. Moreover, the higher the matrix depth, the less chance the preferential flow appears. The results confirmed that the preferential flow developed under the MI treatment, but with the total irrigation quota rising to 650 mm (HI), the formation of the preferential flow was suppressed.

The preferential flow ratio ($P_{\text{F-fr}}$) in the MI treatment was the most prominent (40.03%), which was almost nine times higher than the CK treatment (4.64%) (Figure 10). We can also tell from Figure 10 that as the irrigation quota increased, the $P_{\text{F-fr}}$ increased 2.9 times from the LI to the MI treatment but decreased 1.7 times from the MI to the HI treatment, demonstrating that the preferential flow would have more chances with the MI treatment.

The crop yield was also determined. The MI and HI treatments had a higher output than the LI treatment, but the yield difference between the MI and HI treatments was not significant (Figure 11). In general, we made a quantitative evaluation of the development of the preferential flow in a cotton field under mulched drip irrigation. The degree of preferential flow in the MI treatment was the highest, while no irrigation led to a more uniform flow. The probable reasons were: when the irrigation amount was small, the development of the preferential channels of water was restricted; but as the amount increased,

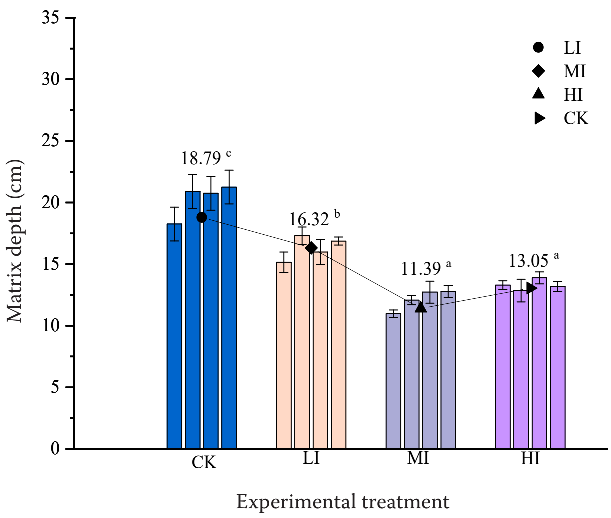

Figure 9. The mean values of the matrix depth under the four different irrigation quotas

a, b, c refer to the correlations between the different irrigation quotas, the error bar represents the standard error; the significance level was P = 0.05; CK, LI, MI, HI represent the set of irrigation quotas of 0, 450, 550, 650 mm, respectively

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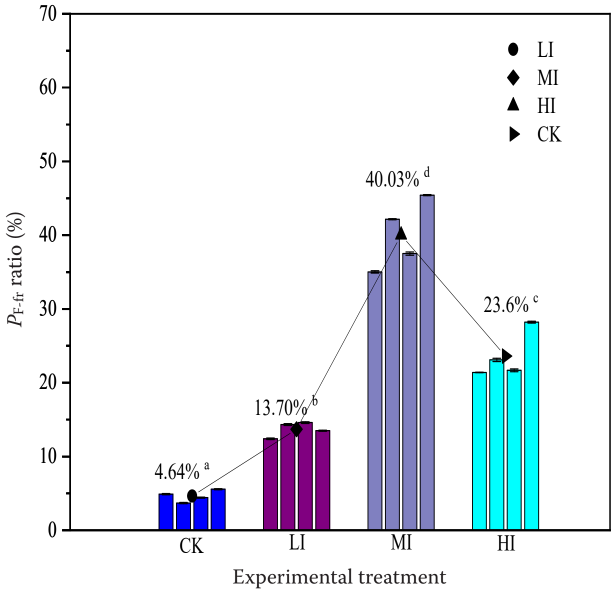

Figure 10. The values of the preferential flow ($P_{F\text{-}fr}$) ratio
[a, b, c]refer to the correlations between the different irrigation quotas, the error bar represents the standard error; the significance level was $P = 0.05$; CK, LI, MI, HI represent the set of irrigation quotas of 0, 450, 550, 650 mm, respectively

the preferential channels were fully formed and connected, the irrigation water could unevenly infiltrate into deeper soil layers, resulting in a higher preferential flow ratio; however, when the amount was up to a certain level, the water infiltration of the upper layer (0 to –15 cm) exceeded the water conductivity of the channels, hindering the water flowing downward and uniformly. The cultivated method of mulched drip irrigation may also play a vital role in forming the preferential flow; the drip irrigation

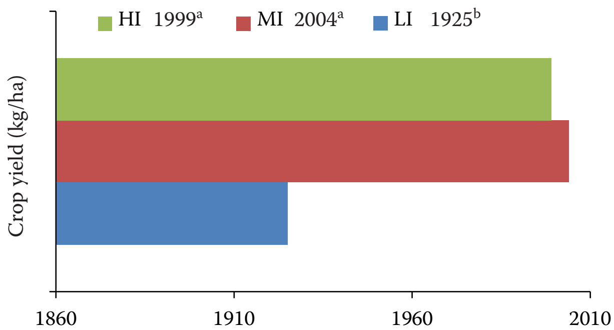

Figure 11. Cotton yield under the different treatments
[a, b]indicate the correlations between the different irrigation quotas with a significance level of $P = 0.05$; LI, MI, HI represent the set of irrigation quotas of 450, 550, 650 mm, respectively

uses a method to distribute the water uniformly, and the covering film can prevent the soil from drying and any unnecessary evaporation. As the irrigation amount increased, the moisture body could swell and move downward, where deep percolation and more preferential flow can occur. However, over-irrigation would make the horizontal distance and range of the soil moisture wider; hence, a lower preferential flow appeared.

CONCLUSION

In summary, this investigation revealed that the non-uniformity and variability became gradually evident with an increasing irrigation quota but reduced when the irrigation quota was up to 650 mm (HI), suggesting that the cultivation and irrigation quota could impact the non-uniform water movement in the soil. The research also showed that the degree of preferential flow in the MI treatment (550 mm) was the highest, which was the local irrigation schedule. The lower irrigation amount hindered the development of preferential channels, yet, the over-irrigation amount affected the soil's non-capillary porosity in the upper soil layers. Though the crop yields in the MI and HI treatments were higher, they could lead to a higher preferential flow; the difference in the yield in the two groups was not significant also, indicating that the higher irrigation amount may not be in line with expectations. The insights gained from this study may be of assistance to reveal the characteristics of preferential flow in a soil with the current irrigation quota (500 to 600 mm), which may bring about more developed non-uniform flow. However, the limitations of this study were the lack of observation of the four key growth stages of cotton in this field experiment and the real-time detection of water flow in the soil.

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