EFFECTS OF FERTIGATION UNIFORMITY ON COTTON YIELD AND QUALITY UNDER ARID CONDITIONS

Hongjie Guan[1], Jiusheng Li[2], Yanfeng Li[3]

ABSTRACT

Drip irrigation under plastic mulch can be the most efficient in-season water application method for cotton production in the arid area of Xinjiang Uygur Autonomous Region, China. One of the biggest obstacles to the widespread adoption of this method is the high cost of initial installations. The costs of drip irrigation installations may be reduced if the systems are designed using a uniformity that is lower than the costs recommended by the current standards. However, it is left unclear that whether lower fustigation uniformity results in a decreased lint yield and quality in the arid regions or not. Field experiments were conducted in the arid environments to evaluate the effects of fertigation uniformities on growth, nitrogen uptake, lint yield, and quality of cotton. In the experiments, three fertigation uniformities of 0.60, 0.80, and 0.99 (referred to as C1, C2, and C3, respectively) and three irrigation levels of 50%, 75%, 100% of irrigation requirements (referred to as I1, I2, and I3) were used. The results demonstrated that plant height and leaf area index (LAI) were sensitive to nonuniformity of water and fertilizer applied. During the growing season of cotton, a great decrease of *CU* for plant height and LAI was observed for the low and medium uniformity treatments of C1 and C2, while a slight increase in the *CU* was observed for the high uniformity treatment of C3. Only at the full irrigation level of I3 did fertigation uniformity have a positive effect on lint yield, although the lint yields among different *CU* treatments were not significantly different. Fertigation uniformity imposed an insignificant influence on the mean values of plant height, LAI, nitrogen uptake, lint yield, and quality parameters; but significantly reduced the uniformity for plant height, LAI, and nitrogen uptake. In the arid regions, the possibility of using a drip irrigation uniformity that is lower than the values recommended by the current standards should balance the installation and operation costs, crop production, and products quality.

1. INTRODUCTION

Agricultural producers are facing decreasing water supplies and are becoming increasingly aware of the need for conservation of limited water resources. An alternative way to address these concerns is to utilize new irrigation technologies such as drip irrigation. Drip irrigation under plastic mulch can be the most efficient in-season water application method for cotton production in Xinjiang Uygur Autonomous Region, China (Cai et al., 2002; Li et al., 2001; Cai et al., 2002; Zhang et al., 2004).

---

[1] -H. Guan, Doctorial student, Department of Irrigation and Drainage, China Institute of Water Resources and Hydropower Research, Beijing 100048, China.

[2] - J. Li, Professor, Department of Irrigation and Drainage, China Institute of Water Resources and Hydropower Research, Beijing 100048, China; E-mail: lijs@iwhr.com.

[3] - Y. Li, Senior Engineer, Department of Irrigation and Drainage, China Institute of Water Resources and Hydropower Research, Beijing 100048, China.

Corresponding author: J. Li

The area irrigated with this method in 2009 was estimated to exceed 429,000 ha, accounting for 30% of the total irrigated area for cotton production based on interviews with Xinjiang Department of Agriculture personnel. One of the biggest obstacles to the widespread adoption of this method is the high cost of initial installations. The design of a drip irrigation system can have a major impact on the initial cost with a direct relationship between level of uniformity and initial cost of the system (Wilde et al., 2009). The costs of drip irrigation installations may be reduced if the systems are designed using a uniformity that is lower than the values recommended by the current standards. However, it is not clear that if a lower fertigation uniformity may result in a decreased yield and quality. Therefore, the effects of irrigation uniformities on plant growth, yield and quality have been a topic for several decades (Varlev, 1976; Seginer, 1978; Seginer, 1983; Warrick and Gardner, 1983; Solomon, 1984; Letey et al., 1984). Using the CERES-Maize model, Pang et al. (1997) simulated the effects of sprinkler uniformity, irrigation amount, and nitrogen applied on crop yield and concluded that decreasing Christiansen uniformity coefficient (*CU*) from 1.00 to 0.75 caused a reduction of yield. Chen and Zheng (1995) presented an optimizing method for irrigation uniformity by minimizing the input-output ratio by assuming a linear crop water production function and equality between volume of deficit irrigation and volume of over-irrigation. Using an economic analysis of optimal irrigation scheduling and the expected relative return, Wu and Barragan (2000) estimated optimal emitter flow uniformity and provided a design criteria for microirrigation systems based on the availability of water resources, considering environmental pollution and groundwater contamination. They also assumed a linear water application function and a linear crop respond model. The studies mentioned above provided useful ideas for selecting the design standard of drip irrigation uniformity, but few experimental data are available for evaluating these models. Few researchers studied the effect of drip fertigation uniformity on crop yield through field experiments. Field experiments conducted by Or and Hanks (1992) indicated that the variability of crop height and crop yield exhibited spatial structures similar to the water applied by nonuniform drip irrigation systems. In a study in the Texas High Plains, Bordovsky and Porter (2008) found no significant differences in cotton yield and value among SDI treatments having three flow variations (Q_{var}) = 5%, 15%, and 27%. Li et al. (2011) studied the effects of fertigation uniformity (*CU* = 0.62, 0.80, and 0.96) on yield and quality of Chinese cabbage in a solar heated greenhouse of semi-humid region and concluded that increasing fertigation uniformity might not necessarily result in an increased yield and an improved quality of Chinese cabbage.

While comparing the simulated to the observed effects of irrigation uniformity on crop yield, one could notice a large difference between them. One reason is that the redistributions of water and nutrients applied through drip fertigation systems in the soil and the inherent variation of soil properties have not been incorporated in the simulation models (Chen and Zheng, 1995; Wu and Barragan, 2000). Further field experiments are necessary to verify and modify the existing simulation models.

The objectives of this study were to evaluate the effects of drip fertigation uniformity on growth, nitrogen uptake, lint yield, and quality of cotton in the arid environments and to give recommendations for selecting the design standard of drip irrigation uniformity in arid regions.

2. MATERIALS AND METHODS

2.1 Experimental field

Field experiment was conducted in the Experimental Station of Irrigation Center at Urumqi (44°06’N，87°30’E), Xinjiang Uygur Autonomous Region, China which has a arid climate. Mean annual rainfall and evaporation of this area was 200 mm and 1600 mm, respectively. The table of groundwater was around 5 m beneath the land surface. The soil of the experimental field was classified as a loam with a bulk density of 1.60 g cm^{-3} and a field capacity (FC) of 20.7% (gravimetric water content).

During the growing season, Cotton (*Gossypium hirsutum* L.) was watered by mulched drip irrigation technique. Using a mulch seeder, four rows of cotton with spacing of 20 cm + 45 cm + 20 cm was seeded under one 115-cm wide plastic film on 5 May 2010 (Figure 1). The plant spacing was 10 cm. A germination water of 37.3 mm was applied immediately after seeding. Pests and weeds control followed the conventional practices in this area.

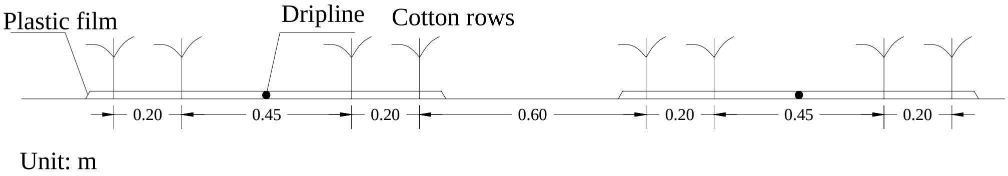


Figure 1. Schematic diagram of cropping pattern and lateral layout of driplines under plastic mulch for cotton.

2.2 Experimental treatments

Christiansen uniformity coefficient (*CU*) defined in Eq. (1) was used to calculate the fertigation uniformity.

$$CU = 1 - \frac{\sum_{i=1}^{n} \left| q_i - \bar{q} \right|}{n\bar{q}} \qquad (1)$$

where *CU* is Christiansen uniformity coefficient; q_i is the ith emitter discharge; $\bar{q}$ is the mean of all n observations.

In the experiments, three fertigation uniformity of 0.60, 0.80, and 0.99 (referred to as low uniformity C1, medium uniformity C2, and high uniformity C3, respectively) and three irrigation levels of 50%, 75%, 100% of irrigation requirements (referred to as low irrigation level I1, medium irrigation level I2, and high irrigation level I3) were used. The experiment was arranged as randomized complete block with three replications. Resultantly, there were 27 experimental plots in total, each having an equal size of 50 m long and 4.35 m wide. Each plot consisted of twelve 50-m long rows of cotton. One dripline was placed in the center of the two inner rows under mulch. Such an installation resulted in a lateral spacing of 145 cm (Figure 1).

The lower *CU* values of 0.60 and 0.80 were obtained by assembling the segments of drip tubes with six different nominal discharges (1.1, 1.4, 1.75, 2.1, 2.7, and 3.0 L/h at 0.1 MPa, respectively) randomly along the entire lateral, but a mean emitter discharge of 2.1 L/h at 0.1 MPa, which was similar to the mean emitter discharge for the *CU* of 0.99, was maintained for the assembled laterals. For all driplines, an emitter spacing was 30 cm. Emitter flow rates for the three *CU* treatments were measured by cans spaced at 90 cm intervals (56 emitters for each lateral tested) prior to lateral installation to confirm if the *CU*s for the assembled laterals were comparable to the designed values. The actual *CU*s were 0.65, 0.78, and 0.94 for the designed values of 0.60, 0.80, and 0.99, respectively.

2.3 Irrigation and fertigation

An individual manifold including a valve, a pressure gauge, and a flow meter, was installed for each plot to control the inlet pressure and record the volume applied during an irrigation event. For all irrigation events, the inlet pressure was maintained at an approximately similar value of 0.1 MPa.

For the full treatment I3, irrigation was conducted when the averaged soil moisture within the root zone (40 cm for squaring period and 60 cm for bloom period) depleted to 60% and 70% of field capacity (FC) for squaring and bloom period, respectively. Accordingly, the upper limit of irrigation was used as 85%FC for the squaring and 95%FC for the bloom. For the deficit treatments of I1 and I2, irrigation was applied on the date similar to the I3 but the water applied was 50% and 75% of the I3. Such an irrigation schedule resulted in a total irrigation of 279.2 mm for the full irrigation of I3 (Table 1).

During the irrigation season, urea was fertigated through drip irrigation systems using a pressure differential tank. The split N applications were scheduled to occur at approximate one week intervals and a total of 110.4 kg ha^{-1} nitrogen was applied for all treatments. Irrigation dates, irrigation depths, and nitrogen applied are summarized in Table 1.

Only three precipitation events with rainfall of larger than 5 mm were observed: 25 June (9.2 mm), 12 July (6.2 mm), 11 August (7.2 mm) during the growing season, resulting in a total of 22.6 mm of effective rainfall.

Table 1. Irrigation and fertigation schedules for the full irrigation treatment of I3.

	Date									
	17 Jun	29 Jun	6 Jul	13 Jul	19 Jul	27 Jul	3 Aug	10 Aug	17 Aug	Total
Water applied (mm)	19.4	19.4	25.9	34.5	40	35	35	35	35	279.2
N applied (kg ha^{-1})	-	-	18.4	18.4	18.4	18.4	18.4	18.4	-	110.4

2.4 Measurements of initial soil water and nitrogen contents

Soil samples were collected from three locations in each plot at 15 m intervals from the water supply manifold starting 10 m from the manifold prior to seeding (28 April 2010) to establish the initial conditions of soil water and nitrogen contents. Soil cores at each location were sampled from 0 to 0.8 m depth at 0.2 m increments. Twenty grams of each soil sample collected were air-dried, passed through a 2-mm sieve, and extracted by 50 ml of 1 mol L^{-1} KCl and used to measure NH_4^+-N and NO_3^--N content using Auto Analyzer 3 (BRAN+LUEBBE, Germany). The remained soil samples were used to determine soil water content gravimetrically. Initial contents, Christiansen uniformity coefficients (*CU*), and coefficients of variation (CV) for soil moisture, NH_4^+-N, and NO_3^--N of the entire field are summarized in Table 2. Both soil water content and NH_4^+-N demonstrated a low to medium spatial variability with CV values of 0.07-0.18 and 0.16-0.17, respectively, while NO_3^--N had a high spatial variability with CV value of 0.59-0.99 (Yang and Lei, 1993).

Table 2. Summary of initial contents, Christiansen uniformity coefficients (*CU*), and coefficients of variation (CV) for soil water, NH_4^+-N, and NO_3^--N in the entire experimental field.

Depth (cm)	Soil moisture			NO_3^--N			NH_4^+-N		
	Mean (cm^3/cm^3)	*CU*	CV	Mean (mg/kg)	*CU*	CV	Mean (mg/kg)	*CU*	CV
0-20	0.20	0.94	0.08	9.74	0.48	0.71	3.25	0.88	0.16
20-40	0.24	0.94	0.07	8.54	0.34	0.99	3.04	0.89	0.16
40-60	0.27	0.91	0.11	10.96	0.54	0.59	2.97	0.87	0.17
60-80	0.25	0.86	0.18	8.30	0.28	0.94	3.10	0.87	0.17
0-80	0.24	0.94	0.08	9.39	0.59	0.49	3.09	0.92	0.10

2.5 Plant measurements

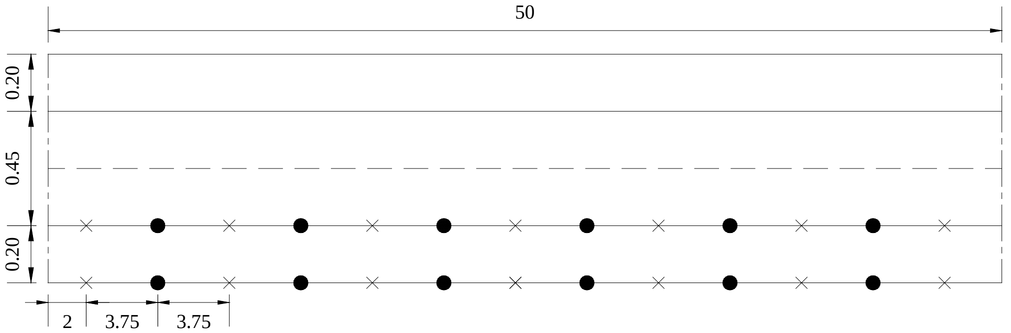
Leaf area index (LAI), aboveground cotton plant biomass, single boll weight, boll number per plant, plant nitrogen uptake, and fiber quality parameters of lint samples were determined from seven locations along the four central rows of each plot at 7.5 m intervals from the water supply manifold starting 2 m from the manifold. Plant height, unopened boll number, and lint cotton yield were determined from thirteen locations along the four central rows of each plot at 3.75 m intervals from the water supply manifold (Figure 2). Plant height and LAI were measured at peak squaring, early bloom, and boll-forming. Two plants of cotton at each location, one in the outer row and the other in the inner row, were marked and used to LAI determination. Similarly, four marked plants, two in the outer rows and other two in the inner rows, were used to plant height determination.

Two plant samples at each location, which also came from the outer and the inner row, respectively, were collected by clipping aboveground plant material at the soil surface at squaring, bloom, and boll-forming stages. The samples were air-dried and weighed to determine aboveground crop biomass. Then the total nitrogen content of the plant samples was measured using Kjeltec Analyzer (FOSS, Denmark). Plant nitrogen uptake was determined by the product of the aboveground crop biomass and the total nitrogen content. Boll number per plant and single boll weight were recorded when biomass collection was conducted at boll-forming stage.

Following crop maturation at the end of growing season, seed cotton for each designed location (Figure 1) was harvested by hand along four central 1.4-m-long planted rows. Seed cotton samples from each plot were weighed, and 50-g subsamples were ginned to determine lint percentage. Lint yield from each sample location was determined by multiplying lint percentage by the respective seed cotton weight. Fiber quality parameters of lint samples such as micronaire, fiber strength, fiber length, fiber uniformity, and elongation were determined by the High Volume Instrument (HVI) system at the Cotton Institute, Chinese Academy of Agricultural Sciences. After harvested, unopened boll number in each harvested area was measured.

In this article, Christiansen uniformity coefficients (*CU*) were also used to quantify the uniformity of plant height, LAI, single boll weight, aboveground cotton biomass, nitrogen uptake, bolls per plant, lint yield, and fiber quality parameters along the driplines.

Standard analysis of variance test were used with F-test considered significant at the 0.05 level of probability. Least significant differences (LSD) were calculated at the 0.05 level of probability for significantly different main effects and interaction means.



× Leaf area index, single boll weight, aboveground cotton biomass, quality of lint cotton, plant height, boll number per plant, lint yield, and unopened boll number

● Plant height, bollnumber per plant, lint yield, and unopened boll number

— — — Dripline ——— Cotton rows

Unit: m

Figure 2. Schematic diagram of measuring locations for growth, lint yield, and quality of cotton in an experimental plot (50 m long × four rows).

3. RESULTS AND ANALYSIS

3.1 Effects of fertigation uniformity on cotton growth

Variations of the mean and the uniformity for plant height during the growing season of cotton are shown in Figure 3 for the different fertigation uniformity and irrigation levels. For all of the treatments, a fast increase of plant height was observed for days after planting (DAP) from 57-77, but the plant height increased slightly after DAP 77 (21 July). For a given fertigation uniformity, the different treatments of irrigation levels produced an approximately similar plant height at DAP 57 (1 July), but a high irrigation level produced a greater plant height after DAP 77. For the treatments of *CU* = 0.94, for example, the plant heights for the irrigation levels of I1, I2, and I3 at DAP 57 were 36, 38, and 41 cm, respectively; while the final height (DAP = 125, 7 September)) for the I3 (54 cm) was 38% greater than that for the I1 (39 cm) and 8% higher than that for the I2 (50 cm). An analysis of variance also indicated that the influence of irrigation level on plant height was significant at a significance level of 0.01 after DAP 57. For the final sample at DAP 125, the influence of the interaction between fertigation uniformity and irrigation level on plant height also become significant.

It can also be seen in Figure 3 that, for the irrigation level of I1, the final plant height for the high *CU* treatment of C3 (39 cm) was lower than that for the medium and low *CU* treatments of C2 (44 cm) and C1 (44 cm). However, for the irrigation levels of I2 and I3, the high *CU* treatment of C3 produced a 6 to 10% greater plant height than the C1 and C2 treatments, although the influence of fertigation uniformity on plant height was not statistically significant.

A great decrease of *CU* for plant height can be seen in Figure 3 for the treatments of C1 and C2 as DAP increased from 57 to 77, but a slight increase of the *CU* was observed for the C3 treatment. After DAP of 77, an approximately similar *CU* was maintained for all of the treatments. During the growing season of cotton, plant height *CU* ranged from 0.88 to 0.96, being greater than the fertigation uniformity, especially for the C1 and C2 treatments. A greater fertigation uniformity usually produced a more uniform distribution of plant height after DAP 77. For the irrigation level of I2, for example, the *CU* values for the final plant height (DAP = 125) increased from 0.88 to 0.94 when the fertigation uniformity increased from 0.65 (C1) to 0.94 (C3). The analysis of variance indicated that the influence of fertigation uniformity on plant height *CU* had become significant since DAP of 77.

Variations of the mean and the uniformity for LAI during the growing season of cotton are presented in Figure 4. For a given fertigation uniformity, a higher irrigation level resulted in a significantly larger LAI after DAP 77, while the influence of fertigation uniformity on LAI was only statistically significant at DAP 102 (25 August).

Comparing Figures 3 and 4 led one to find that *CU* for LAI, ranging from 0.56 to 0.89, was lower than the *CU* for plant height. Generally, LAI *CU* showed a decreasing trend as the plants grew, especially for the low and medium fertigation uniformity treatments of C1 and C2. For a given irrigation level, a greater fertigation uniformity produced a significanty greater LAI *CU* after DAP 102. This suggests that the influence of nonuniformly applied water and fertilizers on plant growth was progressively strengthened as water and fertilizers were applied through sequential fertigation events. Ayars et al. (1991) also reported that the LAI of cotton was uniform across rows at day 175, while by day 209 the row-by-row LAI was affected by the nonuniformity of water application in the low-uniformity treatment at the medium irrigation level. In addition, the analysis of variance indicated that influence of the interaction between fertigation uniformity and irrigation level on the mean and the uniformity for LAI was insignificant.

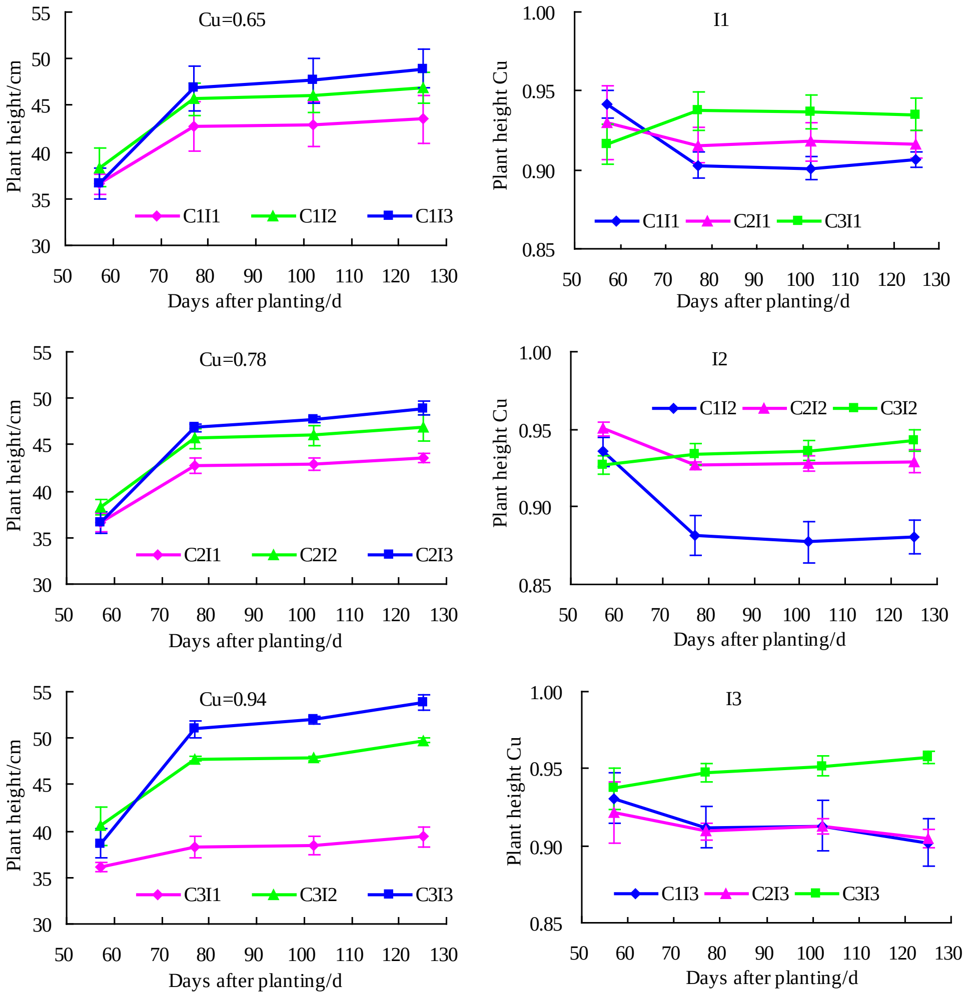
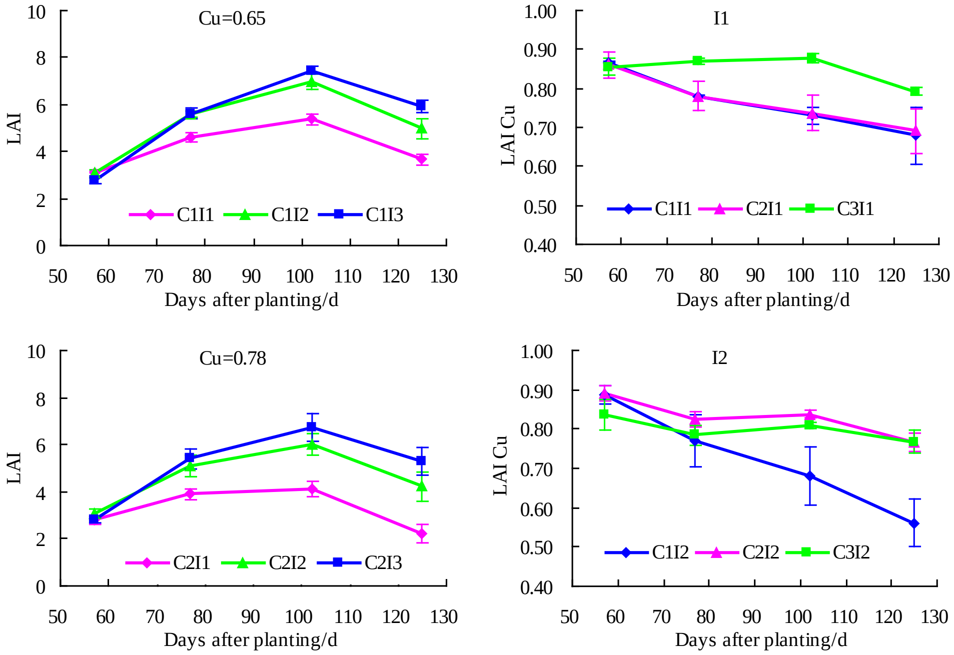


Figure 3. Variations of the mean and uniformity for plant height during the growing season of cotton.



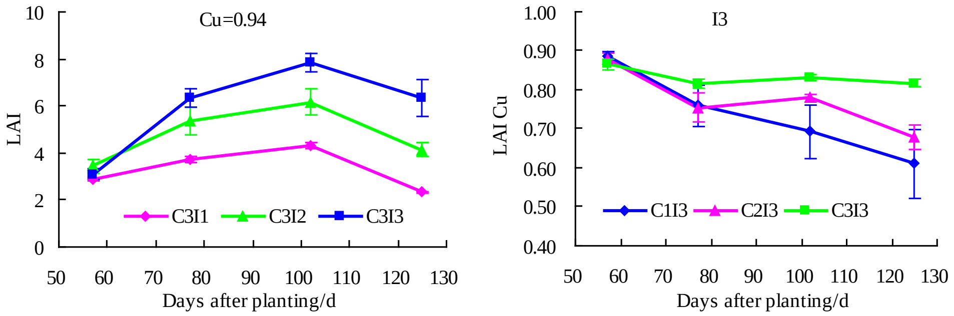


Figure 4. Variations of the mean and uniformity for LAI during the growing season of cotton.

3.2 Effects of fertigation uniformity on aboveground plant biomass and plant nitrogen uptake

The mean and the uniformity for aboveground plant biomass during the growing season of cotton are shown in Table 3. For a given fertigation uniformity, the different treatments of irrigation levels produced an approximately similar aboveground plant biomass on 12 July, but a higher irrigation level produced a significantly greater aboveground plant biomass after 7 August. For the treatments of *CU* = 0.94, for example, the aboveground plant biomass for the irrigation levels of I1, I2, and I3 on 12 July were 8.8, 10.0, and 8.9 t ha^{-1}, respectively; but the aboveground plant biomass on 4 September for the I3 (36.2 t ha^{-1}) was 45% greater than that for the I1 (24.9 t ha^{-1}) and 21% higher than that for I2 (29.8 t ha^{-1}).

It can also be seen in Table 3 that, for the irrigation level of I3, the final aboveground plant biomass for the high *CU* treatment of C3 (36.2 t ha^{-1}) was greater than that for the low *CU* treatment of C1 (32.7 t ha^{-1}). However, for the irrigation levels of I1 and I2, the high *CU* treatment of C3 produced a 2 to 16% lower aboveground plant biomass than the C1 treatment, although the influence of fertigation uniformity on aboveground plant biomass was not statistically significant.

A decrease of *CU* for aboveground plant biomass can be seen in Table 3 for the treatments of C1 and C2 from 12 July to 4 September, but a slight variation of the *CU* was observed for the C3 treatment. During the growing season of cotton, aboveground plant biomass *CU* ranged from 0.76 to 0.91, being greater than the fertigation uniformity, especially for the C1 and C2 treatments. A greater fertigation uniformity usually produced a more uniform distribution of aboveground plant biomass on 4 September. For the irrigation level of I3, for example, the *CU* values for the final aboveground plant biomass increased from 0.76 to 0.83 when the fertigation uniformity increased from 0.65 (C1) to 0.94 (C3). An analysis of variance also indicated that the influence of fertigation uniformity on aboveground plant biomass *CU* was significant on 4 September. This also suggests that the influence of nonuniformly applied water and fertilizers on aboveground plant biomass was progressively strengthened as water and fertilizers were applied through sequential fertigation events.

The mean and the uniformity for plant nitrogen uptake during the growing season of cotton are presented in Table 4. Similarly, for a given fertigation uniformity, the different treatments of irrigation levels produced an approximately similar plant nitrogen uptake on 12 July, but a higher irrigation level produced a greater plant nitrogen uptake after 7 August. An analysis of variance indicated that the influences of irrigation level on plant nitrogen uptake were significant after 7 August.

It can also be seen in Table 4 that, for the irrigation level of I3, the final plant nitrogen uptake for the high *CU* treatment of C3 (898.1 kg ha^{-1}) was greater than that for the low *CU* treatment of C1 (740.0 kg ha^{-1}). However, for the irrigation levels of I1 and I2, the high *CU* treatment of C3 produced a 2 to 17% lower plant nitrogen uptake than the C1 treatment, although the influence of fertigation uniformity on plant nitrogen uptake was not statistically significant.

Table 3. Mean and uniformity coefficient for the aboveground plant biomass of cotton.

Treatment	Mean (t ha^{-1})			*CU*		
	12 Jul	7 Aug	4 Sept	12 Jul	7 Aug	4 Sept
C1I1	9.1 a[a]	16.0 b	29.8 abc	0.87 ab	0.91 a	0.77 a
C2I1	8.4 a	15.6 b	23.0 c	0.90 a	0.84 a	0.87 a
C3I1	8.8 a	15.2 b	24.9 bc	0.86 ab	0.83 a	0.86 a
C1I2	9.7 a	18.1 ab	30.4 abc	0.87 ab	0.84 a	0.83 a
C2I2	8.8 a	17.0 b	26.2 abc	0.87 ab	0.83 a	0.83 a
C3I2	10.0 a	17.0 b	29.8 abc	0.91 a	0.90 a	0.82 a
C1I3	8.7 a	16.8 b	32.7 ab	0.84 ab	0.85 a	0.76 a
C2I3	9.3 a	17.6 ab	30.5 abc	0.86 ab	0.85 a	0.77 a
C3I3	8.9 a	20.4 a	36.2 a	0.84 b	0.87 a	0.83 a

[a] Column means within a parameter followed by the same letter are not significantly different ($P < 0.05$, LSD)

Table 4. Mean and uniformity coefficient for the nitrogen uptake of cotton plant.

Treatment	Mean (kg ha^{-1})			*CU*		
	12 Jul	7 Aug	4 Sept	12 Jul	7 Aug	4 Sept
C1I1	330.8 a[a]	499.0 bcd	674.6 abc	0.86 ab	0.85 ab	0.66 c
C2I1	294.3 a	472.6 cd	502.0 c	0.90 a	0.84 ab	0.83 a
C3I1	305.4 a	456.3 d	559.8 bc	0.84 ab	0.81 ab	0.83 a
C1I2	359.0 a	585.0 ab	693.2 abc	0.85 ab	0.83 ab	0.77 abc
C2I2	321.2 a	520.6 bcd	597.8 bc	0.85 ab	0.77 b	0.78 ab
C3I2	366.0 a	534.2 bcd	681.7 abc	0.91 a	0.90 a	0.80 a
C1I3	303.5 a	529.4 bcd	740.0 ab	0.84 ab	0.80 ab	0.67 bc
C2I3	323.7 a	579.9 bc	752.4 ab	0.86 ab	0.83 ab	0.74 abc
C3I3	348.7 a	680.3 a	898.1 a	0.81 b	0.85 ab	0.81 a

[a] Column means within a parameter followed by the same letter are not significantly different ($P < 0.05$, LSD)

3.3 Effects of fertigation uniformity on yield and quality of cotton

The mean and the uniformity for lint yield are summarized in Table 5. For the *CU* treatments of C1 and C3, irrigation level had a negative effect on lint yield. For the treatments of *CU* = 0.94, for example, lint yield for the I3 was 5% lower than that for the I1 and I2. The negative yield response to the increased irrigation amounts might be attributed to the increased vegetative plant growth and boll-opening delays as water application increased. This had been documented in other studies (Mateos et al., 1997; Bordvosky and Porter, 2008). An analysis of variance indicated that the influence of irrigation level on lint yield was not significant (Table 6).

There were no significant differences in lint yield resulting from fertigation uniformity at each irrigation level; but fertigation uniformity had a positive effect on lint yield at the irrigation level of I3. For the irrigation level of I3, lint yields for the fertigation uniformities of C1, C2, and C3 were 1131, 1244, and 1266 kg ha^{-1}, respectively. Physically, for the low irrigation level, the low uniformity treatment provided more water at the locations having larger emitter rates, which compensated for a decreased yield caused by less water at the locations having lower emitter rates to some extent. However, for the high irrigation level, the low uniformity treatment provided excessive water at the locations having larger emitter rates. This could result in boll-opening delays and a decreased yield, causing a decreased yield. In addition, the analysis of variance also indicated that the influence of fertigation uniformity on lint yield was not significant (Table 6).

A greater fertigation uniformity usually produced a more uniform distribution of lint yield. For the irrigation level of I3, for example, the *CU* values for lint yield increased from 0.78 to 0.86 when the fertigation uniformity increased from 0.65 (C1) to 0.94 (C3). There were no significant differences in yield *CU* resulting from fertigation uniformity at the irrigation levels of I1 and I2, but fertigation uniformity significantly influenced yield *CU* at the irrigation level of I3. Yield *CU*s for the C1 and C2 treatments were greater than the drip fertigation uniformity, which indicated that yield variability may be related to the variability of soil texture and the redistribution of water and nutrients in soil. Since the C3 treatment supplied uniform fertigation, the variations for lint yield in the treatment plot may be due to the variability in soil properties and initial nitrogen content (Table 2).

It can also be seen in Table 5 that, for a given fertigation uniformity, the lint yield *CU* for the high irrigation level of I3 was lower than that for the low irrigation level of I1. For the fertigation uniformity of C3, for example, lint yield *CU*s for the I1, I2, and I3 treatments were 0.93, 0.92, and 0.86, respectively. An analysis of variance indicated that the influence of irrigation level on lint yield *CU* was significant (Table 6). The mean for the number of unopened bolls is summarized in Table 5. For a given fertigation uniformity, a higher irrigation level resulted in a significantly larger number of unopened bolls. A lower fertigation uniformity usually produced a greater number of unopened bolls. For the irrigation level of I2, for example, the unopened bolls decreased from 25.3 to 14.5 when the fertigation uniformity increased from 0.65 (C1) to 0.94 (C3). An analysis of variance indicated that the influence of fertigation uniformity and irrigation level on the number of unopened bolls were significant (Table 6).

Table 5. Yield, yield *CU*, and unopened bolls for different fertigation uniformity and irrigation level treatments.

Treatment	Lint yield (kg ha^{-1})	Yield *CU*	Unopened bolls (no. m^{-2})
C1I1	1336 ab[a]	0.88 ab	15.54 bc
C2I1	1176 b	0.90 ab	5.31 c
C3I1	1338 ab	0.93 a	4.05 c
C1I2	1316 ab	0.89 ab	25.33 b
C2I2	1403 a	0.88 ab	16.36 bc
C3I2	1331 ab	0.92 a	14.54 bc
C1I3	1131 b	0.78 d	48.15 a
C2I3	1244 ab	0.83 c	25.51 b
C3I3	1266 ab	0.86 bc	47.18 a

[a] Column means within a parameter followed by the same letter are not significantly different ($P < 0.05$, LSD)

Table 6. Summary of analysis of variance for the mean and the uniformity coefficient for lint yield and number of unopened bolls of cotton as affected by fertigation uniformity (*CU*) and irrigation level (IL).

	Source	df	Lint yield	Unopened bolls
Mean	*CU*	2	ns	*
	IL	2	ns	**
	CU × *IL*	4	ns	ns
	Error	18		
Uniformity	*CU*	2	**	**
	IL	2	**	**
	CU× *IL*	4	ns	ns
	Error	18		

* Significant at p = 0.05 level; ** Significant at *P* = 0.01 level; ns = nonsignificant.

In order to analyze the effect of fertigation uniformity on the distribution of lint yield visually, lint yield along the drip laterals of the different fertigation uniformities are compared in Figure 5. For the medium and low irrigation level, lint yield demonstrated a variation trend approximately similar to the emitter discharge rates along the laterals. However, lint yield in the high irrigation level treatment did not follow the variability of emitter discharge rates, especially at the locations having higher emitter rates where excessive irrigation had a negative effect on lint yield. For the C1I3 treatment, for example, lint yield of the last five locations were greatly lower than that for the other locations. The variation range of lint yield for the C1 and C2 treatments were greater than that for the C3 treatment.

It can also be seen in Figure 5 that, for the *CU* treatments of C1 and C2, the ratios of maximum to minimum for lint yield were significantly lower than that for emitter discharge, especially at the irrigation levels of I1 and I2; while there was no distinct difference in the C3 treatment. The ratios of maximum to minimum lint yield for the C1I3 and C2I3 treatments were greater than that for the other treatments, which was attributed to the increased vegetative plant growth and boll-opening delays at the locations having larger emitter rates.

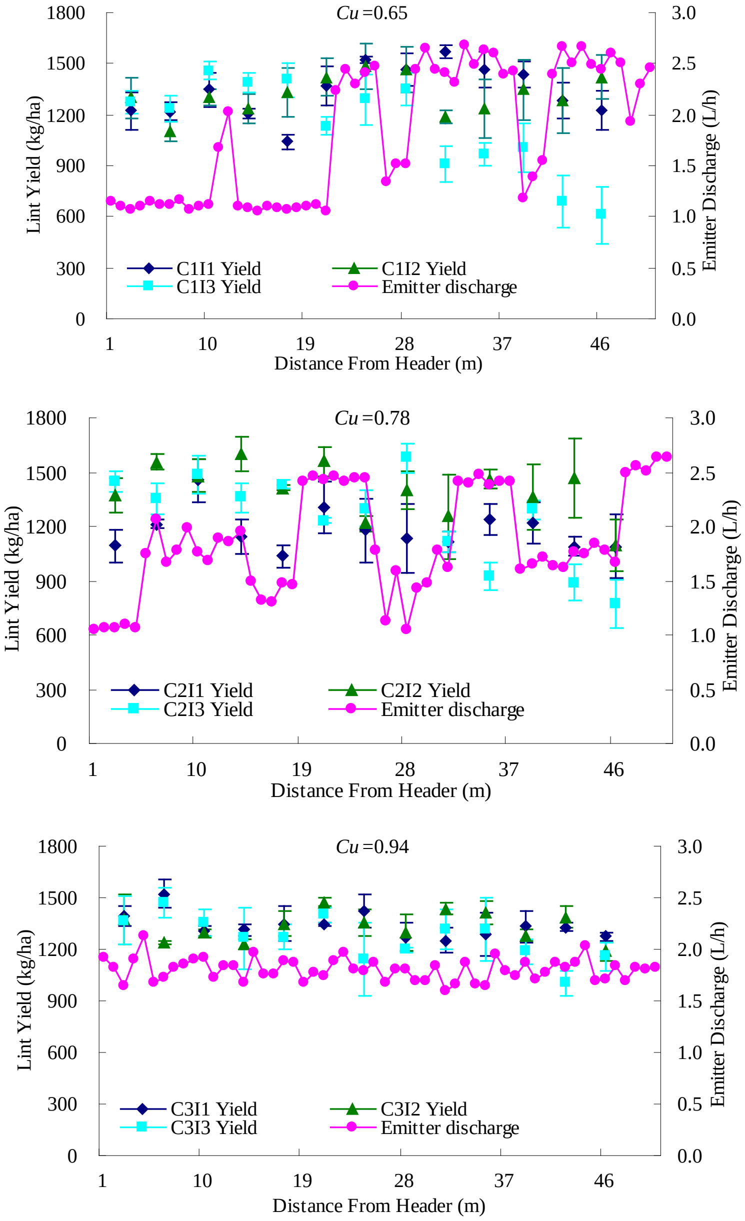


Figure 5. Lint yield at thirteen distances from supply manifold for the different fertigation uniformity and irrigation levels.

The mean for fiber quality is compared in Table 7 for the different fertigation uniformity and irrigation levels. For a given fertigation uniformity, a higher irrigation level produced a significantly lower micronaire. Bajwa and Vories (2007) also reported that the micronaire for well-watered treatment was significantly lower than severely stressed treatment. The ideal level of micronaire is considered to be between 3.7 and 4.2 (Cotton-Upland cotton, GB 1103-2007), and penalties are generally charged when micronaire is more than 4.9 or less than 3.5. Except for the C2I1 treatment, macronaire for all of the treatments was in the normal range. Higher irrigation levels tended to increase fiber length and fiber strength. Similar results have been reported (Dagdelen et al. 2009). There were no significant differences in lint quality parameters resulting from fertigation uniformity for a given irrigation level. An analysis of variance also indicated that the five lint quality parameters tested were not significantly affected by fertigation uniformity, while the fiber length and the micronaire were significantly affected by irrigation levels (Table 8).

Table 7. Mean for quality indexes of cotton for different treatments.

Treatment	Micronaire	Fiber length (mm)	Fiber uniformity (%)	Elongation (%)	Fiber strength (g.tex^{-1})
C1I1	4.72 ab[a]	29.84 cd	84.60 a	6.79 ab	30.35 ab
C2I1	4.97 a	29.48 d	84.34 a	6.76 ab	29.96 b
C3I1	4.75 ab	30.02 bcd	84.75 a	6.74 b	30.52 ab
C1I2	4.60 bc	30.16 abc	84.81 a	6.75 b	31.00 a
C2I2	4.60 bc	30.26 abc	84.87 a	6.78 ab	30.56 ab
C3I2	4.63 bc	30.28 abc	84.69 a	6.77 ab	30.40 ab
C1I3	4.44 bcd	30.62 ab	85.18 a	6.80 ab	30.77 ab
C2I3	4.22 d	30.47 ab	84.84 a	6.77 ab	30.99 a
C3I3	4.32 cd	30.70 a	84.68 a	6.82 a	31.01 a

[a] Column means within a parameter followed by the same letter are not significantly different (P < 0.05, LSD)

Table 8. Summary of analysis of variance for the mean and uniformity coefficient for quality indexes of cotton as affected by fertigation uniformity (*CU*) and irrigation level (*IL*).

	Source	df	Micronaire	Fiber length	Fiber uniformity	Elongation	Fiber strength
Mean	*CU*	2	ns	ns	ns	ns	ns
	IL	2	**	**	ns	ns	ns
	CU × *IL*	4	ns	ns	ns	ns	ns
	Error	18					
Uniformity	*CU*	2	ns	*	**	ns	ns
	IL	2	ns	ns	ns	ns	ns
	CU × *IL*	4	ns	ns	ns	ns	ns
	Error	18					

* Significant at p = 0.05 level; ** Significant at P = 0.01 level; ns = nonsignificant.

4. CONCLUSIONS

Field experiments were conducted in the arid environments to evaluate the effects of fertigation uniformity and irrigation level on growth, nitrogen uptake, lint yield, and quality of cotton. The following conclusions were supported by this study:

(1) During the growing reason of cotton, the uniformity for plant height, LAI, aboveground plant biomass, and nitrogen uptake showed a decreasing trend for the low and medium uniformity treatments (C1 and C2), while a slight variation in the high uniformity treatment (C3) was observed. The influence of nonuniformly applied water and fertilizers on the uniformity for plant growing parameters, aboveground plant

biomass, and plant nitrogen uptake was progressively strengthened as water and fertilizers were applied through sequential fertigation events.

(2) For the low and medium irrigation level, lint yield demonstrated a variation trend approximately similar to the emitter discharge rates along laterals. However, lint yield in the high irrigation level treatment did not follow the variability of emitter discharge rates, especially at the locations having high emitter rates where excessive irrigation had a negative effect on lint yield. Only at the irrigation level of I3 did fertigation uniformity have a positive effect on lint yield.

(3) For a given fertigation uniformity, a higher irrigation level resulted in a significantly larger number of unopened bolls. For a given irrigation level, a lower fertigation uniformity usually produced a greater number of unopened bolls.

(4) Higher irrigation levels tended to increase fiber length and fiber strength, while resulted in a decreased macronaire. Five lint quality parameters tested were not significantly affected by the fertigation uniformity, while the fiber length and the micronaire were significantly affected by irrigation levels.

(5) Fertigation uniformity imposed an insignificant influence on the mean values for plant growing parameters, plant nitrogen uptake, lint yield, and quality parameters; but significantly reduced the uniformity for plant growing parameters and plant nitrogen uptake. In the arid regions, the possibility of using a fertigation uniformity that is lower than the values recommended by the current standards should balance the installation and operation costs, crop production, and products quality.

ACKNOWLEDGEMENTS

This study was financially supported by the National Natural Science Foundation of China (50979115).

REFERENCES

1. Ayars, J.E., R.B. Hutmacher, S.S. Vail, R.A. Schoneman. 1991. Cotton responses to nonuniform and varying depths of irrigation. Agricultural Water Mmangement. 19(2):151-166.
2. Bajwa, S.G., E.D. Vories. 2007. Spatial analysis of cotton (Gossypium hirsutum L.) canopy responses to irrigation in a moderately humid area. Irrigation Science. 25:429-441.
3. Bordovsky, J.P., D.O. Porter. 2008. Effect of subsurface drip irrigation system uniformity on cotton production in the Texas high plains. Applied Engineering in Agriculture. 24(4):465-472.
4. Cai, H., G. Shao, Z. Zhang. 2002. Lateral layout of drip irrigation under plastic mulch for cotton. Transactions of the CSAE. 18(1):45-48. (in Chinese)
5. Cai, H., G. Shao, Z. Zhang. 2002. Water demand and irrigation scheduling of drip irrigation for cotton under plastic mulch. Journal of Hydraulic Engineering. 33(11):119-123. (in Chinese)
6. Chen, Q., Y. Zheng. 1995. Optimizing determination of irrigation uniformity in the design of micro-irrigation system. Transactions of the CSAE. 11(2):128-132. (in Chinese)
7. Dagdelen, N., H. Basal, E. Yilmaz, T. Gurbuz, S. Akcay. 2009. Different drip irrigation regimes affect cotton yield, water use efficiency and fiber quality in western Turkey. Agricultural Water Mmangement. 96(1):111-120.
8. Letey, J., H.J. Vaux, Jr., E. Feinerman. 1984. Optimum crop water application as affected by uniformity of water infiltration. Agronomy Journal. 76:435-441.
9. Li, J., J. Yin, H. Zhang, Y. Li. 2011. Effects of drip fertigation uniformity and

nitrogen application level on growth, yield and quality of Chinese cabbage. Transactions of the CSAE. 27(1):36-43. (in Chinese)

10. Li, M., X. Zheng, H. Jia, G. Yang. 2001. Experimental research on under-mulch drip irrigation regime for cotton. China Rural Water and Hydropower. (11):13-15. (in Chinese)
11. Mateos, L., E.C. Mantovani, F.J. Villalobos. 1997. Cotton response to non-uniformity of conventional sprinkler irrigation. Irrigation Science. 17:47-52.
12. National Standards of the People's Republic of China. 2007. Cotton-Upland cotton, GB 1103-2007. Standards Press of China. (in Chinese)
13. Or, D., R.J. Hanks. 1992. Soil water and crop yield spatial variability induced by irrigation nonuniformity. Soil Science Society American Journal. (56):243-257.
14. Pang, X.P., J. Letey, L. Wu. 1997. Irrigation quantity and uniformity and nitrogen application effects on crop yield and nitrogen leaching. Soil Science Society of America Journal. 61:257-261.
15. Seginer, I. 1978. A note on the economic significance of uniform water application. Irrigation Science. 1:19-25.
16. Seginer, I. 1983. Irrigation uniformity effect on land and water allocation. Transactions of the ASAE. 26(1):116-122.
17. Solomon, K. H. 1984. Yield related interpretations of irrigation uniformity and efficiency measures. Irrigation Science. 5(3):161-172.
18. Varlev, I. 1976. Evaluation of Nonuniformity in Irrigation and Yield. Journal of the Irrigation and Drainage Division. 102(1):149-164.
19. Warrick, A.W., W.R. Gardner. 1983. Crop yield as affected by spatial variations of soil and irrigation. Water Resources Research. 19:181-186.
20. Wilde, C., J. Johnson, J.P. Bordovsky. 2009. Economic analysis of subsurface drip irrigation system uniformity. Applied Engineering in Agriculture. 25(3):357-361.
21. Wu, I.P., J. Barragan. 2000. Design criteria for Microirrigation systems. Transactions of the ASAE. 43(5):1145-1154.
22. Yang, S., Z. Lei. 1993. Spatial structure of soil water contents and determination of sampling number. Acta Geographica Sinica. 48(5):447-456. (in Chinese)
23. Zhang, Q., G. Li, F. Cai. 2004. Effect of mulched drip irrigation frequency on soil salt regime and cotton growth. Journal of Hydraulic Engineering. 35(9):123-126. (in Chinese)