CORN GROWTH AND YIELD AS AFFECTED BY DRIP IRRIGATION UNIFORMITY AND APPLICATION AMOUNT IN NORTH CHINA PLAIN

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ABSTRACT

The uniformity coefficient is an important parameter for designing the drip irrigation systems, but the influence of irrigation uniformity on crop growth is still unclear. Field experiments were conducted in two growing seasons of spring corn (*Zea mays* L.) in the north China plain to evaluate the influence of drip irrigation uniformity and application amount on corn growth and yield. Three Christiansen uniformity coefficients (*CU*) of 0.66, 0.81, and 0.99 and three levels of water application at 50%, 75%, and 100% of the irrigation requirement were used. During both growing seasons, crop parameters including plant height, leaf area index (LAI), chlorophyll meter reading (SPAD reading) and dry biomass above ground were regularly measured, and the yield was recorded on harvest. The results showed that drip irrigation uniformity and application amount had insignificant influence on the mean of plant height, LAI, SPAD reading and dry biomass in both years (α =0.05). The uniformity coefficients of the crop parameters increased with spring corn growing, and their final value were larger than 0.90. The uniformity coefficients for yield along a dripline were larger than 0.93 for the three *CU* treatments tested. The drip irrigation uniformity, application amount and the interaction between the two factors had insignificant influence on the mean and the uniformity of yield (α =0.05). These results demonstrated that the drip uniformity coefficient had less important effect on the spring corn growth and yield. It suggested that the current design standard of drip irrigation uniformity coefficient ($CU \geq 0.80$) could be fairly lowered in the semi-humid regions, such as in the north China plain, to reduce the initial and operation costs of drip irrigation systems.

1. INTRODUCTION

Drip irrigation is one of the microirrigation methods. It can supply water and nutrients precisely to root zone according to crop requirement, and greatly improves the water and nitrogen use efficiency compared with surface irrigation. The uniformity coefficient is one of the important parameters for designing the drip irrigation systems. The design of drip irrigation systems generally requires high irrigation uniformity in order to ensure irrigation quality, but this may increase the costs of investment and operation especially for the crops with less sensitivity to water (Chen, 1993). On the other hand, the low uniformity of irrigation systems may reduce crop yield and quality. A low uniformity may also result in water percolation and nitrogen leaching, causing environment pollution.

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Irrigation uniformity of microirrigation system is affected by many factors, such as system pressure, emitter manufacturing variation, emitter spacing, and emitter clogging. Many studies have been conducted on these factors (Wu and Gitlin, 1973; Warrick and Yitayew, 1988; Zhang et al., 2005; Li et al., 2008). But the influence of irrigation uniformity on crop growth and yield is still unclear under different conditions. For example, Or and Hanks（1992）reported that the water in soil, crop height, and crop yield exhibited spatial variability similar to the variability of water applied, but crop yield variability (mean *CV* of 0.23) was less than the irrigation variability (mean *CV* of 0.57). Li (1996) found that the crop yield increased with the increasing of irrigation uniformity for a given irrigation amount. Mateos et al (1997) showed that irrigation uniformity had no influence on cotton yield for uniformity of 0.52 and 0.80. Bordovsky and Porter（2008）found that the response of cotton yields tended to follow the changes of emitter discharge rates along the drip laterals, but not to the expected extent. Li et al. (2010; 2011) obtained that the influences of fertigation uniformity (*CU*=0.62, 0.80, and 0.96) on the uniformity of soil bulk electrical conductivity and nitrate content in soil were insignificant, and the increasing of fertigation of uniformity might not necessarily result in an increased yield and an improved quality of Chinese cabbage in a solar heated greenhouse of semi-humid region. Crop in different regions seems to show different responses to irrigation uniformity. It is therefore necessary to study the influence of irrigation uniformity on crop growth and yield in different regions.

The objectives of the present study were to investigate the influence of drip irrigation uniformity and application amount on corn growth and yield by field experiments in the semi-arid region and to give recommendations for the design and evaluation of drip irrigation systems.

2. MATERIALS AND METHODS

2.1 Experimental field

Field experiments were conducted at the Experimental Station of the National Center for Efficient Irrigation Engineering and Technology Research in Beijing (39°39' N and 116°15' E), the north China plain. The region belongs to warm and semi-humid continental monsoon climate with an annual mean temperature of 11.6 ℃ and an annual mean precipitation of 556 mm. The experimental field size was 70 m × 50 m. According to the international classification of soil texture (Qin, 2003), the experimental soil was sandy loam in depth of 0-100 cm, and the average bulk density was 1.47 g/cm^3 (Du, 2007).

Field experiments were conducted in two growing seasons of spring corn (*Zea mays* L.) in 2009 and 2010. The experiment field was divided into 27 plots, and each plot size was 32 m × 3 m. A 50 cm buffer zone was used between the adjacent plots to prevent the lateral water exchange and allow to access to each experimental plot. Three driplines having 32 m long and with 1 m spacing were installed in each plot using an individual manifold. A valve, a pressure gauge and a water flow meter were installed at the head of each manifold to control the working pressure and to record the water applied during irrigation event. Corn with the row spacing of 50 cm and plant spacing of 40 cm was grown and driplines were located in alternative row furrows for all experimental plots. Seeding date, plant and row spacing, total and effective rainfall and harvest date for the experiments in both growing seasons are summarized in Table 1.

Table 1. Summery of the related information for field experiment conducted in 2009 and 2010

Year	2009	2010
Variety	Ear No. 1	Ear No. 1
Seeding date	26 April, 2009	3 May, 2010
Plant spacing /cm	40	40
Row spacing /cm	50	50
Total rainfall /mm	402	296
Effective rainfall* /mm	384	260
Harvest date	24 August, 2009	28 August, 2010

* means sum of rainfalls being larger than or equal to 5mm.

2.2 Experimental design

Two factors, irrigation uniformity and application amount, were considered for field experiments. There are several parameters that are used for designing or evaluating of the microirrigation system (Lamm et al., 2007)，and all the uniformity parameters are interrelated to each other when the emitter flow rates considered as a normal distribution or a smooth curve distribution (Barragan et al., 2006). Therefore any single uniformity parameter can be used to describe the microirrigation system uniformity. The Christiansen uniformity coefficient (*CU*) was used to evaluate the uniformity of emitter discharge rates along the dripline, given by Eq. (1).

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

where *CU* is Christiansen uniformity coefficient; q_i is the ith emitter discharge rate, L/h; $\overline{q}$ is the mean of all emitter discharge rates，L/h, and *n* is the total number of emitter discharge rates measured.

Three *CU*s of 0.70 (referred to as low uniformity, C1), 0.80 (medium uniformity, C2), and 0.99 (high uniformity, C3) and three levels of water applied at 50% (low irrigation level, I1), 75% (medium irrigation level, I2), and 100% (high irrigation level, I3) of the irrigation requirement were used. Such an experimental design resulted in nine treatments total (C1I1, C1I2, C1I3, C2I1, C2I2, C2I3, C3I1, C3I2, and C3I3). There were three replications for each treatment.

The driplines with *CU* values of 0.70 and 0.80 were obtained from random combination of five different emitter discharge rates: 1.05 L/h (Super Typhoon, Netafim, Israel), 1.4 L/h (RY125, Ruisheng-Yamit, China), 1.65 L/h (Super Typhoon, Netafim, Israel), 2.3 L/h (Pressure compensation，Luckrain, China), and 2.6 L/h (Super Typhoon, Netafim, Israel) at 0.1 MPa pressure. The driplines with *CU* value of 0.99 were obtained using the emitter discharge rate of 1.65 L/h at 0.1 MPa pressure (Super Typhoon, Netafim, Israel). The emitter spacing for all *CU* treatments was 40 cm and the mean of emitter discharge rates were 1.65 L/h at 0.1 MPa pressure. The random combination of different emitter discharge rates was determined by Monte-Carlo method (Jin, 2005), provided that the normal distribution of emitter discharge rates along the dripline could be represented by a normal distribution function (Nakayama, 1979). The emitter discharge rates along the dripline were measured prior to installing to test the actual uniformity of dripline. For a 32-m long dripline, the emitter discharge rates of forty emitters spaced at 80 cm intervals along the dripline were measured. The measured uniformities for low, medium, and high uniformity treatments were 0.66, 0.81, and 0.99, respectively (Table 2). After harvest in 2009 and 2010, the emitter discharge rates for one selected dripline of each plot were measured again to check if the uniformity agreed with the designed value. The mean and the uniformity coefficient for emitter discharge rates along the dripline at different measurements are summarized in Table 2. No significant difference of *CU* was found after one and two seasons application, while the mean emitter discharge after 2010 harvest had a reduction of less than 5% from the initial measurement.

Table 2. The mean and the uniformity coefficient for emitter discharge rates along the dripline at different stages.

Level	*CU*				Mean discharge rate /L·h^{-1}			
	Initial design value	Initial measured value	After 2009	After 2010	Initial design value	Initial measured value	After 2009	After 2010
C1	0.70	0.66	0.66	0.65	1.65	1.67	1.68	1.66
C2	0.80	0.81	0.80	0.80	1.65	1.62	1.63	1.58
C3	0.99	0.99	0.98	0.97	1.65	1.61	1.60	1.53

C1, C2, and C3 mean the low, medium, and high irrigation uniformity, respectively.

The irrigation amount and intervals varied according to the growing stages and climate conditions. An automatic weather station was installed 50 m apart from the experimental field to monitor the meteorological data, such as temperature, wind speed and direction, humidity, radiation, and precipitation, every 30 min during the experiment. Irrigation was applied when the application amount (*m*) value calculated by Eq. (2) was about 20-30 mm (about 60% - 70% of field capacity) (Liu et al., 2009).

$$m = ET - P_o \tag{2}$$

$$ET = ET_0 \times K_s \times K_c \tag{3}$$

where *m* is application amount, mm; *ET* is crop water requirement (evapotranspiration) calculated by Eq. (3), mm (Fig. 1); P_0 is the effective rainfall, mm (Fig. 1); ET_0 is reference crop evapotranspiration, calculated using modified Penman－Monteith formula by FAO recommended (Allen et al., 1998), mm; K_s is water stress coefficient recommended by Hu et al. (2006); K_c is crop coefficient recommended by FAO (Allen et al., 1998).

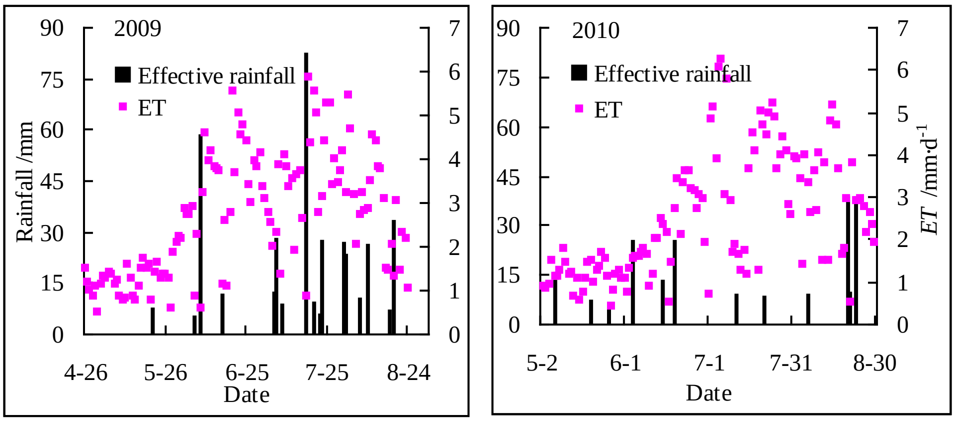


Figure 1. Effective rainfall and crop water requirement (*ET*) during the both growing seasons of spring corn.

A similar nitrogen application rate was applied to all of the experimental treatments. In 2009, 25% of the total nitrogen (45 kg N/ha) was applied before planting, and the remained 75% of the total nitrogen (135 kg N/ha) were fertigated in season. In 2010, all the nitrogen (162 kg N/ha) were fertigated in season. An empirical rule of quarter-half-quarter was used for each fertigation event, using a water-driven adjustable proportional pump (Model 2504, Tefen, Israel) (Li et al., 2003). Schedules of irrigation and fertilization for different application amount treatments in 2009 and 2010 are summarized in Table 3.

Table 3. Schedules of irrigation and fertilization for different treatments.

Year	Sequence	Date	Application amount /mm			Nitrogen applied /kg N·ha^{-1}
			I1	I2	I3	
2009	Fertilizer applied before planting					45
	Irrigation for emergence	27 April	10	10	10	
	1	20 May	10	15	20	36
	2	14 June	10	15	20	45
	3	29 June	12.5	18.8	25	18
	4	14 July	10	15	20	36
	Total		52.5	73.8	95	180
2010	1	22 June	10	15	20	45
	2	1 July	10	15	20	36
	3	23 July	15	22.5	30	81
	4	8 August	15	22.5	30	
	Total		50	75	100	162

I1, I2, and I3 mean the low, medium, and high application amount, respectively.

2.3 Plant measurement

Two corn plants were randomly marked at five observation points that were spaced at 7 m intervals and started 2 m from the inlet of the lateral in each plot to measure plant height, leaf area index (LAI), and chlorophyll meter reading (SPAD reading) during the two growing seasons. Plant height and length and width of leaves were measured at 10 d intervals, and weekly SPAD readings (SPAD-502, KONICA MINOLTA，Japan） were taken on the mid-point of the youngest fully expanded leaf (before silking) and on the ear leaf (after silking) (Rostami et al., 2008). Two corn plants near each observation point were selected to measure dry biomass above ground at elongation, filling, and maturity stages. At the maturity stage, the stem and seed were sampled separately to determine the stem mass to seed mass ratio.

A total of six plants were harvested at maturity stage to determine the spring corn yield and yield components (ear length, barren ear tip, grain number, and 100-seed weight) from two 1.2-m long middle-rows at each observation point. For each plot, five observation points mentioned above were used in 2009, while in 2010 eight observation points spaced at 4 m intervals and started 2 m from the ahead of plot were used.

The uniformity of plant height, leaf area index, chlorophyll meter reading, dry biomass above ground and yield along the row for all of the experimental treatments were also evaluated by using Christiansen uniformity coefficient (Eq. (1)).

2.4 Statistical tests

The two-way analysis of variance was conducted to quantify whether the influence of Christiansen uniformity coefficient and application amount on plant growth and yield was significant at a probability level of 0.05. Similarly, the least significance difference (LSD) tests were also performed on Christiansen uniformity coefficient, application amount and the interaction between the two factors. These statistical tests were performed using the SPSS software package (version 15.0, SPSS, Inc., America)

3. RESULTS AND ANALYSIS

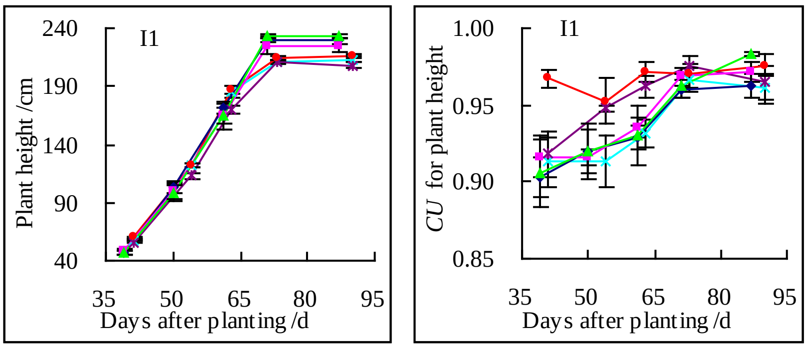
3.1 Plant height and leaf area index

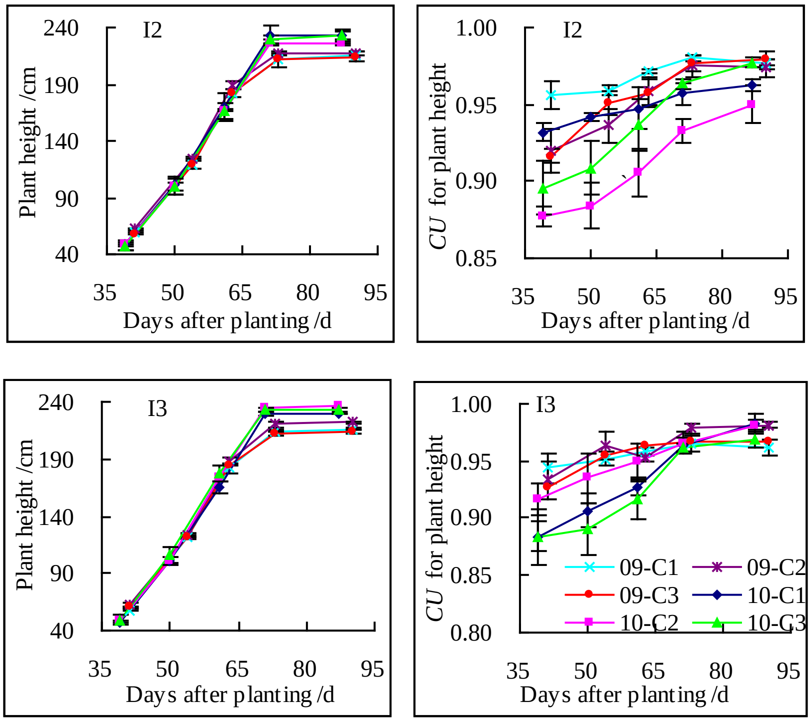
Variations of the mean and the uniformity coefficient for plant height during the growing seasons of 2009 and 2010 are shown in Fig. 2a and 2b for all treatments, respectively. In both seasons, the mean plant height increased rapidly during 40-70 days after planting (DAP), and then maintained constant. The plant heights for all of the treatments were similar at a given growing stage. The variance analysis also indicated that irrigation uniformity and application amount had insignificant influence on plant height.

The uniformity of plant height showed the trend similar to the mean of plant height. Though the uniformity coefficient of plant height for different treatments at about 40 DAP ranged from 0.91 to 0.97 in 2009 and from 0.88 to 0.93 in 2010, respectively, the final values for all treatments were larger than 0.95 in both years. For the C1 and C2 treatments, the final uniformity of plant height were larger than the irrigation uniformity (*CU*=0.66 and 0.81). The irrigation uniformity and application amount had insignificant influence on uniformity of plant height, except that the application amount had significant influence on the uniformity of plant height at DAP 87 (28 July) in 2010.

Variations of the mean leaf area index (LAI) for all treatments in 2009 and 2010 are shown in Fig. 3a. The mean LAI increased rapidly during DAP 40-70, then reached the maximum, and declined slowly at later stage for all treatments in both growing seasons. The variance analysis indicated that irrigation uniformity and application amount had insignificant influence on the mean LAI.

The trend of LAI *CU* (Fig. 3b) was similar to that of plant height *CU* (Fig. 2b). The uniformity coefficient of LAI ranged from 0.77 to 0.87 in 2009 and from 0.76 to 0.83 in 2010 at about DAP 40, respectively, but the final values were larger than 0.93 in both years for all treatments. Irrigation uniformity had significant influence on the uniformity of LAI at DAP 73 and 90 (7 and 24 July) in 2009. The higher irrigation uniformity produced more uniform distribution of LAI. For example, LAI *CU*s for the C3 treatments (0.96) were larger than that for the C2 and C1 treatments (0.94 and 0.94, respectively) both at DAP 73 and 90 (7 and 24 July) in 2009. At other stages in 2009 and at all stages in 2010, irrigation uniformity coefficient and application amount had insignificant influence on the LAI uniformity.

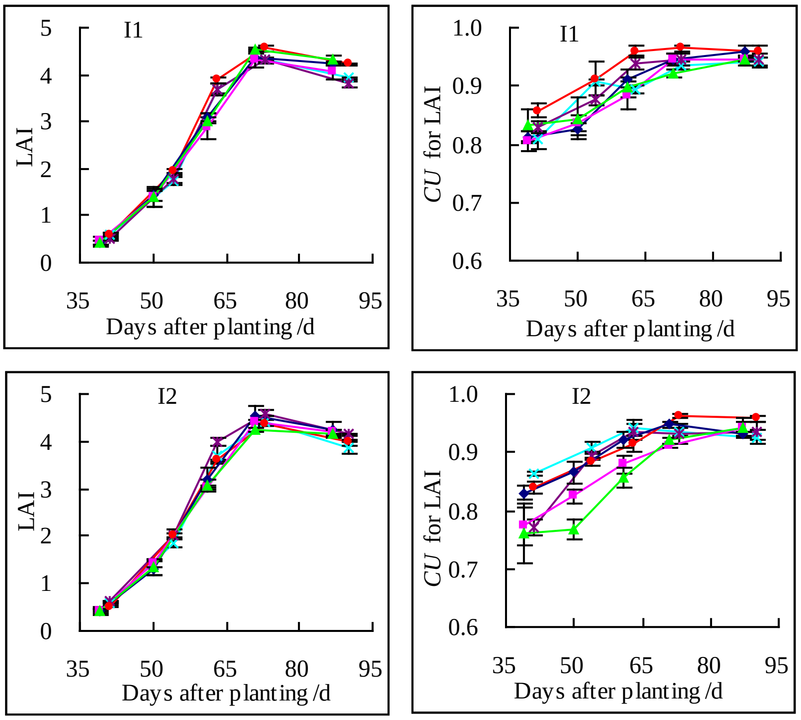


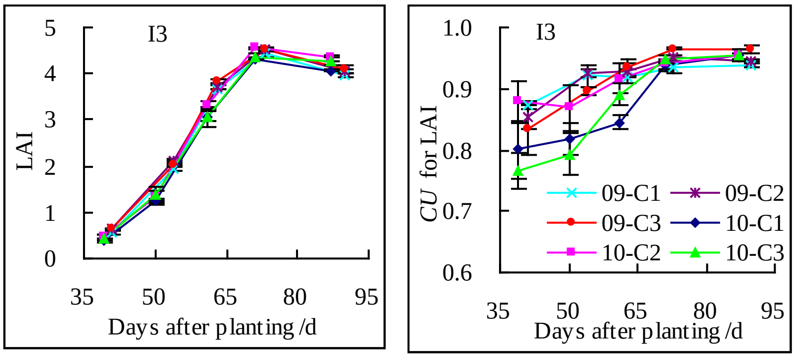


(a) Plant height (b) *CU* for plant height

Figure 2. Variations of the mean and the uniformity coefficient for plant height during the both growing seasons of spring corn.

09-C1, 09-C2, and 09-C3 represent the mean or the uniformity coefficient of plant heigh for the treatments of irrigation uniformity of 0.66, 0.81, and 0.99 in growing season of 2009, respectively; 10-C1, 10-C2, and 10-C3 represent the mean or the uniformity coefficient of plant height for the treatments of irrigation uniformity of 0.66, 0.81, and 0.99 in growing season of 2010, respectively.



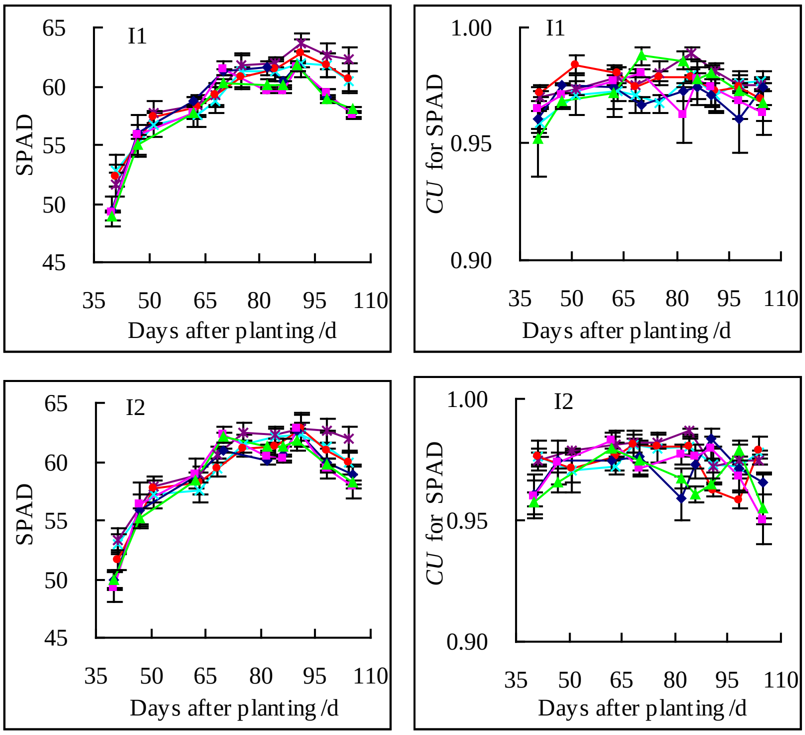


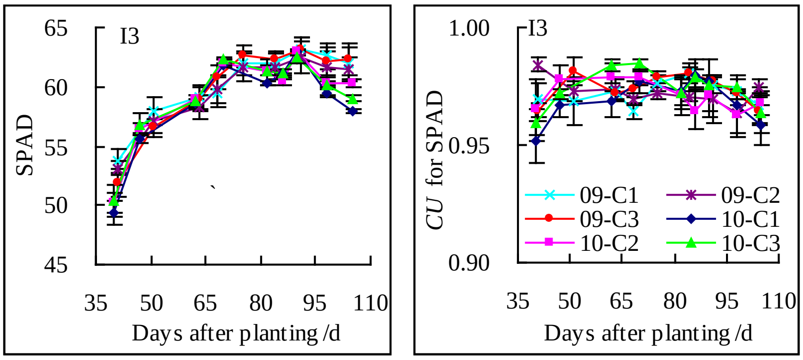
(a) LAI (b) *CU* for LAI

Figure 3. Variations of the mean and the uniformity coefficient for LAI during the both growing seasons of spring corn.]

3.2 Chlorophyll meter readings

The mean and the uniformity coefficient of SPAD readings for all treatments in 2009 and 2010 are shown in Fig. 4. The mean SPAD readings for all treatments increased at early stage, then changed slightly, and declined to some extent at later stages, consistent with the LAI changing during the growing seasons. The uniformities of SPAD readings for all treatments were more than 0.95 in both growing seasons and the variance analysis indicated that the irrigation uniformity coefficient and application amount had insignificant influence on the mean and the uniformity for SPAD readings, except that the irrigation uniformity had significant influence on the uniformity of SPAD readings at DAP 68 (11 July) in 2010.





(a) SPAD readings (b) *CU* for SPAD readings

Figure 4. Variations of the mean and the uniformity coefficient for SPAD readings during the both growing seasons of spring corn.

3.3 Dry biomass

The dry biomass for all treatments had quite small difference for a given growing stage (Fig. 5). The average *CU*s of dry biomass for all treatments reached 0.93 and 0.92 at harvest in 2009 and 2010, respectively. The variance analysis indicated that the application amount had significant influence on the uniformity of dry biomass at DAP 41 in 2009, while the irrigation uniformity coefficient and application amount had insignificant influence on the mean of dry biomass and its uniformity at other stages in 2009 and at all stages in 2010. The mainly reason was that the precipitation was less (only 7.4 mm, Fig.1) before 5 June (DAP=41 d), and the crop water requirement mainly came from the irrigation amount.

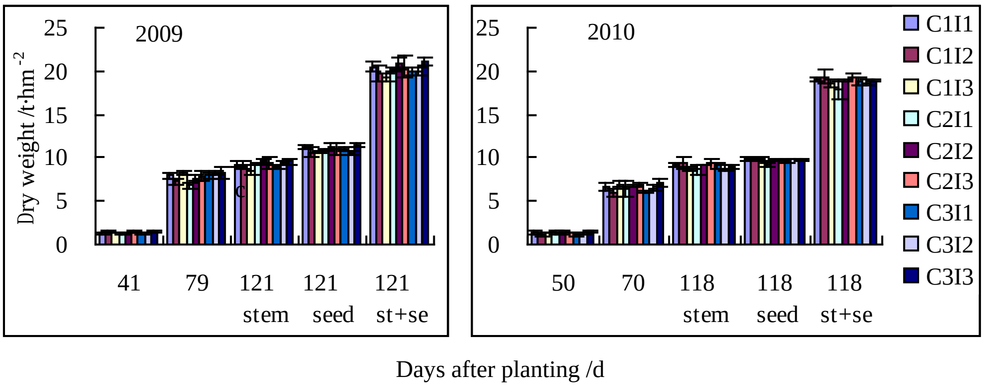


Figure 5. Variations of dry biomass during the both growing seasons of spring corn.

3.4 Yield and yield components

The yield and yield components for all treatments in 2009 and 2010 are summarized in Table 4 and Table 5. The yield were 10.9-11.3 t/ha and 8.5-9.2 t/ha for 2009 and 2010 experiments, respectively. The uniformity of yield did not obviously decline with the declining of irrigation uniformity. For example, the uniformity of yield were 0.96, 0.96, 0.96 and 0.93, 0.94，0.94 for the low, medium, and high irrigation uniformity treatments (mean of three application amount levels) in 2009 and 2010, respectively. The uniformity of yield for the low and the medium irrigation uniformity treatments (0.96, 0.96 in 2009 and 0.93, 0.94 in 2010) were larger than the irrigation uniformity (0.66 and 0.81). This illustrated that irrigation uniformity had little influence on yield. The variance analysis also indicated that uniformity coefficient, application amount and the interaction between the two factors had insignificant influence on the mean and uniformity of yield.

In order to clearly illustrate the relationship between the irrigation uniformity and the yield, the variation of emitter discharge rates and yield along the dripline are shown in Fig. 6. As shown in the figure, yield did not follow the pattern of emitter discharge rates for the treatments of *CU*s of 0.66 and 0.81. Though maximum to minimum ratio of emitter discharge rates for the low and medium *CU* treatments were larger than that for the high *CU* treatments, the maximum to minimum ratio of yield for all treatments were almost similar.

The insignificant influence of irrigation uniformity on yield may be caused by the precipitation (384 mm and 260 mm in 2009 and 2010, respectively, Table 1) in the experimental site of semi-humid regions, like in north China plain. The result simulated by Chen and Zheng (1995) also reported that the precipitation can reduce the influence of irrigation uniformity on yield.

Table 4. Effects of different treatments on yield and its components in 2009.

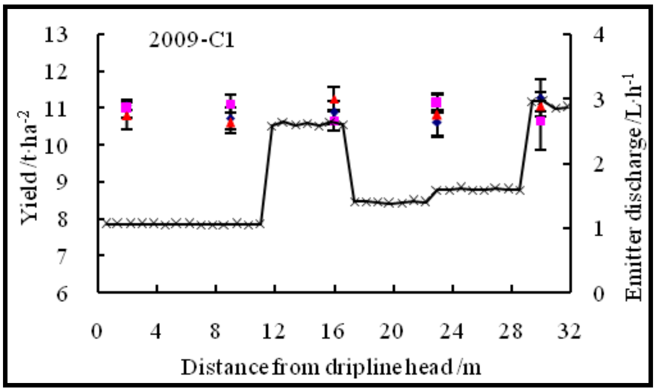
Treatment	Ear length /cm	barren ear tip /cm	grain number	100-seed weight /g	Yield /t·ha^{-1}
C1I1	23.28a[a]	2.52a	504.2a	44.56cB	10.90a
C1I2	23.60a	2.50a	498.13a	44.85bcAB	10.89a
C1I3	23.33a	2.61a	501.40a	44.82bcAB	10.89a
C2I1	24.02a	2.63a	505.80a	44.99bcAB	10.94a
C2I2	23.71a	2.38a	515.80a	45.09bcAB	11.17a
C2I3	23.68a	2.52a	518.07a	45.45abcAB	11.34a
C3I1	23.74a	2.45a	507.13a	45.88abAB	11.24a
C3I2	23.35a	2.44a	492.27a	46.56aA	10.90a
C3I3	23.73a	2.41a	516.33a	45.47abcAB	11.24a
Average	23.61	2.50	506.57	45.28	11.06
Two-way analysis of variance					
CU	NS(P=0.54)	NS(P=0.79)	NS(P=0.37)	**(P=0.01)	NS(P=0.44)
I	NS(P=0.93)	NS(P=0.82)	NS(P=0.51)	NS(P=0.52)	NS(P=0.72)
CU×*I*	NS(P=0.89)	NS(P=0.96)	NS(P=0.68)	NS(P=0.58)	NS(P=0.80)

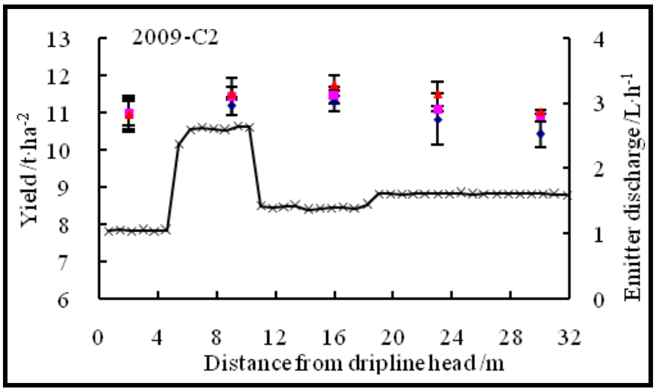
[a] Column means within a parameter followed by the same letter are not significantly different（P＜0.05，LSD); “**” means a significance level of 0.01

Table 5. Effects of different treatments on yield and its components in 2010.

Treatment	Ear length /cm	barren ear tip /cm	grain number	100-seed weight /g	Yield /t·ha^{-1}
C1I1	20.74a[a]	1.53abcAB	498.42a	32.57a	8.94a
C1I2	20.91a	1.36bcAB	509.33a	33.00a	9.04a
C1I3	21.02a	1.59abcAB	489.83a	32.98a	8.90a
C2I1	20.84a	1.47abcB	484.21a	32.50a	8.53a
C2I2	20.82a	1.17cB	496.75a	32.02a	8.80a
C2I3	21.45a	1.21cAB	501.71a	33.35a	9.21a
C3I1	21.02a	1.55abcAB	485.75a	32.38a	9.03a
C3I2	21.07a	1.76abAB	475.00a	33.06a	9.00a
C3I3	20.89a	1.84aA	494.92a	33.36a	9.20a
Average	20.99	1.50	492.88	32.80	8.96
Two-way analysis of variance					
CU	NS(P=0.74)	**(P=0.01)	NS(P=0.14)	NS(P=1.00)	NS(P=0.69)
I	NS(P=0.63)	NS(P=0.59)	NS(P=0.67)	NS(P=0.99)	NS(P=0.60)
CU×*I*	NS(P=0.49)	NS(P=0.45)	NS(P=0.18)	NS(P=1.00)	NS(P=0.83)

[a] Column means within a parameter followed by the same letter are not significantly different（P＜0.05，LSD); “**” means a significance level of 0.01


2009-C1
Yield /t·ha-2
Emitter discharge/L·h-1
Distance from dripline head /m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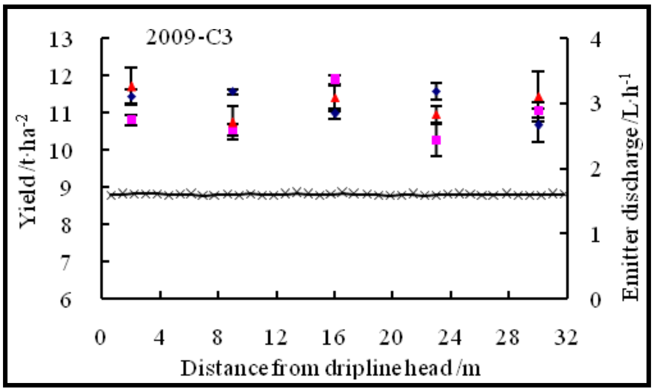
Emitter discharge/L·h-1
Distance from dripline head /m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Emitter discharge/L·h-1
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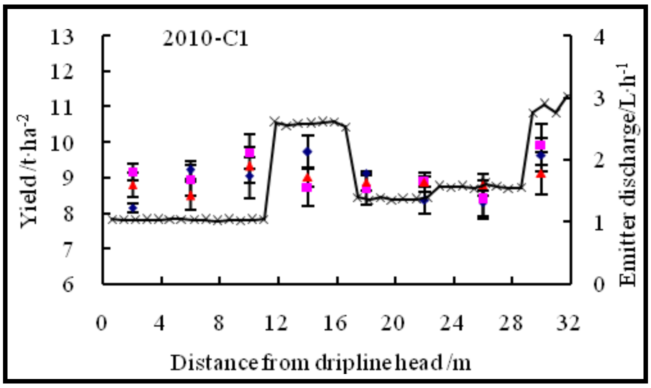
2010-C1
Yield /t·ha-2
Emitter discharge/L·h-1
Distance from dripline head /m

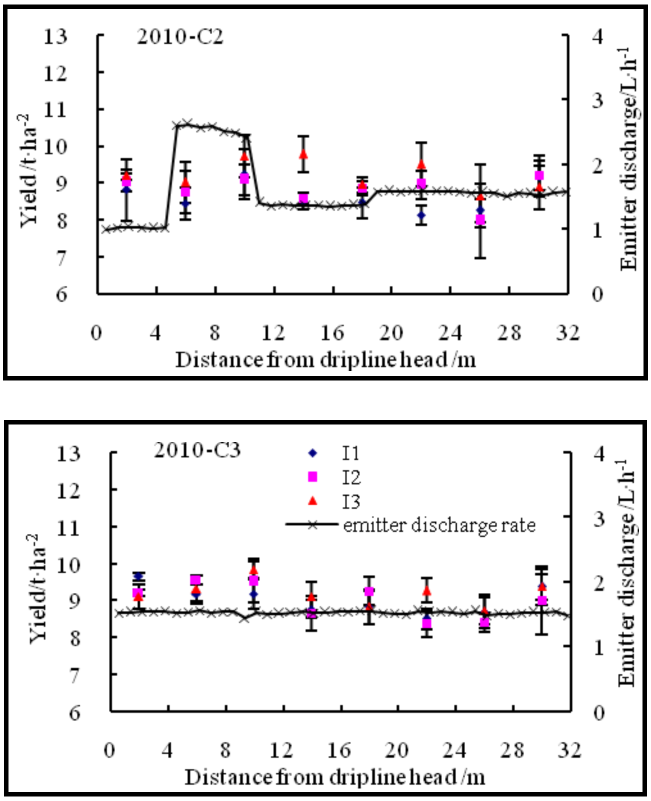

Figure 6. Variations of yield and emitter discharge rates along the dripline.

4. CONCLUSIONS

Field experiments were conducted in 2009 and 2010 growing seasons of spring corn (*Zea mays* L.) to evaluate the influence of irrigation uniformity and application amount on plant height, LAI, SPAD readings, dry biomass, and yield. The following conclusions were supported by this study.

- Drip irrigation uniformity and application amount had insignificant influence on the mean of plant height, LAI, SPAD readings and dry biomass in both 2009 and 2010 (α =0.05). The uniformity coefficients for all parameters mentioned above increased with spring corn growing and reached a final value of larger than 0.90, being greater than the irrigation uniformity for the treatments of *CU*s of 0.66 and 0.81.
- The yield demonstrated a quite uniform distribution along the dripline for all *CU* treatments tested and an insignificant influence of drip irrigation uniformity and application amount on the mean and uniformity of yield was observed. This suggests that the current design standard of irrigation uniformity coefficient (CU≥0.8) might be fairly lowered in the semi-humid regions, likely north China plain, in order to reduce the initial and operation costs of drip irrigation systems.

ACKNOWLEDGEMENTS

This study was financially supported by the National Natural Science Foundation of China (grant no. 50979115). We would like to acknowledge Drs. Yanfeng Li and Weixia Zhao, Department of Irrigation and Drainage, China Institute of Water Resources and Hydropower Research, for their assistance in this study.

REFERENCES

1. Allen R. G., L. S. Pereira, D. Raes, and M. Smith. 1998. Crop Evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No.56, FAO, Rome.
2. Barragan J., V. Bralts, and I. P. WU. 2006. Assessment of emission uniformity for micro-irrigation design. Biosystems Engineering. 93(1): 89-97.
3. Bordovsky J. P. and 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. Chen Q. 1993. Simulation and research of uniformity for drip irrigation. Beijing: Beijing Agricultural University (in Chinese).
5. Chen Q. and Y. Zheng. 1995. Optimizing determination of irrigation uniformity in the design. Transaction of the CSAE. 11(2): 128-132 (in Chinese).
6. Du Z. 2007. Water and Nitrogen Distributions and Summer Maize Growth as Affected by Spatial Variability of Soil Properties and Lateral Depths of SDI Systems. Beijing: China Agricultural University (in Chinese).
7. Hu Q., S. Shang, J. Tian, and B. Meng. 2006. Application of water stress coefficient from FA056 to the field water balance analysis. Transaction of the CSAE. 22(5): 40-43 (in Chinese).
8. Jin C. 2005. Study on Random Number Generator and Random Sampling in Monte Carlo Method. Dalian: Dalian University of Technology.
9. Lamm F. R., J. E. Ayars, and F. S. Nakayama. 2007. Microirrigation for Crop Production: Design, Operation, and Management. Amsterdam: Elsevier.
10. Li J. 1996. Simulation of the effects of sprinkle uniformity on crop yield. Transaction of the CSAE. 12(4): 102-107 (in Chinese).
11. Li J., L. Chen, and Y. Li. 2008. Field evaluation of emitter clogging in subsurface drip irrigation system. Transaction of the CSAE. 39(10): 1272-1278 (in Chinese).
12. Li J., J. Yin, H. Zhang, and Y. Li. 2010. Field evaluation of drip fertigation uniformity effects on distributions of water and nitrate in soil. Transactions of the CSAE. 26(12): 27-33 (in Chinese).
13. Li J., J. Yin, H. Zhang, and 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).
14. Li J., J. Zhang, and K. Xue. 2003. Principles and Applications of Fertigation through Drip Irrigation Systems. Beijing: China Agricultural Science and Technology Press (in Chinese).
15. Liu Y., L. Wang, G. Ni, and Z. Cong. 2009. Spatial distribution characteristics of irrigation water requirement for main crops in China[J]. Transactions of the CSAE. 25(12): 6-12 (in Chinese).
16. Mateos L., E. C. Mantovani, and F. Villalobos. 1997. Cotton response to non-uniformity of conventional sprinkler irrigation. Irrigation Science. 17: 47-52.
17. Nakayama F. S., D. A. Bucks, and A. J. Clemmens. 1979. Assessing trickle emitter application uniformity. Transactions of the ASAE. 22(4): 816-821.
18. Or D. and R. J. Hanks. 1992. Soil water and crop yield spatial variability induced by irrigation nonuniformity. Soil Science Society of America Journal. 56: 226-233.
19. Qin Y. Soil Physics. 2003. Beijing: Higher Education Press (in Chinese).
20. Rostami M., A. R. Koocheki, M. N. Mahallati, and M. Kafi. 2008. Evaluation of Chlorophyll meter (SPAD) Date for Prediction of Nitrogen Status in Corn (Zea mays L.). American-Eurasian Journal of Agricultural & Environmental science. 3(1): 79-85.
21. SPSS. 2006. SPSS 15.0 for Windows. Verison 15.0. Chicago, IL.: SPSS, Inc.
22. Warrick A. W. and M. Yitayew. 1988. Trickle lateral hydraulics. I. Analytical solution. Journal of Irrigation and Drainage Engineering, ASCE. 114(2): 281-288.
23. Wu I. P. and H. M. Gitlin. 1973. Hydraulics and uniformity for drip irrigation. Journal of Irrigation and Drainage Division, Proc. of the ASCE. 99(IR2): 157-168.
24. Zhang G. and P. Wu. 2005. Determination of the design working head of emitter. Transaction of the CSAE. 21(9): 20-22 (in Chinese).